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

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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 shal­

INTRODUCTION*

Despite the work of many geologists, "serpentine plugs" have been recognized as significant petroleum targets on a national scale only since the early 1970s. Although volcanic features are rarely sites for petroleum exploration, one of the most unusual and profitable hydrocarbon plays in central and southern Texas coincides exactly with these volcanic features, each of which has the potential to produce from both volcanic and associated sediments. The belt of volcanic activity roughly parallels the ancient Ouachita structural belt and marks the southeastern margin of the East Texas Andean 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.

Although volcanic features are rarely sites for petroleum exploration, one of the most unusual and profitable hydrocarbon plays in central and southern Texas coincides exactly with these volcanic features, each of which has the potential to produce from both volcanic and associated sediments. The belt of volcanic activity roughly parallels the ancient Ouachita structural belt and marks the southeastern margin of the East Texas Andean 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 geophysics, and strategically placed seismic lines.
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 facies, and (3) a southern group characterized by well-attractive venture.

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 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

METHODS

The methods used in this investigation included limited field reconnaissance of known "serpentine plugs" in the study area; examinations 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

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 Palaeozoic 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: Balones, 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).
first solely geologic work was done by Owen (1889 in Spencer, 1965, p. 13) who 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. Tait and Comstock (1892 in Spencer, 1965, p. 13) both recognized and commented on igneous rocks in Uvalde County. Osanti (1893, p. 341-346) gave a petrographic description of a melilitic 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 Vaughan (1898 in Spencer, 1965, p. 13) observed that solid igneous masses occurred in Uvalde County, whereas buttresses capped by igneous rock occurred in Kinney County. Vaughan (1890 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 Vaughan (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 rocks were 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 origin of the Thrall "plug" and to its relationship to petroleum occurrence. They believed the reservoir was extensile 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 to form a "serpentine" for convenience. They gave the name "serpentine" to the characteristic green, greasy rock. Bybee recorded the production history of the Thrall oil field and concluded that the source of the oil was adjacent shales either above or below the volcanic rock (Bybee, 1921, p. 659). Bybee and Short (1925) invented the Lytton Springs oil field, the largest of the fields then produced from volcanic rock. They discovered in it 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 alternations seen in surface exposures such as Pilot Knob (Bybee and Short, 1925, p. 13). Collingwood and Retger (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 "serpentinite" originated in three ways: (1) weathering residue of volcanlastic detritus, (2) sedimentary redeposition of volcanic ejecta, and (3) alteration of massive volcanic 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 Retger (1930, p. 191) 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 Yeast field, Bastrop County, Texas. A magnetometer investigation of igneous intrusions along the western end of the Balcones fault zone, exemplified by the Little Fy Pan area, Uvalde and Kinney Counties, Texas, was discussed by Liddle (1930, p. 509), and some "plugs" were found to be represented by oil-enriched rocks, whereas others were marked by negative anomalies. Adkins (1932) in an overview of Cretaceous stratigraphy of Texas, summarized briefly the then recognized occurrence of "serpentine plugs" and their structural setting. Sellards (1932) in a similar study also summarized briefly the known occurrences of "serpentine plugs" and their structural setting. McCallum (1933, p. 32) reported the occurrence of reworked igneous deposits peripheral to a "plug" that originated in the Darien Creek formation, Uvalde County, Texas. Smiser and Wintemberg (1932, p. 260) discussed the characteristic and possible origin of the producing rock in Hill oil field, Bastrop County, Texas. They concluded that the reservoir rock was "serpentine" and lapilli tuff, and related the occurrence of the "serpentine" to its effect on hydrocarbon occurrence in Hill oil field. Sayre (1936) mapped and reported locations of igneous bodies within Uvalde and Medina Counties, Texas, with emphasis on those exposed at the surface. McKinley (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 Messa 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 occurrence. 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 evidence of shallow-water, high-energy conditions, whereas the outlying areas of Austin Chalk were indicative of quieter-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. Mike McCallum (1955, p. 136) described the mineralogy of the "serpentine" at Pilot Knob, but 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 subsurface to the Coastal Plain and related the geometry of the igneous activity that took place during Late Cretaceous, Austin and Taylor time. He believed that the igneous activity was contemporaneous with normal

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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.
faulting in the northern San Marcos arch area. Greenwood (1956) considered the possible occurrence of submarine volcanic mudflows in the Cretaceous age (Coniacian / Campanian) and related these deposits to the "serpentine plug" trend, which he 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 stratigraphic and structural entrapment of hydrocarbons in the Cretaceous age (Coniacian / Campanian) and related the structural traps to the "serpentine plug" trend, which he 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 stratigraphic and structural entrapment of hydrocarbons in the Cretaceous age (Coniacian / Campanian) and related the structural traps to the "serpentine plug" trend, which he 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.

Wilson (1977, p. 23-24) considered recent tectonism in south Texas and believed that injection of mantle material gave rise to hydrocarbon generation. He indicated that the injection of mantle material gave rise to hydrocarbon generation. He also described the structural and stratigraphic entrapment of hydrocarbons in the Cretaceous age (Coniacian / Campanian) and related the structural traps to the "serpentine plug" trend, which he 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.

Barker and Young (1979) described Pilot Knob as a subaqueous Cretaceous nepheline basanite volcano. They described the stratigraphic and structural entrapment of hydrocarbons in the Cretaceous age (Coniacian / Campanian) and related the structural traps to the "serpentine plug" trend, which he 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.

Hunter and Davis (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 limestone, interpreted 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.

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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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REGIONAL SETTING OF "SERPENTINE PLUGS"

Igneous rocks of Cretaceous age (Coniacian / Campanian) are distributed on the shelf in south Texas. They are associated with a surface exposure of basaltic volcano. He recognized this as a surface parallel to subsurface occurrences.

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 paragneiss-mylonite zone that formed on the flanks of the Pilot Knob volcano of Travis County.

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

Wilson (1983, p. 22) described the stratigraphic relations of the Anacacho Formation of south Texas, which he recognized as an ophiolite complex on igneous-plutonic bathymeric highs. He indicated that the paleoenvironmental conditions in the northern Gulf Coastal Plain were significantly influenced during Late Cretaceous time by such features.

Fish and Seely (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.
**PETROLEUM POTENTIAL, "SERPENTINE PLUGS"**

The approximately 225 surface and subsurface occurrences of "serpentine plugs" and the associated "serpentinite" are divided into three subsprovinces based on production histories and associated facies.

**NORTHERN SUBPROVINCE**

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

Stratigraphically, the "serpentine plugs" of the northern subprovince 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. Five of the largest groupings of "serpentine plugs" in the northern subprovince appear to extend from southwest Bastrop County, through central Caldwell County, into northern Guadalupe County (Fig. 2). This concentration of volcanic centers coincides closely with the down-to-the-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 concentrations 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 volcanic activity in the northern subprovince 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 suggests that Luling faulting was active in central Texas during Austin/Taylor time.

The surfaces of larger volcanic mounds are relatively flattened oval shapes, whereas smaller mounds may tend to rise to peaks. The volcanic mounds rise from approximately 150 to 300 ft (=46-90 m) above the Austin sea floor, and present dips in adjacent and overlying beds tend to be eastward (Ewing and Caran, 1992, 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 (Fig. 3), the drill pierced igneous rock into chalk and back into igneous rock, thus demonstrating the stratification of the volcanics and 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 the altered igneous rocks being thought to be intrusive in origin; thus, the term "serpentine plug" is appropriate.

Further work on surface and subsurface examples revealed that the rocks were not serpentine nor intrusive. They instead represent an alteration assemblage of hydrated magnesium silicates derived from the alteration of extrusive basaltic rocks. Texturally, the "serpentine" is similar to that derived from extrusive volcanic activity in a submarine environment. Therefore, the name most widely used to describe these rocks is appropriate 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.

The term "serpentine plug" to describe these unique features has come under much criticism. Initially, the altered igneous rocks were thought to be intrusive in origin, thus the term "serpentine plug" was appropriate. Further work on surface and subsurface examples revealed that the rocks were not serpentine nor intrusive. They instead represent an alteration assemblage of hydrated magnesium silicates derived from the alteration of extrusive basaltic rocks. Texturally, the "serpentine" is similar to that derived from extrusive volcanic activity in a submarine environment. Therefore, the name most widely used to describe these rocks is appropriate 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.
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 occurs as a result of 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).

Hillig 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 Hillig field is best illustrated by the Humble Oil. Hillig 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-west. 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 negligible 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 Hillig field were examined both in hand specimen and microscopically and are described in Appendix I in Band 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, moderately sorted, subangular-subrounded, lapilli limearenite to litharenite 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 Hillig 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).

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

Porosity in the altered pyroclastic rock is both original and secondary. Porosity is commonly reduced with the occurrence of diagenesis 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

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

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

The source for oil in Hillig 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 in Appendix I in Band 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, moderately sorted, subangular-subrounded, lapilli limearenite to litharenite 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 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-west. 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 negligible 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 Hillig field were examined both in hand specimen and microscopically and are described in Appendix I in Band 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, moderately sorted, subangular-subrounded, lapilli limearenite to litharenite 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 Hillig 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 diagenesis 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
and their associated facies in the northern subprovince. Note the typical Austin shelf facies on the flanks of the volcanic center. Volcaniclastic facies, the truncation of the McKown Formation, and volcanic tuff filling the explosion crater, the reworked pyroclastic and volcanic tuff mound. (mk = McKown, pf = Pflugerville, vc = volcaniclastic, pc = pyroclastic, bd = Burditt).

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

The occurrence of relatively thin biocalcaritentrices 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). Sutli 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 mi² (15 km²).

The stratigraphic section in Sutli field is best illustrated by the Barker Exploration Company, Bienen #1 well (Fig. 12). The Eagle Ford and Buda Formations were deposited 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 biocalcarerite 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, Dooge #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 biocalcarerite 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 biocalcarerite 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 biocalcareite 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 biocalcareal algal packstone-to-grainstone (Fig. 11; Appendix I). The occurrence of the red algae Goniolithon within the biocalcareite facies is indicative of a high energy environment (Fig. 16). This unit reaches a maximum thickness of 30 ft (9 m).
and thickens 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 interstratified 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 near 6500 ft (1981 m) in the south.

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 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) (Weider 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

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Fig. 8. (A-B). A core from the Humble Oil & Refining Co. Wolfbarger #2 at 2557-2575 ft (= 778-785 m), coarse grained and 2650-2668 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.

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Fig. 9. McKown Formation exposed at McKinney Falls State Park. The McKown Formation is a shallow-water carbonate facies of the Austin Group, here underlain by fine-grained marlstone 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.

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

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Fig. 11. Representative diagrammatic section of a "serpentine plug" and its associated facies in the middle subprovince.
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 biothermal carbonates of Taylor age, the Anacacho Formation, overlie the volcanic centers. The best documented development of the Anacacho 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, 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.
on the southwest side. Similar relationships should hold for other "plugs" in the southern subprovince.

Porosity within the shalow-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 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

(Taylor, 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 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. 120).

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
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) melilitite 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 perphyritic, holocrystalline, melilitite-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 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. 25). 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 coquinaid 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. 18. Original sea floor topography of volcanics, Sutil field, Wilson County.

Fig. 19. Schematic model of the facies associated with the Elaine field volcanic complex, Dimmit County. The carbonate facies represent beach, lagoon, algal-pelletstone halo, high-energy reef, and open-shelf environments (from Luttrell, 1977, p. 277).

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 exploded into a phreatomagmatic eruption (Fig. 25). These explosions, at or below sea level, created craters on 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 on the surface. Upon breaching the sea floor, or encountering aquifers below the sea floor, the ascending magma exploded into a phreatomagmatic eruption (Fig. 25). This accumulation of coarser material around the vent formed a 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 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 subaerially 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-beded, 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 basaltic and rarer basanite and olivine nephelinite magmas, apparently derived from partial melting of upper mantle garnet peridotites. All magmas were erupted through the subaerial volcanoes and submarine feeder systems and the Ouachita system. During and after 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 southern 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-beded 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 Upton 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 systems and the Ouachita system.

**Fig. 25.** 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 plug." The San Miguel and Olmos sands form a compositional dome 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.

**Fig. 23.** NW-SE structure cross-section C-C', Torch field, Zavala County. Datum sea level. Adapted from Lewis, 1962.
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 Carra, 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 Bastrop County, was discovered on February 2, 1915 (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 gravity oil were taken from the 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.

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 in exploration in this area are mainly shallow depth, between 500 and 3500 ft (=152-1067 m), and longevity of production. The largest known field, Lyston 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 bioclastic 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 1967. 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 bioclastic 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. 1). Two wells were drilled to an average depth of 6000 ft (=1829 m) and produced 4,240 barrels the first year. The total production from the Sutil 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 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 Buda and Austin Formations, in addition to reservoirs directly related to the “serpentine plug.”
production for the middle subprovince to the end of 1983 was approximately 3,508,221 barrels, and four of these 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. 29). 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 its 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 100,906 barrels (Fig. 2).
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) 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," thus making the deeper horizon of "serpentine plugs," thus making the deeper horizon of this study. The distinct dipolar anomaly, which encircles the field, may be modeled as a squat cylinder (Gibson, 1985). This suggests that 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 fruitful, 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 the value of satellite data and airborne photography for searching for oil fields. Microseepage of hydrocarbons and color variations resulting from chemical alteration have been recognized in several hydrocarbon producing areas (Patton and Maxwarin, 1984, p. 441). Stressed vegetation, visible on thematic mapper data, coincided with an area of marked leakage of hydrocarbons in the Patrick Creek field, Wyoming (Mathews 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, Hardin 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 anomalous population of maple trees in a climax oak forest apparently due to hydrocarbon leakage. Lost River field was also found to coincide with an area of greater lineament density (ibid., p. 564).

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 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...
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 magnetic surveys appear to give more conclusive response. "Serpentine plug" 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).

Magnetic 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 magnetic surveys. Magnetic has been used with success predominately in the northern and southern subprovinces where depths rarely exceed 3500 ft (≈ 1050 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. With most of the igneous material emplaced as ash or tuff and hydrothermally altered to clay, density contrasts should be minimal. The small size and relatively small 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 fps (≈ 5486-7315 m/s). These are substantially higher than those of the Austin Formation, 12,000 to 15,000 fps (≈ 3700-4570 m/s), or the Taylor Formation, 10,000 to 13,000 fps (≈ 3050-4000 m/s). However, palagonite tuff mounds have low compressional wave velocities, averaging 9,500 fps (≈ 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 "plug." With the proper use of exploration tools such as enhanced remote-sensing techniques, magnetics, and seismic reflection, further 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, 2537-2863 ft

Goree #1, 2536-2867 ft

Friske #2, 2489-2173 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 porphyric, 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 chlorite or calcite (Fig. 33). The rock fragments and basaltic glass are commonly associated with alteration products such as chlorite or chalcedony, which appears greenish in this section (a hydrous Mg, Fe, Al silicate similar to dike and gneiss), and chlorite. Calcite and zeolites form rims surrounding the grains. Sherd 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. 100). This contrast suggests that palagonitization of fragment rims occurred prior to chloritization. Locally, port fillings and fractures are filled with calcite or chalcedony, and chlorite either runs out of grain or occurs in vein form (Fig. 34a, 34b). A probable paragenetic sequence is: (1) the occurrence of chlorite as a pore filling or clay rim due to the alteration of feldspar, pyroxene, or amphibole, (2) the introduction of silica in the form of chalcedony, as pore and/or fracture fill, and (3) the advent of carbonate material as a result of partial dissolution of silica due to alkali 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 basalt (Burke, 1965).
LOCALITIES

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


APPENDIX II

Fig. 32. Photograph of thin section from Humble Oil & Refining Co. Wolfenbarger #2 at 2273-2283 ft (§ 762-766 m) (X40). Note the rounded, poorly sorted, porphyritic nature of the altered igneous rock fragments. The major constituents are plagiolitic laths, skeletal olivine, pyroxene, 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. Frisk #2 at 2460-2461 ft (§ 750-756 m) (X40). The basaltic glass occurs as rims around pyroclastic rock fragments and is light in color. Dark chlorite occurs within fragment interiors. Silica and carbonate chalcedony or calcite.

Fig. 34. (A) Photograph of thin section from the Humble Oil & Refining Co. Wolfenbarger #2 at 2575-2587 ft (§ 785-788 m) (X40). Note the wavy, fibrous outline shows chlorite developing as a pore lining associated with calcite grains (4 micron).
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