Geological Circular 82-1

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LINEAMENT ANALYSIS AND INFERENCE OF GEOLOGIC STRUCTURE — EXAMPLES FROM THE BALCONES/OUACHITA TREND OF TEXAS[1]

S. Christopher Caran, C. M. Woodruff, Jr., and Eric J. Thompson[2]

ABSTRACT

Lineaments perceived in remotely sensed images are reliable indicators of geologic structure. Lineaments on ten Landsat multispectral scanner images (band 5; 1:250,000 scale) were mapped covering the Ouachita/Balcones-Luling-Mexia-Talco structural trend between the Rio Grande and Red River in Texas. More than 5,000 lineaments were perceived in these images. Maps depicting the lineaments (individually and in various combinations) were compared with maps of structural/tectonic features and geothermal gradient contours, noting instances of apparent correlation among these themes.

Lineaments are correlative with the individual faults and the aggregate fault patterns of the Balcones, Luling, Mexia, and Talco fault zones. Transverse lineaments, which trend almost perpendicular to these fault zones, mark the northernmost extent of the Balcones fault system and outline carbonate platforms, such as the Belton High/Moffatt Mound trend and the San Marcos arch. Transverse lineaments are coincident also with the axes of the buried Chittim and Preston anticlines and with the flanks of the Sherman and Round Rock synclines. Numerous salt domes occur at depth in the western part of the east Texas basin near the trend; many of these domes, particularly those in Henderson, Anderson, and Freestone Counties, are found along and at the intersection of major lineament zones where the concentration of individual lineaments is greatest. Most of the buried Late Cretaceous volcanoes of central Texas near Austin lie along northeast-southwest-trending lineament zones; the altered pyroclastic rocks and associated beachrock facies at many of these volcanoes are hydrocarbon reservoirs. The orientation and spacing of geothermal gradient contour lines ("isograds") also correspond to major structures and, thus, to the pattern of lineaments throughout the region. Correlation of (1) individual lineaments, zones of contiguous or nearly parallel lineaments, and areas of homogeneous lineament density and orientation to (2) surface and subsurface structures and (3) geothermal "isograd" patterns indicates that lineament analysis has many potential applications to regional mineral resource assessment.

INTRODUCTION

The Ouachita/Balcones-Luling-Mexia-Talco structural trend in central Texas is an arcuate band of 1) deformed, locally intruded Paleozoic rocks composing a foundered orogenic complex (Ouachita System of Flawn *et al.,* 1961) and 2) superjacent Mesozoic and Cenozoic sedimentary units displaced by mostly down-to-the-gulf normal faults (Balcones, Luling, Mexia, and Talco fault zones). For simplicity, this structural belt is termed the Balcones/Ouachita trend and this discussion is concerned with the segment that extends from the Rio Grande near Del Rio to the Red River near Texarkana (Fig. 1). This part of the trend is approximately 600 mi (965 km) long and 30 to 80 mi (50 to 130 km) wide.

OUACHITA SYSTEM

The Ouachita component of the Balcones/Ouachita trend comprises a suite of stacked Paleozoic lithofacies and imbricated overthrust sheets that separates the North American Central Stable Region (craton) on the north and west from the downwarping Gulf of Mexico Basin on the south and east (Flawn, 1961a). This tectonic boundary has remained structurally active throughout most of Phanerozoic time, influencing deposition, structural deformation, and volcanism along most of the southern margin of the continental craton. Clastic and siliceous rocks were deposited in orogenic troughs bordering the craton and were folded and thrusted to the west and north during the Ouachita orogeny. The orogeny culminated in Pennsylvanian to Early Permian time, creating the Ouachita orogenic belt (King, 1975). Clastic sediment eroded from these highlands filled the adjacent Val Verde, Kerr, and Fort Worth basins of the foreland, which were rapidly subsiding (Flawn, 1961b; and King, 1961). The belt began to subside in Mesozoic time, concomitant with the marine transgression that controlled deposition during the Cretaceous Period throughout the region. A thick, marine carbonate sequence above basal Cretaceous sands covered most of the Ouachita System in central Texas. This stratigraphic section includes Late Cretaceous igneous rocks associated with volcanoes and dikes that are coincident with the Balcones/Ouachita trend.

FAULT ZONES

By Miocene time, but beginning locally perhaps as early as the Cretaceous Period (Hayward, 1978), the second principal component of the trend had been superimposed on the first. En echelon normal faults composing the Balcones, Luling, Mexia, and Talco fault zones (Figs. 2a and 2b) displaced a few thousand feet of the Mesozoic to lower Tertiary section above the Ouachita System subcrop. The faults, in aggregate, trend approximately parallel to the Ouachita structural grain. Foundered Ouachita structures acted as a hinge for downwarping into the ancestral Gulf of Mexico Basin (Miser, 1934). This downwarping, along with upward flexing of the continental interior west of the

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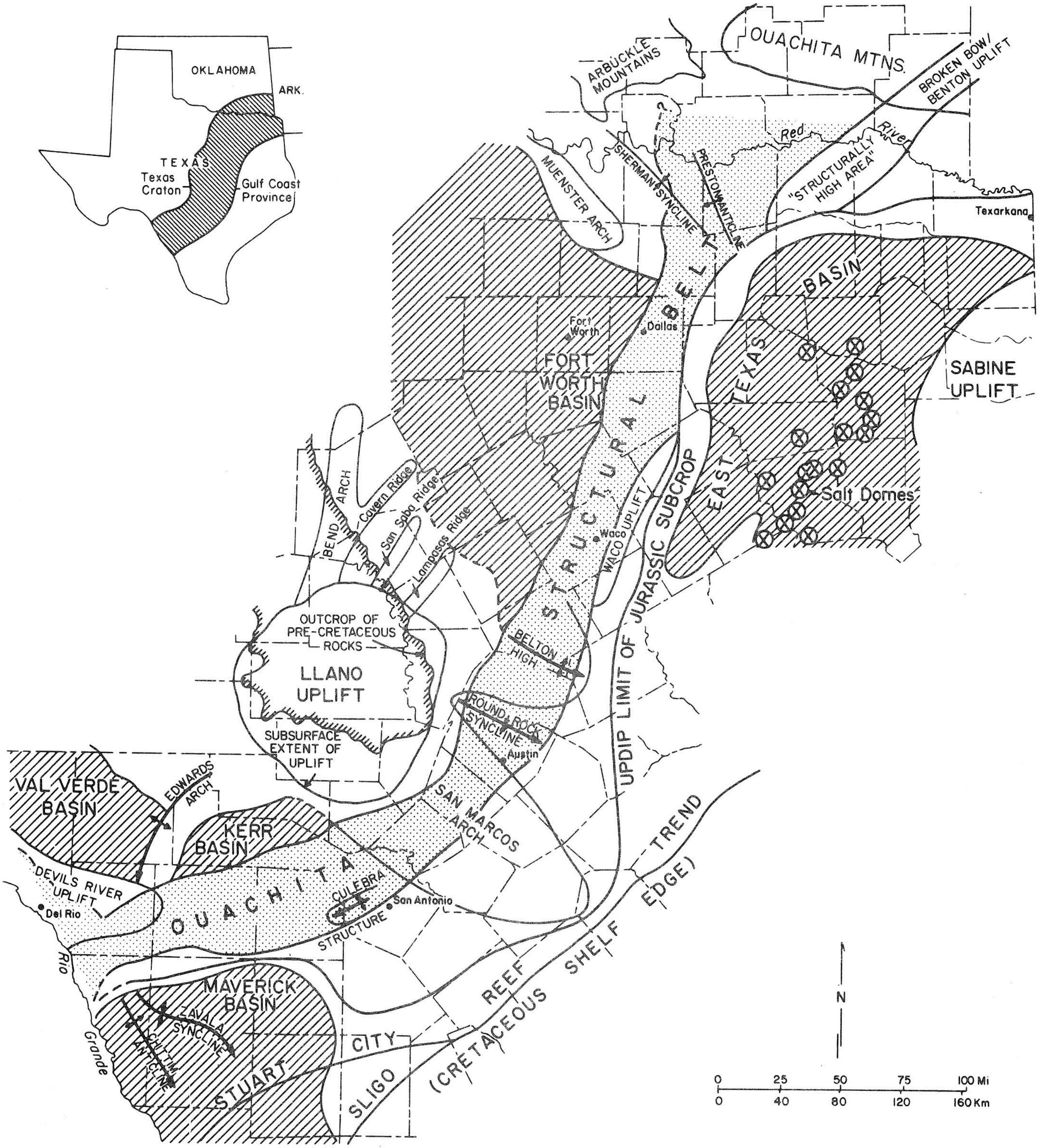

Figure 1. Major structural/tectonic features associated with the Balcones/Ouachita trend, Central Texas Region (after Flawn *et al.,* 1961, plate 2; Sellards and Hendricks, 1946; and others cited in text).

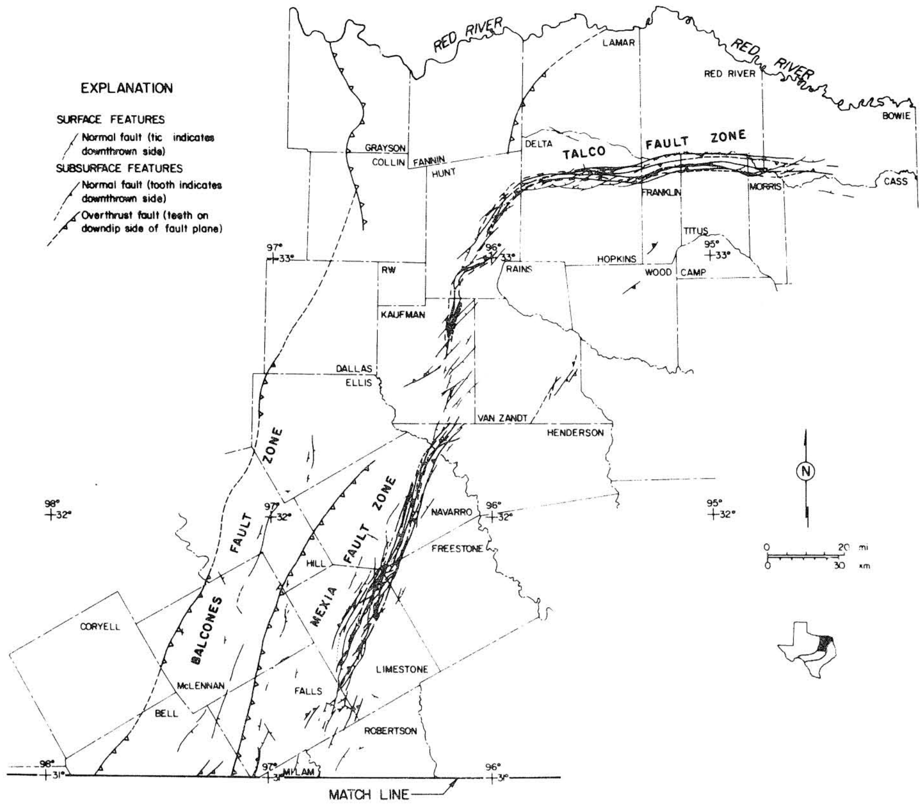

Figure 2a. Faults and fault zones of the Balcones/Ouachita trend, northern part (surface faults from Bureau of Economic Geology geologic atlas series; thrust faults from Flawn *et al.*, 1961, plate 2).

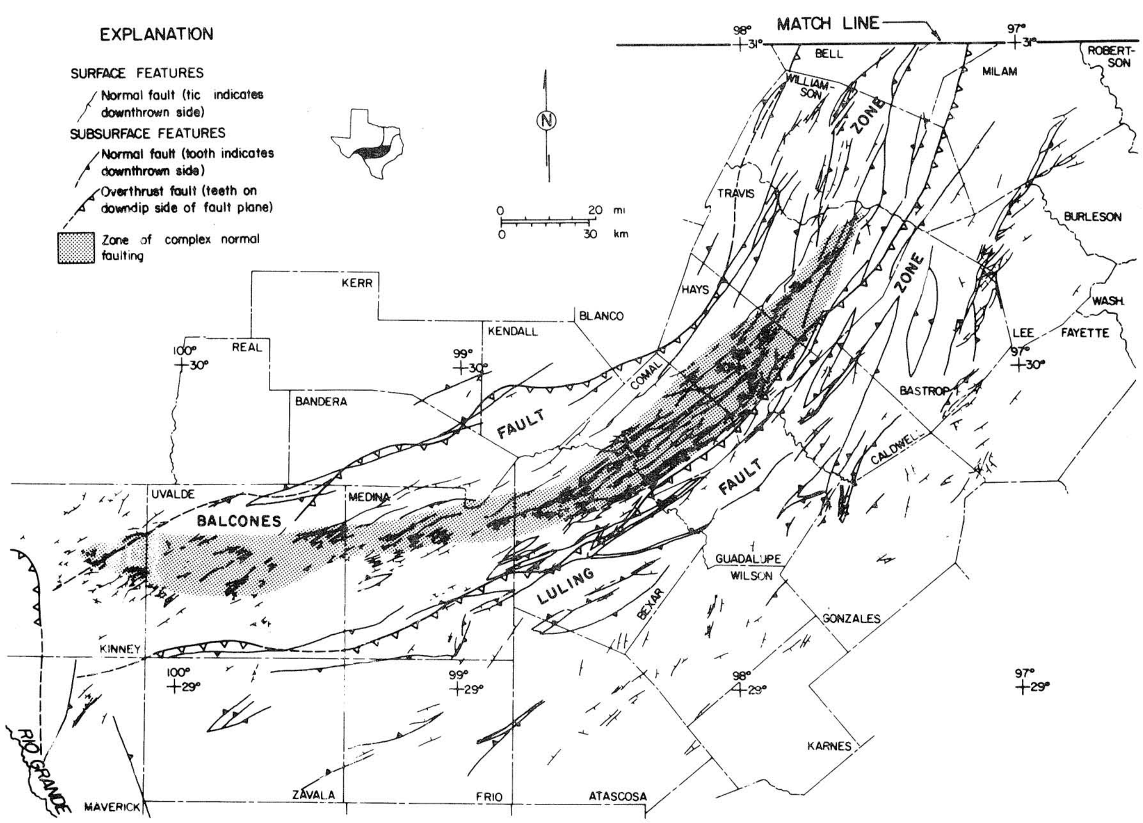

Figure 2b. Faults and fault zones of the Balcones/Ouachita trend, southern part (surface faults from Bureau of Economic Geology geologic atlas series; thrust faults from Flawn *et al.*, 1961, plate 2).

Balcones/Ouachita trend, continues at a measurable rate (Holdahl and Morrison, 1974). Local structural disturbances have occurred within the east Texas basin just east of the Balcones/Ouachita trend, where salt diapirs warped and pierced the overlying strata. Some of these diapirs reached the surface; and the movement of certain salt domes, including Oakwood dome in Leon and Freestone Counties (Collins *et al.*, 1981), has probably continued to the present (Sheets, 1947).

RESOURCES

The tectonic history of the Balcones/Ouachita trend also has affected the distribution of the mineral resources in the region, including fluid and solid hydrocarbons, potable ground water, iron, industrial clay, and construction materials such as lime, basalt, building stone, and sand. The authors became interested in this structural trend when its apparent influence on the distribution and properties of warm ground waters in the area was recognized (Woodruff and McBride, 1979). Geothermal ground water occurs at moderate depths in several aquifers along the trend. Although the quality of these waters is variable, affecting their use, the aquifers are found near the region's major population centers where institutional and industrial applications would be most practical. Growing interest in this potential heat source has stimulated a continuing research effort to define the region's geothermal resource potential (Woodruff *et al.*, 1981).

Data concerning these geothermal aquifers were scanty. There was relatively little available information from oil test wells along the Balcones/Ouachita trend; few wells of sufficient depth had been drilled because the Paleozoic (Ouachita facies) units were not (until recently) considered favorable target zones for petroleum exploration. Where drilling had occurred, the Lower Cretaceous aquifers, which are the principal sources of geothermal waters in the region, were usually cased before logging. This was done to prevent leakage of the frequently saline waters of these units into fresh-water aquifers penetrated higher in the section, but it also prevents acquisition of electric-log data from the cased interval. Because available well control is limited, other means of exploring for and assessing these geothermal resources were investigated.

METHODS

An alternate approach was described by Trexler *et al.* (1978). These investigators mapped lineaments perceived in satellite images covering known geothermal resource areas in Nevada and attempted to correlate these lineaments with the distribution of thermal springs and wells. Procedures used in this study, although different from those employed by Trexler and his coworkers, are predicated on a similar, two-part premise: that lineaments are correlative with structural features, including buried structures with subtle or obscure surface expression; and that these structures control the distribution and characteristics of geothermal (and other) resources. Warm-water aquifers can thus be investigated by using lineaments as a guide to structures governing resource distribution. Lineament analysis is particularly useful in areas where other types of control are inadequate, or where an independent confirmation of conclusions derived from other data is desired.

Landsat multispectral scanner (MSS) images were used to conduct a lineament survey of Texas. Lineaments across the state were mapped and these maps were compared with the pattern of known structural/tectonic features in selected areas. The largest of these areas was the Central Texas Region, which includes all the Balcones/Ouachita trend between the Rio Grande and Red River. Also tested was the hypothesis that structural features control the location and properties of geothermal aquifers, as inferred from maps of calculated geothermal gradient values. The main purpose was to investigate the structural relations of geothermal waters; however, this approach is equally applicable to exploration for other resources.

LINEAMENTS

Definition

For purposes of this paper, a lineament is a pattern or "figure" in a factual representation (photograph, map, model) of either the earth's surface or a subsurface datum (whether stratigraphically, structurally, or geophysically defined) and the figure must be linear (straight), continuous, reasonably well expressed (having discernible end points, width, and azimuth), and be related to features of the solid earth. Figures are not lineaments by this definition if they represent either cultural features (such as pipeline corridors, roads, or canals), superficial geomorphic features (such as eolian dunes or shoals of current-transported sediments), or transient climatic or hydrographic features (clouds or cloud shadows, waves, snow drifts, or, as in one example, a tornado pathway through a forest) unless these features are in fact controlled by geologic trends. Some linear stream channels, lines of vegetation, soil and relief breaks, and other surface alignments do coincide with patterns in the geologic substrate; these features can, therefore, be recognized as lineaments in photographs, maps, or scanner images (Caran *et al.*, 1981). For regional lineament studies, Landsat MSS imagery constitutes an ideal image base.

Landsat Imagery

Observers have perceived lineaments in virtually every kind of map, aerial and orbital photograph, and orbital scanner image ("scanogram"). This investigation is primarily concerned with lineaments perceived in photographic images derived from Landsat MSS (band 5) data. The multispectral scanner acts as a recording light meter, responding to the intensity of sunlight reflected from the earth's surface. Responses in spectral band 5, the orange to magenta region (0.5 to 0.6 micrometers wavelength) of the visible spectrum, and other bands are recorded as digital entries for every 1.1-acre (0.45 ha) area of the surface scene (each scene covers more than 12,000 mi^2 or 31,200 km^2). The reflectance values are then converted photographically to gray tones. The resulting image or scanogram is a photographic product that resembles a conventional photograph of the scene. Color images can be prepared in a similar manner (U.S. Geological Survey, 1979).

Images were selected that were prepared from winter (October to March) imagery data when the angle of solar elevation was lowest, thereby emphasizing low-relief topographic features. Each image is a snow- and cloud-free, high-quality, positive black-and-white print on a paper base in 1:250,000-scale format. The images are unenhanced and were obtained from EROS Data Center (a division of the U.S. Geological Survey), Sioux Falls, South Dakota.

Lineaments, Lineament Zones, and Lineament Areas

Ten Landsat images (scene numbers 24, 25, 27 to 30, 33 to 35, and 39 of Woodruff *et al.*, 1981) cover the Balcones/Ouachita trend of central Texas. These images revealed more than 5,000 lineaments. The lineaments were evaluated individually and their distribution compared with features shown on topographic and geologic maps of the region. However, for ease of correlation adjacent lineaments were combined, if they were either parallel or essentially continuous in aggregate, to form "lineament zones" (Figs. 3a and 3b); this process reduced the number of lineaments to more manageable and cartographically practical proportions. Each lineament zone includes two or more lineaments along with narrow intervening gaps. Lineament zones are not always linear — their width and length are variable — and they are somewhat subjectively defined. Nevertheless, aggregation of the individual lineaments in this manner was extremely helpful, particularly for simplifying comparisons with other thematic maps.

The lineament pattern in each image was further consolidated by denoting areas in which the individual lineaments and zones exhibited relatively uniform properties (length, azimuth, continuity, and density). Each resulting "lineament area" (Figs. 3a and 3b) is internally uniform and indistinguishable from adjacent lineament areas in terms of their predominant properties; therefore, all the lineaments and lineament zones within a single lineament area can generally be treated as a unit. Like the lineaments and lineament zones, lineament areas generally conform to regional geologic features, as represented on conventional structural/tectonic maps (Figs. 1, 2a, and 2b). The patterns of individual lineaments, lineament zones, and lineament areas also compare favorably to the regional and local trends of geothermal gradient values.

GEOTHERMAL GRADIENT

Bottom-hole temperatures and depths on selected electric-log headings were used to calculate unrefined geothermal gradient values. The gradient calculation requires adjustment of the reported temperature at each control point by subtraction of the mean surface air temperature (Guyod, 1946). The long-term average air temperature is assumed to equal the mean surface ground temperature at the control point. Our downhole temperature data consist of otherwise uncorrected bottom-hole temperature and depth measurements from approximately 5 to 20 wells per county. Data from wells shallower than 1,000 ft generally were omitted because such data often reflect highly variable surface influences (such as air temperature variations and effects from infiltration of shallow ground water), which are essentially unrelated to actual earth temperatures.

From this temperature-depth data the geothermal gradient values were calculated by the following formula:

$$G = (T_z - T_o)\ (Z^{-1})\ (100^{-1}) \text{ where}$$

G = geothermal gradient value at a point,
T_z = recorded bottom hole tzmperature (°F) at depth Z (ft); and
T_o = mean air temperature at the surface (°F).

Gradient values are thus given as temperature change per 100 ft of depth (°F/100) ft). Using these data, contours were constructed on maps of gradient values at control wells by interpolating geothermal gradient "isograds" (equal gradient contour lines) throughout our study area. These preliminary isograd maps (Figs. 4a and 4b) were compared to maps of lineaments, lineament zones, lineament areas, and major structural/tectonic features of the region; and numerous apparent correlations were noted.

LINEAMENT CORRELATION WITH STRUCTURES AND GEOTHERMAL GRADIENT ANOMALIES

Lineaments, as expected, are strongly correlative with structures that have obvious surface expression. When a lineament is perceived, actually a tonal representation of reflectance contrast that is related to variations in vegetation, soils, and topography is seen. These surface characteristics are often influenced by structural features, such as folds, faults, and joints. More surprising is the coincidence between individual lineaments, as well as lineament zones and lineament areas, and buried structural features. These deep-seated structures and tectonic features include, for example, buried uplifts, buried igneous plugs and salt diapirs, subsurface folds and faults (both thrust and normal faults), strata affected by subtle regional warping, and stratigraphic pinch-outs. Few mechanisms for surface expression of such features are available, yet major subsurface and surface structures in most of the survey region were detected by association with lineaments.

Northern Part of Region

The northern part of the Central Texas Region (Figs. 2a, 3a, and 4a) extends northward and northeastward from lat 31° N. in Burnet, Bell, Falls, Milam, and Robertson Counties to the Red River. This area covers the northern half of the Balcones/Ouachita trend in Texas and much of the east Texas basin. Gaps in the lineament pattern coincide with Dallas and other cities in the area because intensive urban land use obscures the kinds of natural surface features that might be perceived as lineaments when represented in Landsat images.

In the northern part of the Central Texas Region, surface features that are correlative with lineaments include the Mexia and Talco fault zones, which define the northern and most of the western margins of the east Texas basin. The fault zones are outlined by nearly continuous lineament zones and coincide with a series of lineament areas. Within lineament areas that coincide with the strike of the Talco fault zone, especially along the Delta-Hopkins County line, many of the individual lineaments are oriented oblique to their trend in aggregate; individual Talco faults bear much the same relation to the fault zone as a whole. The Mexia fault zone is suggested in a similar manner by oblique lineaments and lineament zones in Navarro and Limestone Counties. Geothermal gradient anomalies also converge with the structural grain and, thus, with the corresponding lineament pattern. A group of isolated high gradient anomalies and isograd deflections (Fig. 4a) follows the Talco and Mexia fault zones where they correspond to the edges of the east Texas basin.

The highest gradient values in the area (in excess of 2.5°F/100 ft of depth) occur within the northern part of the Balcones fault zone; this may result from heat convection in ground water ascending from depth along faults and fractures (Woodruff and McBride, 1979). Although relatively few surface faults of the Balcones system have been mapped in the northern part of the Central Texas Region (Fig. 2a), unmapped faults probably exist. This conclusion is supported by the concentration of lineaments along the trend of the Balcones fault zone because lineament zones and lineament area boundaries are correlative with the entire fault system and with many of the known faults.

Transverse lineament zones (oriented oblique or perpendicular to the regional strike) are present at several points along the Balcones and Luling-Mexia-Talco fault zones. In fact, the Balcones faults appear to terminate to the north at a point coincident with a transverse lineament zone and lineament area

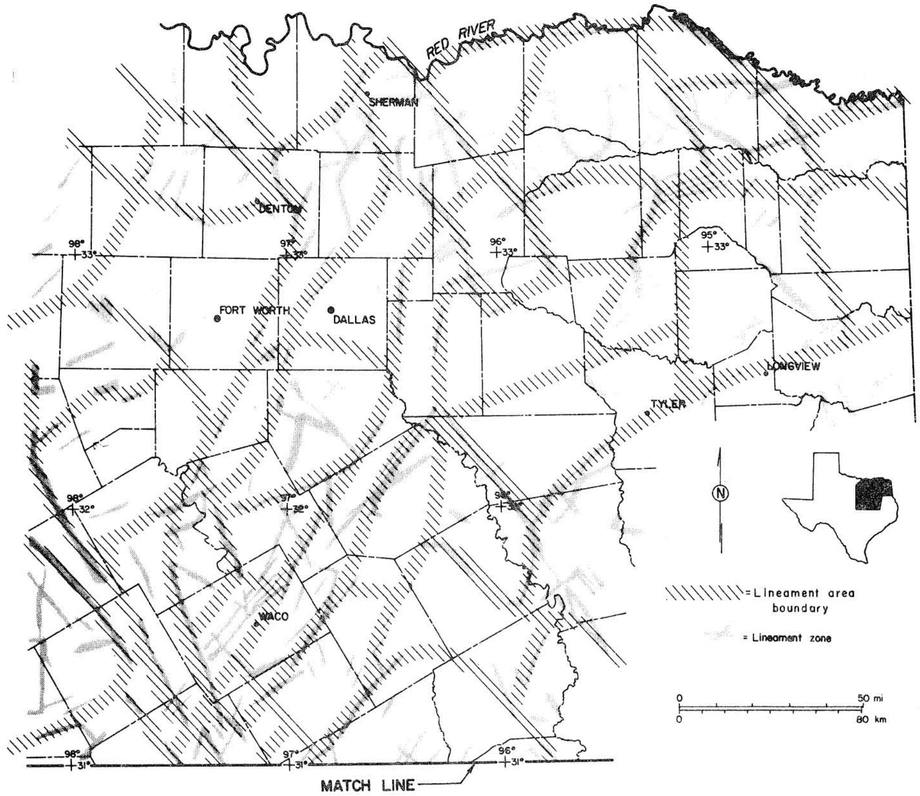

Figure 3a. Lineament zones and lineament areas of the Balcones/Ouachita trend, northern part.

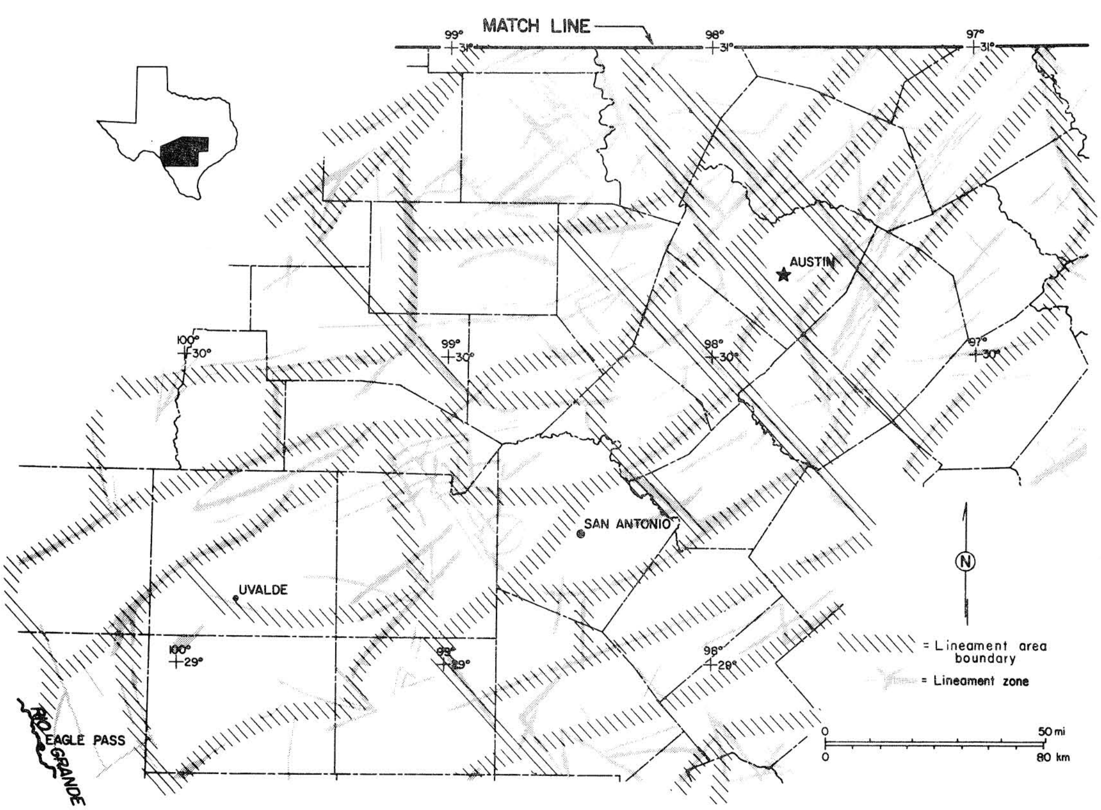

Figure 3b. Lineament zones and lineament areas of the Balcones/Ouachita trend, southern part.

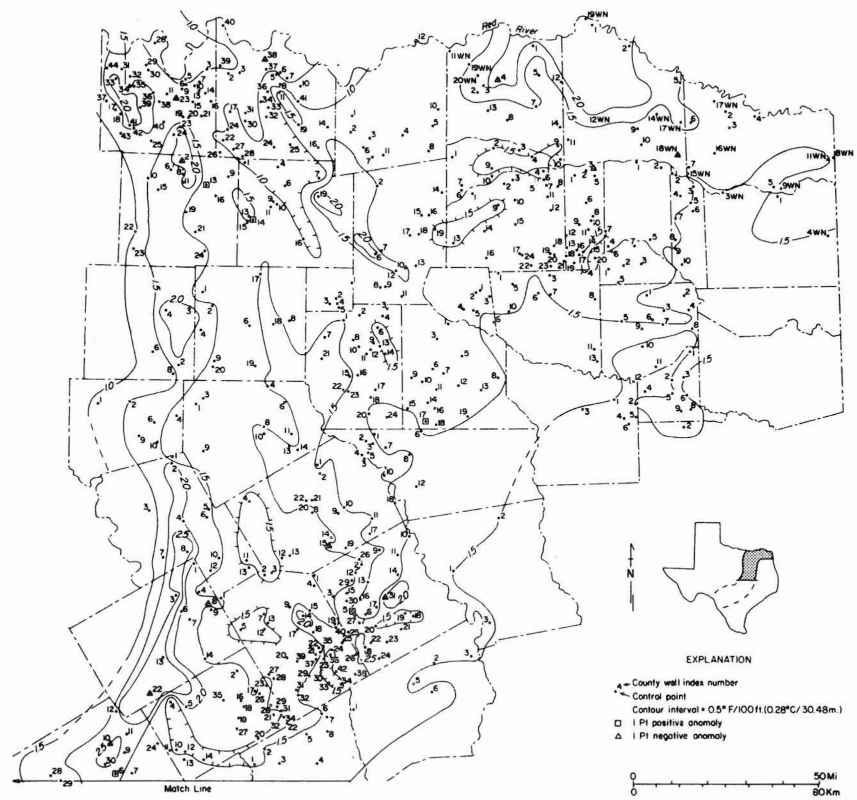

Figure 4a. Geothermal gradient contour map of the Balcones/Ouachita trend, northern part.

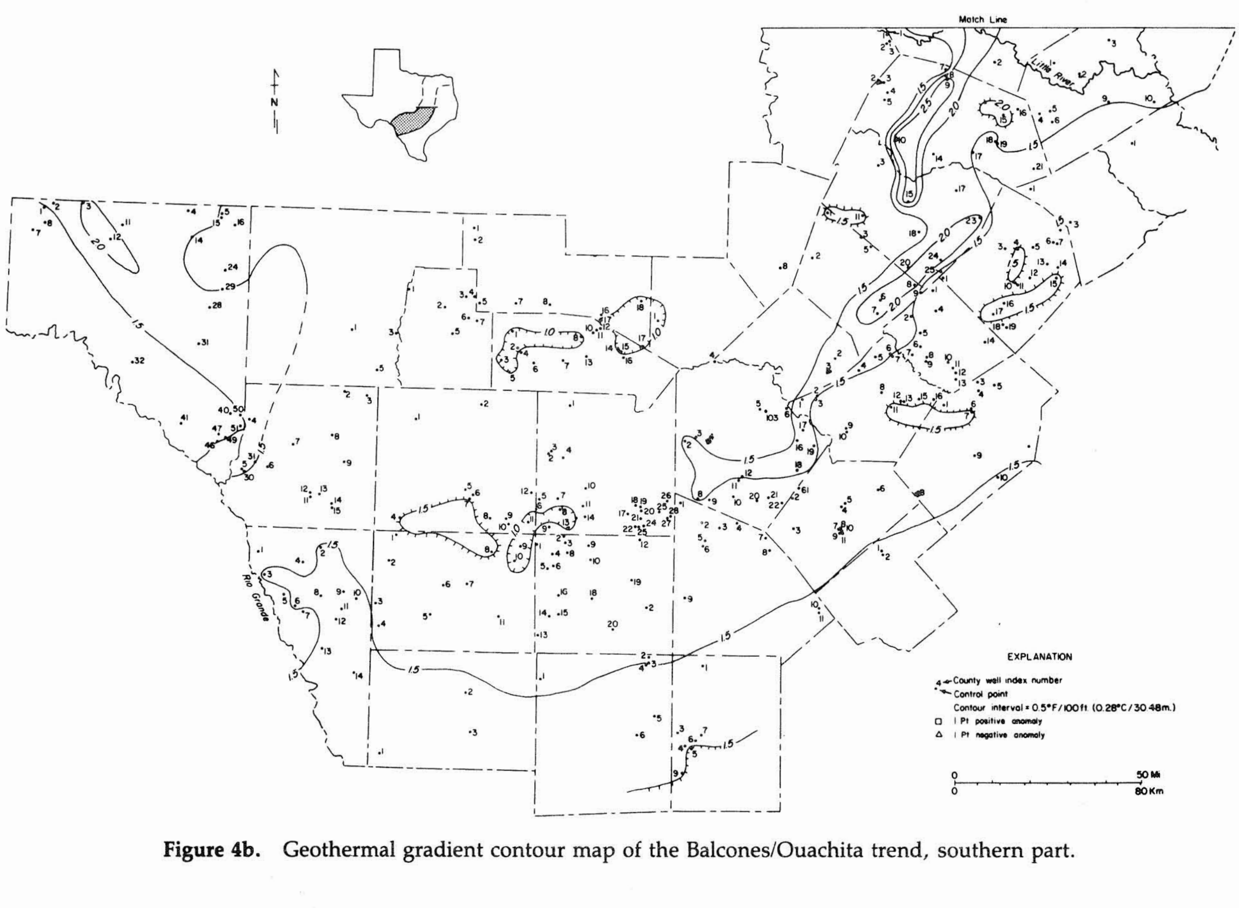

Figure 4b. Geothermal gradient contour map of the Balcones/Ouachita trend, southern part.

boundary in central Ellis County (approximately 31 mi or 50 km south of Dallas). For the most part, transverse lineament zones appear to coincide with structural features known primarily from subsurface data, such as platforms, anticlines, and synclines. Most of these structures cross the regional fault zones, as do the transverse lineament zones. The Belton High-Moffatt Mound trend (Cleaves, 1972; and Amsbury *et al.*, 1977) in northern Bell County is an example of a structure of this type (Fig. 1). A transverse lineament zone and a lineament area boundary mark the northern margin of the Belton High; a prominent northwestward offset of the general axial trend of the Balcones fault zone in southern McLennan and northern Bell Counties (approximately 25 mi or 40 km south-southwest of Waco) also is associated with this transverse lineament zone and boundary. Moffatt Mound is a northwesterly trending area on the Belton High in which the Edwards Formation abruptly trebles in thickness and changes laterally from miliolid wackestones and grainstones to oolite-pellet grainstones diagnostic of local high-energy shoaling adjacent to a shallow-marine shelf sequence (Amsbury *et al.*, 1977). However, the Edwards Formation is present only in the subsurface across most of this area, which includes outcrops of latest Late Cretaceous units. An isolated geothermal gradient high is also evident in this location (Fig. 4a).

Another example of a major transverse structure is the Preston anticline (Fig. 1) in Fannin and Hunt Counties. A prominent transverse lineament zone appears to be the surface expression of the anticlinal axis, whose location, azimuth, and length are precisely correlative with those of this lineament zone. The axis also appears to form the eastern boundary of a complex pattern of high and low geothermal gradient anomalies extending southeastward from the Red River and the Arbuckle Mountains of Oklahoma.

An area of high gradient values is coincident with the axis of the Sherman syncline at a sharp bend in the westernmost thrust fault of the Ouachita overthrust system (Fig. 2a). Another area of anomalously high geothermal gradients occurs southeast of the syncline along a projection of its axis and extends southward and southeastward along the same azimuth following a projection of the flank. The high gradient anomaly terminates to the southeast at the Talco fault zone on the margin of the east Texas basin, in an area in which Crosby (1971) noted a strongly positive gravity anomaly. Low gradient anomalies occur along the southwestern flank of the Sherman syncline and are deflected northwestward (up the regional dip) across the trough of the syncline. The syncline also is suggested by a pattern of lineaments, but in a complex manner primarily involving the faulted limbs rather than the axis of this fold structure (Bradfield, 1959; and Sellards and Hendricks, 1946).

An elongate, transverse lineament pattern, similar to that characterizing the Preston anticline and Sherman syncline, is seen in Lamar, Delta, Red River, and Bowie Counties in extreme northeast Texas (Fig. 3a). The lineament areas there appear to correspond to the "structurally high area" of Flawn *et al.* (1961, plates 1 and 4) associated with the Broken Bow/Benton uplift north of the Red River. The western and part of the eastern lobes of a two-lobed geothermal isogradient high in Lamar and Red River Counties are coincident with this structure. The axis of the western lobe also follows the easternmost thrust fault of the Ouachita overthrust. The eastern lobe extends in a southeasterly direction and is not obviously related to any major structure. However, this gradient lobe does correspond very closely to an intersecting pattern of lineament zones. Throughout the region, isolated gradient anomalies (highs and lows) are almost invariably found at concentrations of intersecting lineament zones.

Concentrations of long, intersecting lineament zones also coincide with alignments of salt domes near the eastern limit of the Balcones/Ouachita trend, particularly those in the southwestern part of the east Texas basin in Henderson, Anderson, Smith, and Freestone Counties (Anderson *et al.*, 1973). The 1.5° geothermal gradient contours appear to deflect around and to roughly outline this group of domes.

Nearby, in Limestone and western Freestone Counties, a cluster of isolated high and low gradient anomalies traces the southwestern closure of the east Texas basin, whereas a more random pattern of isograds is seen elsewhere in the basin. Basins throughout the region exhibit the same general tendency to be flanked by isolated geothermal gradient anomalies (both highs and lows) but to have generally undistinguished gradient patterns in their interiors. Another example of this tendency is the narrow, roughly north-south gradient anomaly that crosses the Fort Worth basin. This isograd pattern extends northward from the Balcones fault zone in southern Hill County to the Muenster arch and then northwestward along the axis of the arch, possibly suggesting an underlying structural continuity along the trend.

The Muenster arch is one of several uplifts of Precambrian to Late Paleozoic rocks in Montague, Cooke, and Denton Counties. It is well defined by both isolated and extended, northwest-trending, high geothermal gradient anomalies and corresponds to an elongate northwest-southeast lineament area. In fact, the fault that forms the western boundary of the arch in southwest Cooke and northwest Denton Counties (Bradfield, 1959; p.56, 57, 62, 63; and Flawn *et al.*, 1961, plate 2) precisely coincides with a lineament zone.

The Waco uplift in Falls, McLennan, Hill, Limestone, and Navarro Counties is bounded on the west by a thrust fault that is nearly coincident and possibly penecontemporaneous with a Ouachita thrust fault in the Paleozoic subcrop just east of Waco (Nicholas and Rozendal, 1975). The eastern limit of this structure coincides with a lineament zone and area boundary; the southern end coincides with a transverse, southeast-trending lineament zone.

Transverse lineament zones exhibit a similar pattern correlation with the Cavern, San Saba, and Lampasas "Ridges" (uplifts?), which extend northeastward from the Llano uplift into Comanche, Hamilton, and Coryell Counties, Texas (Belforte, 1971). The set of nearly parallel, transverse lineament zones found just southwest of Waco (Fig. 3a) is bounded laterally to the southwest by the distal ends of the San Saba and Lampasas Ridges in Hamilton and Coryell Counties and appears to terminate to the northwest at the longer Cavern Ridge in Comanche County.

Southern Part of Region

The southern part of the Central Texas Region (Figs. 2b, 3b, and 4b) extends southward and southwestward from lat 31° N. in Burnet, Bell, Falls, Milam, and Robertson Counties to the Rio Grande on the southwest and to Dimmit, La Salle, and McMullen Counties on the south. This area covers the southern half of the Balcones/Ouachita trend and part of the Maverick basin. As in the northern part of the region, several instances of apparent correlation were found among the geothermal isograd patterns, the major structural features, and the lineaments, lineament zones, and lineament areas.

The extensive Balcones and Luling fault zones are demonstrably correlative with lineament patterns, as are individual faults (Fig. 2b). The complexity of these fault zones in the southern part of the region is reflected in the highly fragmented appearance of the lineament areas (Fig. 3b), although coincidence of the fault zone and lineament area boundaries is imperfect. Lineament patterns clearly suggest the existence of many more faults in the region than are presently mapped, which may explain the limited correlation with fault zone boundaries as conventionally represented.

The distribution of geothermal gradient values (Fig. 4b) generally aligns with the trends of the Balcones and Luling fault zones (Fig. 2b). The isograds are deflected wherever they cross a fault zone boundary. Isolated high and low gradient anomalies lie between the fault zones and are partly within or at the western margin of the Luling fault zone. However, the highest gradient values (in excess of 2.5°F/100 ft of depth) in the southern part of the region are found in the Balcones fault zone in Travis and Williamson Counties. Other high anomalies approximately trace the southeasternmost mapped thrust fault of the Ouachita system in several counties, and two, small low gradient anomalies are roughly coincident with the northernmost thrust fault in Bandera and Kerr Counties. The two areas of low geothermal gradient values may be related to recharge or other hydrologic effects in Lower Cretaceous aquifers overlying the Kerr basin, south of the Llano uplift.

The Balcones and Luling fault zones extend across the San Marcos arch. Both the arch and the presumed flank areas to the northeast and southwest are very well expressed as lineament zones and areas, particularly by the long transverse zones. Transverse lineament zones mark the axis and margins of the arch, and both the density and orientation of other lineament zones varies sharply at these breaks.

The San Marcos arch also coincides with deflections of the geothermal gradient contours. The offset of the 1.5° isograd near the northern boundary of Bexar County coincides with the flank of the arch. Isolated high gradient anomalies are concentrated across and along the structure, and the 1.5°, 2.0°, and 2.5° isograds are offset or terminate along its northern boundary at the edge of the Round Rock syncline. Identical offsets occur at the northern edge of the syncline. These offsets and terminations also coincide with the positions of transverse lineament zones.

Transverse lineament zones along the Balcones/Ouachita trend are almost invariably associated with major structural features, including the Chittim anticline along the west side of the Maverick basin. A lineament zone having precisely the same azimuth and location as the anticlinal axis is evident, and even the slightly asymmetric flanks of the structure (Sellards and Hendricks, 1946) are expressed. A prominent northwestward deflection of the 1.5°F/100-ft isograd in Maverick County along the Rio Grande is presumably related to the Chittim anticline.

Another, smaller anticline is found in this part of the region. It, too, is expressed as a lineament zone, although the type of expression is quite different from that previously described. The Culebra structure (Fig. 1) is a small, southwest-plunging anticline (Sellards, 1934; and Sellards and Hendricks, 1946) that coincides with a circular lineament zone along the Bexar-Medina County line (Fig. 3b). The axis of this structure and faults associated with it coincide with part of the subsurface Ouachita thrust fault as mapped in these counties by Flawn *et al.* (1961, plate 2). A small, southwestward bend in the thrust fault also appears to coincide with the edge of the circular lineament zone.

The margin of the Maverick basin is correlative with lineament patterns only on its east side. The minimal coincidence elsewhere may be due partly to the author's somewhat oversimplified representation of the basin margin, when compared with that of Loucks (1977), for example. However, it may be equally significant that the quality of the Landsat image (scene number 25 of Woodruff *et al.*, 1981) covering this area is relatively poor. The Kerr basin is more compatible with the lineament areas as shown (Fig. 3b).

Two large uplifts in the area, which are flanked by platforms or anticlines, are reasonably coincident with lineament zones and areas. The Llano uplift, as shown in Figure 1, includes the approximate subsurface extent of the uplift, as well as the outcrop area of associated rock units. The lineament zones coincide with the outcrop extent of Paleozoic and Precambrian rocks, rather than the uplift's subsurface extent. The Devils River uplift in the southwestern part of the region also is shown in Figure 1, although this rendering of the uplift (after Flawn *et al.*, 1961) corresponds imperfectly to lineament area boundaries.

Two other structurally significiant features, which extend across the nothern and southern parts of the Central Texas Region, are the thrust faults of the Ouachita System and the updip limit of the Jurassic subcrop (Fig. 1). The thrust faults, which mark the boundaries of the Ouachita structural belt, correspond to the lineament zones (Figs. 3a and 3b) both in general and, locally, in detail. However, correlation with lineament areas is certainly imperfect. Complete coincidence would not be expected because of uncertainties in the positions of the thrust faults where deep well control is insufficient for detailed mapping (dash symbols in plate 2 of Flawn *et al.*, 1961).

The mapped updip limit of the Jurassic subcrop is also based on poor well control; and, as might be expected, correlation with lineaments is poor. Marine Jurassic deposits defined the updip extent of the incipient Gulf basin. The pinch-out coincides with the Mexia and Talco fault zones and, thus, with the western and northern margins of the east Texas basin. It also coincides with the northern and northeastern margins of the Maverick basin. These structures are partly correlative with lineament and geothermal gradient patterns. Each of the major platforms, anticlines, or synclines that approach or cross the regional fault zones (and are expressed as long, transverse lineaments) appears to terminate at the pinch-out line.

Structural Interpretation of Lineament Patterns

Each lineament map initially was seen as a nearly undecipherable montage. Instances of probable affinity were recognized when lineaments and structures were geographically convergent; but structural relations of lineaments in other areas could not be predicted, and apparent conflicts with the structural/tectonic data base could not be resolved. Gradually, however, the lineaments were qualitatively characterized in terms of their relative densities, lengths, and intersection angles (perpendicular, oblique, subparallel, or parallel). This approach has proved a means of grouping the lineaments on the basis of similar characteristics. Recurring patterns of association were noted among the lineaments, both individually and in combination as lineament zones and areas. Moreover, each type of association appears to be correlative with a particular kind of structure. If this conclusion is true, this method of lineament analysis could prove useful for exploration.

The primary method of classifying lineament patterns was, thus, based on recognition of morphometric similarities without prior resort to genetic interpretations. Whether the resulting classes were consistently correlative with structures throughout the region was determined. If the correlation were consistent, a class became a "model" (Table 1) by which we

(1) High-density, short to moderate length, parallel to subparallel lineaments and lineament zones, composing rectangular lineament areas whose long axes are approximately parallel to the regional strike.

(2) Low-density, long, perpendicular and parallel lineaments and lineament zones, composing square to rectangular lineament areas grouped end to end perpendicular to the regional strike.

(3) Variable-density, short to moderate length, perpendicular and parallel lineaments and lineament zones, composing square to rectangular lineament areas (generally with well-defined perimeters).

(4) Very low density, long, oblique lineaments and lineament zones (generally well defined) composing irregularly shaped lineament areas.

Table 1. Lineament models.

Structure	Lineament model	Isogradient pattern	Example
Zone of normal faults	1	1	Balcones and Luling-Mexia-Talco fault zones
Platform, anticline, or syncline	2	2 (sharp) along flanks, axis; 3	San Marcos arch, Chittim anticline, Sherman syncline
Uplift	3	2 (sharp) along flanks, axis; 3	Muenster arch, Devils River uplift
Basin	4	3 (margins); 4	Fort Worth and east Texas basins
Group of salt domes	4	2 (slight)	Domes in western Anderson and southern Henderson Counties

Table 3. Relations among structures, geothermal gradient patterns, and lineament models.

could extend our interpretations. Each of these lineament models corresponds to a particular kind of structure and to characteristic geothermal gradient patterns (Table 2). Table 3 summarizes the relations among the structures, gradient trends, and lineament models that were considered structurally diagnostic, as exemplified by the major structures of the Central Texas Region.

(1) Closely spaced isograds composing elongate high gradient anomalies parallel to the regional strike.

(2) Sharply to slightly offset isograds (usually two or more, roughly parallel) generally following the local strike.

(3) Comparatively small, isolated high or low gradient, or both, anomalies generally following the local strike or a structural axis.

(4) Extended, virtually featureless isograds (one or two together) generally following the local strike.

Table 2. Geothermal gradient contour patterns.

SUMMARY AND CONCLUSIONS

Individual lineaments often coincide with discrete structures, such as faults or fold axes, and with structurally controlled facies boundaries. More extensive, regional structural trends are generally correlative with families of lineaments or with breaks in the predominant lineament pattern. Although lineaments are expected to correspond to exposed structural elements, many instances of convergence of lineaments with subsurface features are found that are not known to have conventional surface expression. Lineaments that are perceived in remotely sensed images must be related to surface features capable of creating variations in surface reflectance, hue, or relief, even if the identity of those features is unknown. This study's correlation of lineaments with subsurface features suggests the existence of poorly understood mechanisms for propagating an inherited structural grain through superjacent strata. Thus, empirical evaluations of structural patterns by lineament analysis can be considered an acceptable basis for assessment and exploration for structurally controlled resources.

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