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LINEAMENTS OF TEXAS--

Possible Surface Expressions of Deep-Seated Phenomena

by

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FINAL REPORT

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EXECUTIVE SUMMARY

Geologic structures are important controls on geothermal resources. Buried plutons, intrusions, or diapirs may provide either localized areas of high heat flow or zones of high thermal conductivity. Various structures such as faults, joints, folds, or buried massifs may affect underground fluid flow and thus may alter local thermal regimes. These subsurface hydrologic effects may either enhance or detract from geothermal potential, because upwelling of deep-seated fluids increases local geothermal gradient, but recharge decreases geothermal gradient. Geologic structures provide direct controls on heat flow and indirect controls on geothermal gradients via hydrologic processes. Understanding geologic structures, especially buried structures, will therefore aid in assessing the geothermal potential of a given area.

Some lineaments are surface indicators of geologic structures. An analysis of lineaments and an awareness of general hydrologic regimes provide means for delimiting promising areas for geothermal development. Lineaments, however, are polygenetic; not all linear features are related to earth structures at depth. Some are expressions of surface processes alone. Others seem to be essentially random alignments of features such as drainage, topography, soils, or vegetation, and the cause of many such features is unknown or ambiguous. Because of the varying quality of information imparted by individual lineaments, a high "noise-to-signal" ratio exists in lineament data. The geologist's task, in collecting lineament data and in subsequently analyzing them, is to winnow noise from signal--that is, to eliminate patterns that impart no geologic information, and thereby to ascertain which features are significant with respect to local or regional geologic structures. This process entails correlation of lineaments with other mapped features. For geothermal assessment, special emphasis must be placed on recognition of buried structures or other irregularities that may control thermal conditions in subsurface fluids.

Using lineament analysis for ascertaining geothermal potential entails a consideration of the structural (subsurface) control on surface features--especially the recurring motifs of

aligned features that constitute regional or statewide linear trends or "grain." In places, lineaments are clearly correlative with buried structures. But lineaments also occur in areas without known subsurface discontinuities, and lineaments also occur in many places that have no geothermal potential. Thus, lineament analysis as a prospecting tool must be used carefully. Some workers have tended to assume that the very presence of a lineament invariably implies geologic control. The data we obtained do not support such a view, but they do indicate that many lineaments are expressions of local structural conditions that may be otherwise hidden or subtle.

Scale of view is an important factor in lineament analysis. Entirely different features are perceived at different scales and geologic interpretations have to be judged accordingly. Certain through-going, extensive features may not even be perceived in detailed surveys. On the other hand, detailed lineament data obtained in a survey of large-scale photographs covering a small area may constitute mere noise from a regional perspective. This survey of lineaments in Texas has a regional perspective. For initial data gathering we used Landsat images at a scale of 1:250,000. These data were reduced to 1:500,000 scale for initial analysis and are presented here at a scale of 1:1,000,000 (see Plate).

Interpretation of statewide lineament data has entailed comparison of various 1:1,000,000-scale thematic maps of Texas. These maps depict statewide physiography, topography, drainage, surface geology, structure, and locations of hydrothermal and petroleum resources. This perspective has resulted in our depiction of distinctive physical regions of Texas and the most prominent linear grain within or across these regions. The lineaments mapped have been subsequently quantified in terms of their areal density, the frequency of their intersection, and their azimuth. These simple, derivative analyses in selected areas suggest correlation of lineaments with structural control, and such correlations allow some extrapolation into regions in which the subsurface geologic information is sparse.

In summary, lineaments indicate broad areas that may be subject to structural control of hydrodynamic processes at depth. All available supporting data on subsurface geologic conditions should be considered whenever lineament assessment is applied to structural problems; the type and quality of data will vary from place to place. For example, lineaments may suggest either enhanced fracture porosity or the presence of a buried lithic discontinuity; detailed subsurface geologic mapping and various geophysical surveys will lessen the uncertainty. Lineament analysis is thus an adjunct to these fundamental research avenues.

INTRODUCTION

The "grain of Texas" was the topic of a brief report by R. E. Rettger published in 1932. Rettger based his study on small-scale maps depicting various geologic relations and on local field observations, and thus presented an overview of dominant structural trends across the state. Although mapping techniques and concepts of tectonic processes have changed markedly during the ensuing 52 years, recognition of regional structural trends, or "grain," is still a valid area of investigation. And it has special implications for the vast areas of Texas that are covered by nearly flat sedimentary rocks. Rettger's (1932) study is a point of departure for our discussion of lineaments and their relations to structures seen in a regional context. Our premise is that there are regionally distinctive trends that are characteristic of the state's various structural provinces.

We have identified lineaments on Landsat images, hence we are seeing some kind of surface expression. The key question is, what is the geologic context of these lineaments? We propose that certain linear features recognized in images of the earth's surface provide clues to buried geologic features. It is our aim to analyze these general trends, lineaments, in terms of the geologic information that they convey. But this is a difficult task. Lineaments are polygenetic. Trying to ascertain the phenomena responsible for any single lineament poses problems with cause and effect (fig. 1).

Lineaments may correlate to: (1) known surface structures; (2) surface expressions of known buried structures; (3) surface expressions of either buried or surface structures that were previously unknown; (4) physiographic features that have no known structural affinity; and (5) features of unknown or unclear affinity. Note that in all but the first two cases, what is perceived are features without clear structural connotations. Drainage nets, topographic alignments, changes in soils or vegetation, human land-use patterns, or other surface features may correlate to some visible or hidden geologic control and exhibit preferred (linear) orientations. Moreover, the absence of corroborating information does not necessarily mean

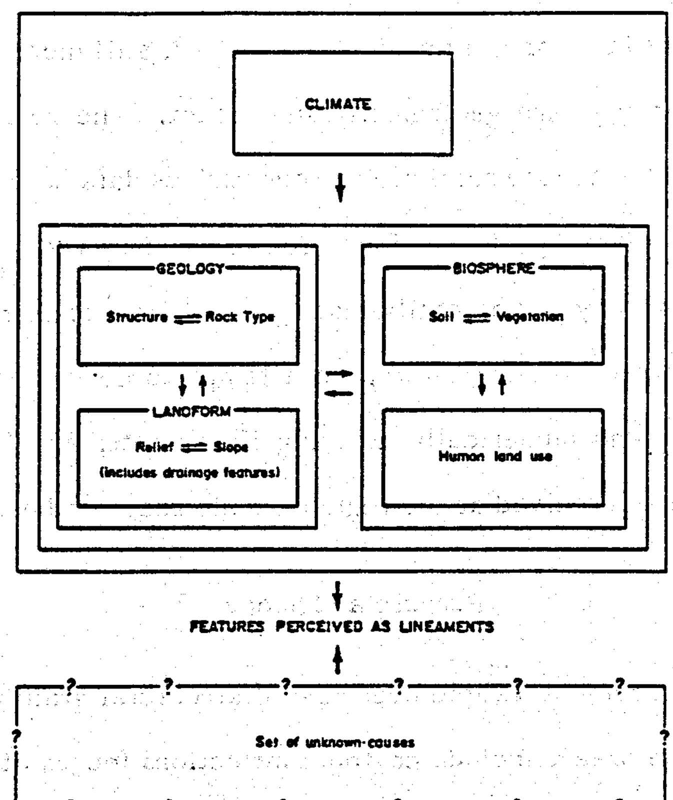

Figure 1. Schematic diagram of interactions among the various causes of lineaments.

that structural control is absent. Analysis of lineaments invites consideration of possible structural controls on many features that are commonly thought to be merely surficial.

The uncertain cause-and-effect relations among the various phenomena that may be perceived as lineaments indicate a problem with the discrimination of meaningful information. Scale of view, quality of images, and the amount of human overprint (that is, type, extent, and intensity of human land-use patterns) within the scene influence the perception of features that are real (as opposed to artifacts of the imaging process). A still more difficult task lies in the discrimination of features that are geologically significant. The regional scale at which we conducted this study (and hence, the resolution of our various data bases) may be inadequate for distinguishing the origins of many of the linear features perceived. Hence, the identifiable "signal" (geologic meaning) may not be easily distinguished from background "noise" (ambiguous or meaningless data). To reduce uncertainty, we attempt to codify: (1) definitions of terms; (2) methods of perceiving and numerically assaying lineaments; and (3) means for accurately interpreting the lineaments perceived at the regional scale presented here.

Purpose and Scope

Lineament surveys provide a a rapid overview of structural grain related to major crustal breaks. Examples of these breaks include cratonic inflections (edges of basins and uplifts), loci of past igneous activity, salt or shale diapirism, fault zones, and other such features. As mentioned, the premise underlying the application of lineament surveys is that some buried geologic features are subtly expressed at the earth's surface. This premise is still open to question by many geologists; see, for example, Wise (1982). Thus, we attempted (1) to correlate lineaments with documented geologic features that are not commonly recognized as having surface expression; and (2) to discriminate other recurring linear surface trends that may have a subsurface control.

Because of local correlations with major structures, lineaments have been commonly used in assessing hydrothermal resources (see Ruscetta and Foley, 1981, for recent examples).

This application is valid because hydrothermal phenomena and lineaments are expressions of structural and tectonic influences. Endogenetic heat drives tectonic forces, hence active tectonic areas are loci of high heat flow. This is evidenced by volcanism, hot springs, active hydrothermal ore deposition, and other thermal manifestations within zones of modern crustal plate divergence or convergence. Active tectonic belts also commonly display distinct linear features such as fault zones and associated abrupt lithic discontinuities, aligned intrusive bodies, and topographic escarpments. However, clear correlations among structures, geothermal phenomena, and lineaments are also apparent in other settings. Buried orogens may be the sites of anomalously high heat flow owing to various causes; above-average geothermal gradients or other thermal anomalies commonly occur in these relict structural belts because of deep ground-water circulation (Bedinger and others, 1979). Lineaments have commonly been mapped along these trends, including areas where the structures are buried. An example of surface expression of a buried orogen is along the Nemaha Ridge of Kansas and Nebraska, where a correlation exists among geophysical and geothermal anomalies (Steeples and others, 1979) and lineaments (McCauley and others, 1978). Another example of this three-way correlation is the Balcones/Ouachita trend of Central Texas (Woodruff and Caran, 1981).

The geographic scope of this study is statewide. However, statewide data quality is uneven. This applies both to the quality of Landsat images used in perceiving lineaments (see Appendix A) and to the geologic data with which the lineaments are compared. This statewide scope has encouraged our discrimination of distinctive physical regions of Texas--that is, broad provinces within the state that have similar geologic controls and thus similar surface expressions. The scale of view presented here (1:1,000,000, see enclosed Plate) does not allow detailed, site-specific examination of individual lineaments, so this regional and supra-regional approach is appropriate to both the quality and quantity of data at hand.

Since our assessment of geothermal resources entails some discrimination of buried features, we paid little attention to the two areas in Texas where deformed rock occurs at the earth's surface: the Llano Uplift of Central Texas and the deformed areas of Trans-Pecos

Texas. The Trans-Pecos region has well-documented geothermal resources (Henry, 1979), but the lineaments apparently do not provide information regarding controls on the geothermal resources beyond that provided by conventional geologic maps. Instead, we have chosen to focus on lineaments as a tool for distinguishing buried structures or other subsurface geologic discontinuities, such as reef trends, major unconformities, changes in regional depositional systems, and the like--any of which may, in turn, be controlled by structural processes. Findings regarding such features have a bearing not only on geothermal potential but also on any phenomenon that may be localized by structurally controlled avenues of fluid flow in the subsurface. Hence, lineament surveys may provide information useful for regional assessments of other ground-water resources, hydrothermal mineralization, and oil and gas migration and accumulation.

LINEAMENTS--DEFINITION AND DISCUSSION

The term lineaments and the concepts that led to their investigation are more than 100 years old (see discussions by O'Leary and others, 1976, and by Woodruff and others, 1982a). Hobbs (1912, p. 227) described lineaments as "significant lines of landscapes which reveal the hidden architecture of the rock basement." Hobbs sought to deduce the nature and configuration of structures that were too extensive or too subtle to be recognized by conventional mapping practices. He saw that these structures could influence topography and thus be expressed at the surface in a way that was then not fully appreciated.

Hobbs's concepts are implied in our working definition of lineament:

> *a pattern of tones, textures, contours, and other such features that is straight, linear, and more or less continuous, has definable end points and lateral boundaries (high length/width ratio), and hence a discernible azimuth, and is related to inherent features of the solid earth.*

This definition bears a strong structural connotation, even though what generally is perceived is physiographic. Hence, we avoid defining lineaments in terms of implied structural relations, because this would impose genetic interpretations on a definition that is otherwise descriptive. At the outset, while perceiving lineaments in an image, we merely tried to discriminate straight features of the solid earth. However, while viewing the images, we did attempt to filter out cultural features, artifacts of the imaging process, and transient climatic or hydrographic features such as clouds, cloud shadows, and wave and wind current patterns. After viewing the images and recording the lineaments perceived, we winnowed nonstructural features as part of the interpretive process.

Much confusion regarding the semantics of lineaments exists in the literature. O'Leary and others (1976) provided an in-depth discussion of these semantic problems, and Woodruff and others (1982a) explicated the evolution of the current definition. Examples of the semantic confusion include: Can a mapped fault zone be a lineament? Or must a lineament refer only to a straight feature of unknown affinity? In response to these questions, we emphasize that lineaments are, by their nature, generally perceived or sensed remotely, usually by means of aerial photographs, orbital images, or maps. But this provision is not inviolate; it is generally applicable simply because of the overview afforded by these sources. Lineaments, of course, may be perceived from an airplane window, or even from a ground view, given distance sufficient for a vista. The key point is that lineaments are straight features "viewed from afar," that is, from a remote vantage that permits recognition of linear features. Yet the detached viewpoint prevents direct assessment of the on-ground control of any specific lineament. Lineaments are inherently ambiguous features. Very important to recognition of lineaments is scale of view (or distance by which the viewer is removed from the area scanned): large-scale (close) views often provide different information from that provided by small-scale (distant) views.

METHOD

We identified lineaments on 51 Landsat images (fig. 2 and Appendix A) covering Texas and parts of adjacent states in Mexico and the United States (see also Woodruff and others, 1981).

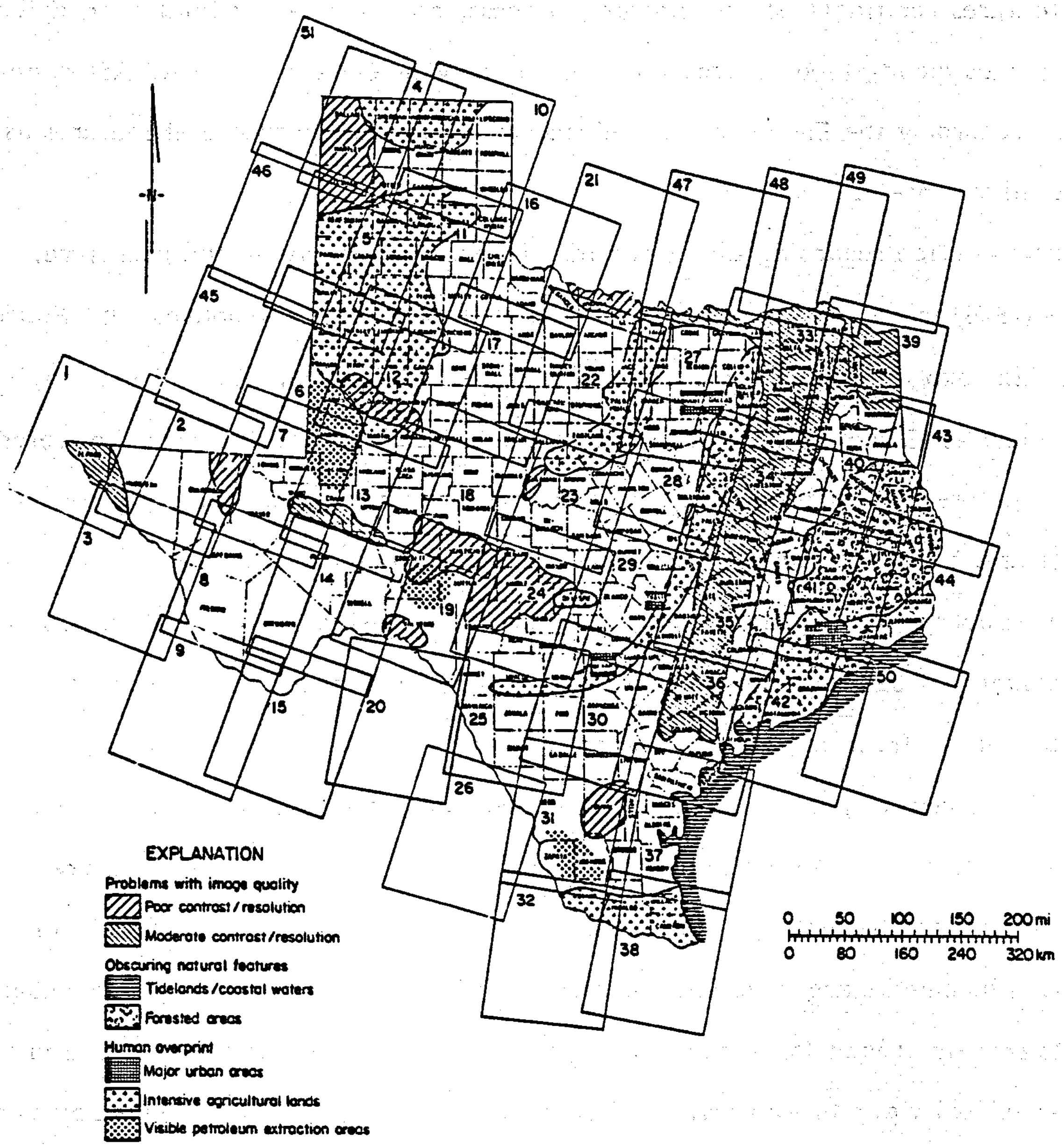

Figure 2. Index map showing Landsat images used in perceiving lineaments; various biasing factors are also indicated as described in the comment section in Appendix A.

The images were standard product, "band 5" black-and-white prints at a nominal scale of 1:250,000. The prints were prepared at the Earth Resources Observation System (EROS) Data Center, Sioux Falls, South Dakota, from data collected over several years by the National Aeronautics and Space Administration. Many of the images used in this project were fall and winter scenes, so chosen to minimize vegetative cover and to enhance topographic features owing to low sun angle and the consequent increase in shadow length during these months.

We designed a method of identifying lineaments so that our findings would be consistent (that is, acceptable to most observers viewing the images independently), uncomplicated, objective, and reproducible. Three observers independently examined each Landsat image for two 30-minute periods; this 3-man-hour time period allowed the most features to be perceived in the shortest time. This viewing period corresponds to an "inflection point in the number of lineaments perceived per unit of time during a test study" (in Woodruff and others, 1982a). The lineaments perceived by each observer were marked on the image, then registered on Mylar film. The image was subsequently cleaned completely before the next observer's viewing period to prevent potential bias among observers. Detailed discussion of method, comparison to methods employed by other researchers, and evaluation of the reproducibility of results are presented in Woodruff and others (1982a).

Lineaments denoted on the Landsat images were traced onto 1:250,000-scale work maps and then rendered cartographically on maps representing each of the 51 Landsat images at a scale of 1:500,000 (Woodruff and others, 1981). At this stage more than 31,000 lineaments were identified, but this included all three observers' findings, regardless of repetition. It also included significant areas outside of Texas. In preparing the final lineament map of Texas at 1:1,000,000-scale from the 1:500,000-scale maps, we eliminated all features that lay outside Texas, and we eliminated repetition among features perceived by individual workers. We also checked for cultural features before reducing and cartographically fitting the mosaic of 51 individual map sheets to a single map base. Lineaments that were partly colinear but with different end points were modified into a single lineament trace with the combined length of the two or more colinear lineaments. Finally, we checked each lineament to determine its validity according to our definition. In this way, we once again edited the features to eliminate processing artifacts within the image itself, as well as representations of cultural features (fencelines, roads, and the like) and geomorphic patterns unrelated to bedrock structure (most sand dunes and longshore barrier bars, for instance). We thus reduced the more than 31,000 lineaments originally perceived to the approximately 15,000 presented on the 1:1,000,000 map.

In this process, validated lineaments were initially transferred from the 51 Landsat image base maps to a 1:500,000-scale film-base map of the state printed with county outlines, rivers, and latitude and longitude lines in 1° increments. Small registration and scale differences and occasional geometric distortions necessitated the use of a Saltzmann projector to fit some of the individual (single scene) lineament maps to the statewide base map. When this was accomplished, the 1:500,000-scale map of the state's lineaments was photographically reduced by 50 percent to fit the standard 1:1,000,000-scale statewide base map, on which the features were scribed. Geographic registration of lineaments is within a single line width (about 0.6 mi or 1 km) with azimuth deviation of less than 1 °.

LINEAMENT DATA BASE

General

The lineaments presented at the 1:1,000,000 scale constitute raw data. We performed simple mensural and statistical operations to numerically reduce these data, including area-by-area enumerations of lineaments and lineament intersections and construction of histograms of azimuths. An evaluation of apparent consistencies in alignments of lineaments and geologic features followed.

The mensural and statistical operations were to have been done by computer. However, after attempting to digitize the lineaments of a test area, we discovered inherent geometric discrepancies in some of the older Landsat images that caused the digitized data from these images to be incompatible with data from newer images. This problem could not be resolved in the time allotted for testing the procedure. We therefore performed the data-analysis operations manually. This caused certain deviations from our initial study plan, but overall our data reductions are probably comparable to those that would have been produced by machine.

Data Reduction Procedures

The manual steps we employed entailed the use of a uniform grid that allowed the subdivision of the lineament data into discrete subsets, which in turn, allowed us to repetitively compare specific areas. The grid cell or unit cell is a 1-inch square registered to key latitude/longitude coordinates at a scale of 1:1,000,000. Thus, the unit area represented by each cell represents approximately 249 mi^2 (645 km^2). This size is appropriate for use with the various thematic maps of geologic and physiographic features (using work copies compiled at 1:1,000,000-scale). The unit cell is large enough to allow easy discrimination of lineaments within its boundary, yet not so large that any single cell includes numerous types of terrain. The total number of unit cells across the state is 1,190. This is an optimum number given the resolution of data, and it represents a reasonable compromise between having fewer, larger grid cells for convenience in tallying lineaments and smaller, more numerous grid cells for better resolution of contoured data.

Lineament Density

We counted the lineaments per unit cell in order to determine the relative densities of lineaments statewide. A cell was said to contain a lineament if all or part of that lineament extended into the cell. Thus, a single lineament may be counted more than once, as it may extend into more than one cell; this results in a weighting of the data according to the length of lineaments. Results of this enumeration were contoured as a baseline with which to compare other lineament data (fig. 3). The second counting operation entailed the use of a moving four-cell (2 by 2) grid. The number of lineaments counted within any four adjacent unit cells

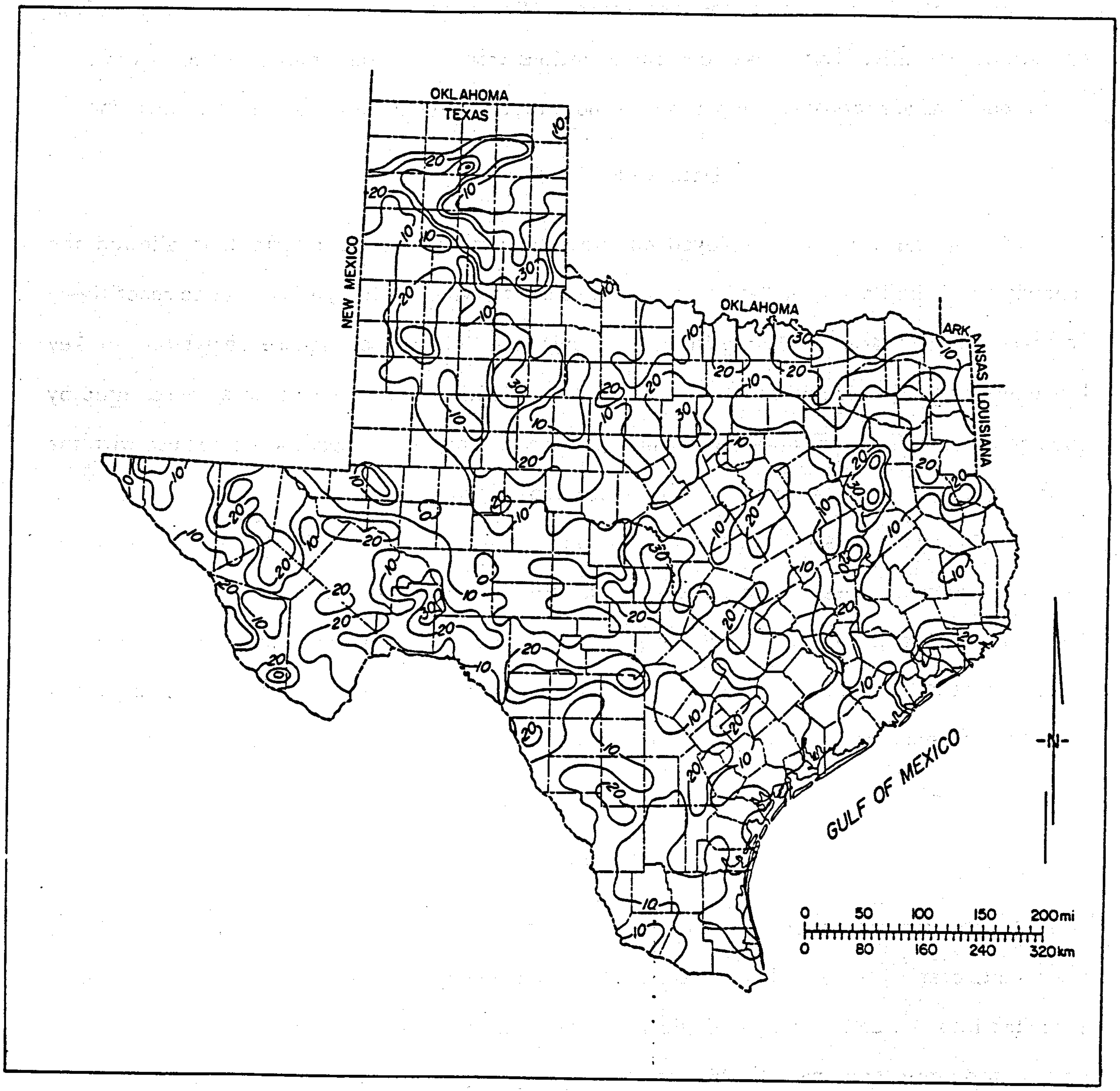

Figure 3. Number of lineaments per unit area (249 mi^2 or 645 km^2) without a moving average.

was totalled, and the sum was recorded at the center of each four-cell area for subsequent contouring. Because the center of the four-cell grid moved in increments of one cell--both vertically and horizontally--the number of lineaments in each cell was summed four times. This operation smoothes the data, thereby emphasizing broader patterns. The magnitude of the contour interval is increased by this repetitive count, but the resolution of contours is diminished compared to the baseline (non-moving average). Overall, though, the two contour maps of lineament densities show the same general trends. The moving average contour is presented on the margin of the statewide map of lineaments (Plate, in pocket).

A problem arose at the state borders because lineaments outside of Texas were not counted, and no lineaments occur in Texas' coastal waters. As the rectilinear grid pattern did not necessarily follow the state boundary, some cells along the borders received an artificially low count. However, the relatively small number of cells so affected reduces the importance of the problem, and the overall pattern of lineament density is not materially affected.

There is an average of 13.6 lineaments per unit cell. The maximum for any cell is 57, at a point along the Canadian River in Hutchinson County. Two areas--not along the border of the state--comprise contiguous unit cells that contain no lineaments: one area along the Crockett-Schleicher county line and the other near the junction of Glasscock, Midland, Reagan, and Upton Counties. Both are areas of low relief and have little tonal contrast in the ground cover as seen in Landsat images.

Density of Lineament Intersections

A contour map showing moving averages of numbers of lineament intersections is presented on one of the insets of the statewide lineaments map (Plate, in pocket). Two lineaments are said to intersect if they cross, abut, or terminate at a common point.

These data were counted and tallied by the same procedures used to determine lineament density, and the contours showing moving averages of intersections reflect the same type of edge bias along the state's borders as seen for the other depiction of relative lineament densities.

Lineament Orientation

We measured azimuth orientations (within 10° increments) for all lineaments in each unit cell. Frequency of distribution of lineament orientations is bimodal (fig. 4). Almost half the lineaments in the state lie within two 30° intervals of azimuth: from 40° to 70° (27 percent of the total) and 300° to 330° (22 percent of the total). Two maps depict the densities of lineaments that fall into these two dominant intervals (insets on Plate, in pocket). These maps employ a simple rather than a moving-average count. A density of at least 4 lineaments per 30° interval was considered to be the threshold for contouring. A density of 3 or less implies that in most cases, no more than one lineament fell within each of the three 10° increments--a distribution too easily influenced by rare or chance orientations to be meaningful. Using four as the threshold thus ensures that at least one of the 10° azimuth increments will have two or more lineaments.

Within a single unit cell the maximum number of lineaments oriented in the primary azimuth mode (40° to 70°) is 19; this was in Hutchinson County, at the same place where the total lineament density is highest. There are many areas throughout the state in which several contiguous unit cells contain no lineaments in the primary azimuth mode. These null areas, as well as many cells wherein the requisite contouring threshold is not reached, underscore the selective distribution of lineaments across the state. This demonstrates that "grain" is not defined by any single orientation. In short, there is no single grain for Texas.

In the secondary azimuth mode, the maximum number of lineaments within a single unit cell is 18. This occurs along the Hockley-Lubbock county line. Also, as with the geographic distribution of lineaments within the primary mode, there are vast areas of the state that appear on the map as null areas because the contouring threshold is not attained.

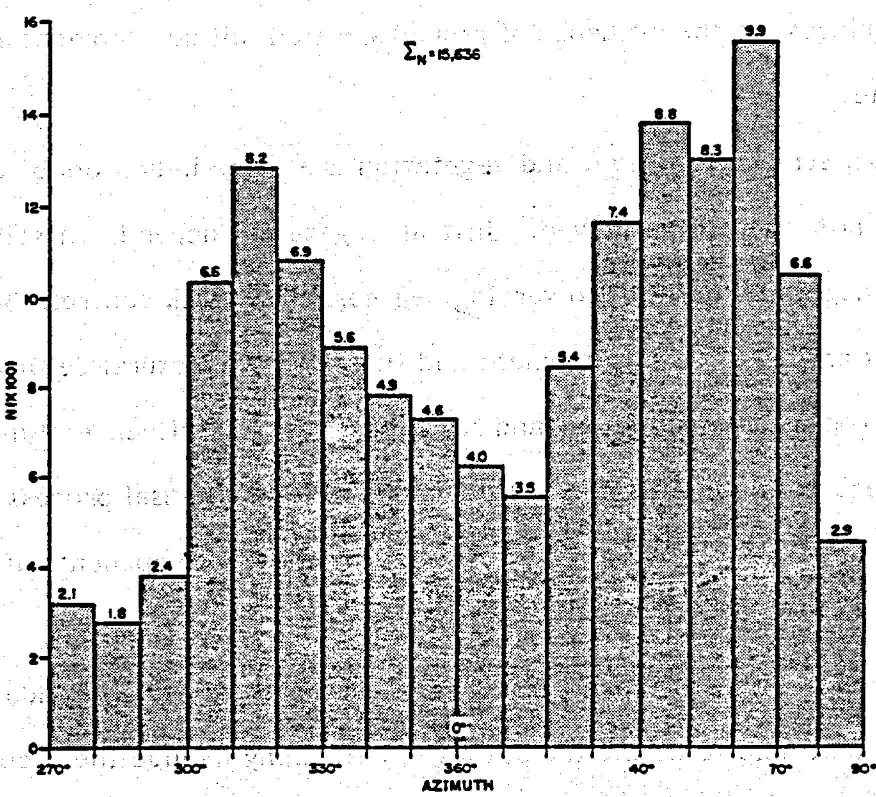

Figure 4. Histogram of lineament orientations within 10° azimuth increments. Numbers at the tops of the histogram bars show percentage of each increment with respect to the total population of lineaments.

INTERPRETATIONS

Physiographic Grain

"Grain" as used herein applies to the dominant directional attributes of the landscape within an area. Grain is most commonly expressed by topographic or drainage features. It is thus indicated by linear escarpments, ridge lines, or valleys, all of which exert control on vegetative assemblages via the influence of ground slope on soil development and erosion and on local water regimes.

Ground slope, surface drainage, and vegetation are often indicators of other deep-seated controls that are not directly perceived. Just as vegetation depends on soil, slope, and to a large extent, drainage, all conform, to varying degrees, to bedrock control. Bedrock, in turn, is a result of ancient processes of emplacement and subsequent structural deformation controlling the position of a rock mass. Structure and rock-mass position influence climate--both modern climate and aggregate climatic processes through time. Grain causal processes are similar to those affecting lineaments (see fig. 1) because lineaments are components of the overall grain of a region.

Certain aspects of the grain of Texas could be predicted without conducting a lineament survey. Features that help to define the state's physiography include the arcuate coastline and coastal plain rising to the northwest (fig. 5) and the complementary drainage development with major streams flowing at roughly right angles to this topographic grain (fig. 6). The surface geology of the state is both a response to and a control on regional topographic features. Many sedimentary rock units of Texas define a northeast-southwest trend, although these are exceptions, especially in the Trans-Pecos region, North Texas, and northeast Texas. In the Gulf Coastal Plain, certain Tertiary sandstones form linear escarpments such that the strata have been compared to a gently inclined stack of books with the spines as the scarps and the covers as the dip slopes of the Gulf Coast cuestas. On the basis of these prevailing trends, it might appear that the two major azimuth modes are accounted for by topography and geologic strike

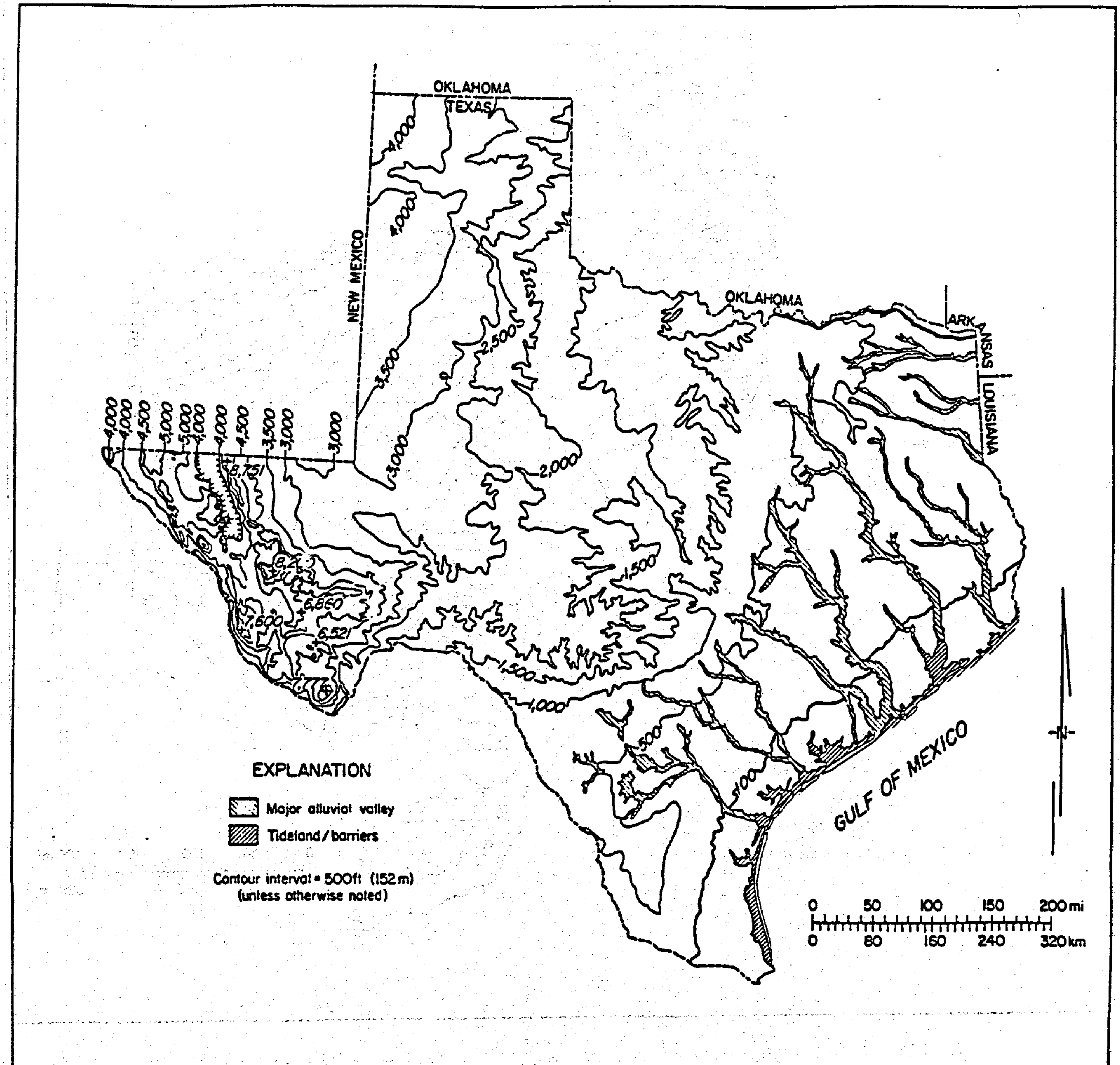

Figure 5. Generalized topography of Texas.

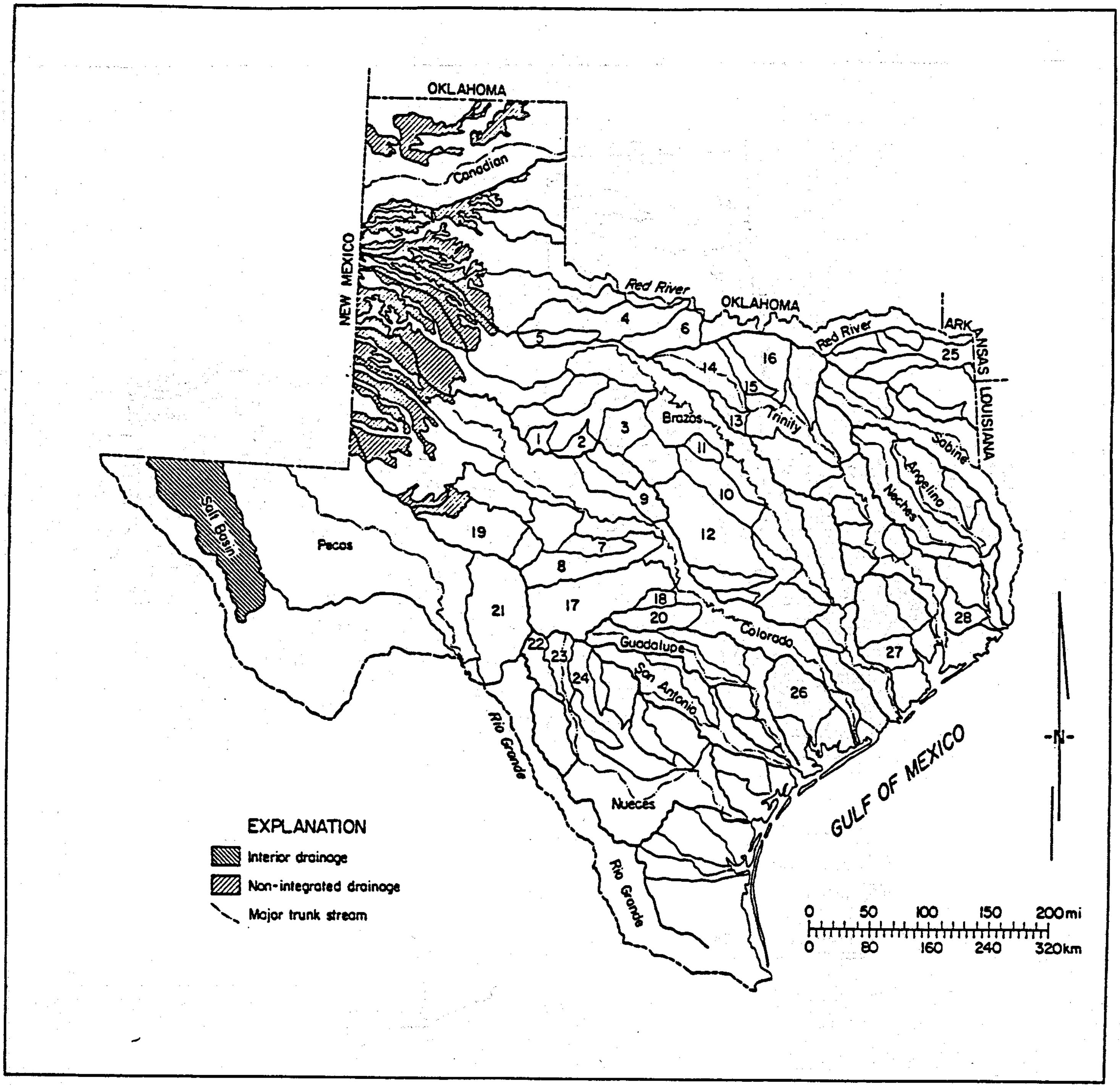

Figure 6. Generalized drainage basins of Texas. Selected basins denoted are: 1--Sweetwater Creek; 2--Elm Creek; 3--Hubbard Creek; 4--Wichita River; 5--South Wichita River; 6--Little Wichita River; 7--Brady Creek; 8--San Saba River; 9--Pecan Bayou; 10-- Bosque River; 11--Paluxy River; 12--Leon/Lampasas Rivers; 13--Clear Fork of Trinity River; 14--West Fork of Trinity River; 15--Denton Creek; 16--Elm Fork of Trinity River; 17--Llano River; 18--Sandy Creek; 19--Middle Concho River; 20--Pedernales River; 21--Devils River; 22--West Nueces River; 23--Nueces River; 24--Frio River; 25--Sulphur River; 26--Lavaca/Navidad Rivers; 27--Buffalo Bayou; 28--Pine Island Bayou.

(primary mode), and by major drainage trends (secondary mode). But there are many other ways in which structures control drainage and topography; for example, low-order tributary streams are more commonly perceived as lineaments than are major trunk streams.

In short, the grain is a generalized expression of physiographic orientation, which is at least in part controlled by geologic structures. Lineaments are components, and hence expressions, of this grain. There seem to be subtle topographic expressions of certain geologic structures, even in areas where the controlling structures are long dormant or are buried. Many geologists overlook the structural imprint on surficial phenomena, yet surface features may provide important insights about any region's subsurface structural makeup (Arvidson and others, 1982; Schowengerdt and Glass, 1983).

Physiography is the broad-scale lay of the land. It is chiefly a result of interactions among surface geology, topography, and drainage. These three factors are, in turn, surface manifestations of several other controlling factors including structural setting (fig. 8) and climate (fig. 9). Physiography is a composite expression of these factors, and it imposes controls on soils, biota, and human land use. Major physiographic subdivisions afford a region-by-region approach for understanding the various attributes of grain--of which lineaments constitute one aspect. Since these physiographic regions afford a means of considering subset areas of the state, they are the basis for much of the subsequent discussion of lineaments.

A refined physiographic depiction of Texas was compiled (by CMW, Jr.) as part of this lineament survey. The main basis for this new compilation was the Geologic Atlas of Texas (Barnes, project director). These geologic data were also assayed in terms of regional topography as derived from Army Map Service (AMS) 1:250,000 quadrangles, and occasionally using statewide soils information (Godfrey and others, 1973). The names of the various provinces generally conform to earlier works by Hill (1900), Johnson (1931), and Chambers (1948); however, the precise boundaries are different and are new products of this statewide lineament assessment. For example, the physiographic map presented here contains the first published depiction of the boundary of the plateau terrain of the Edwards Plateau region.

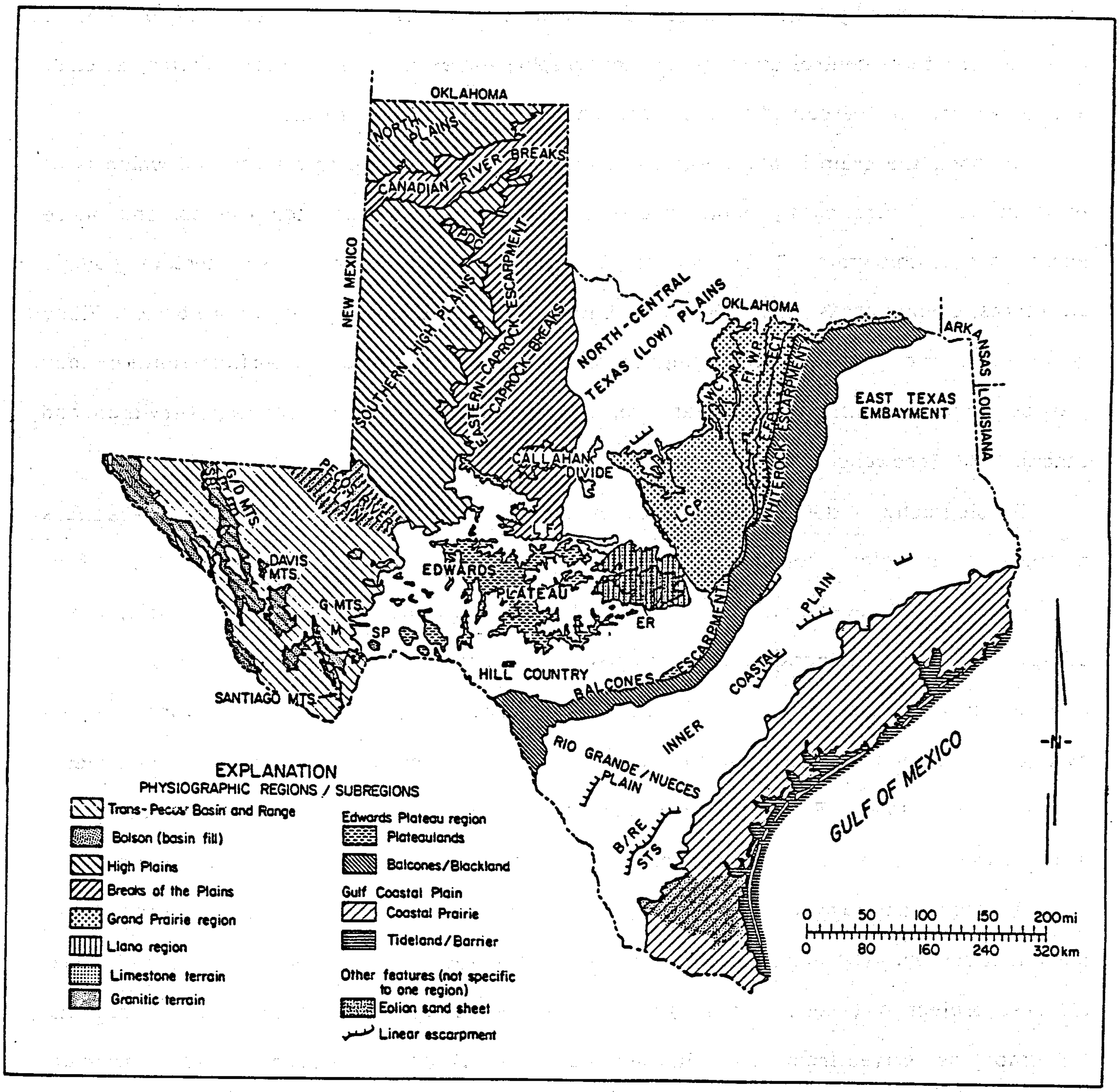

Figure 7. Generalized physiography of Texas. Selected areas abbreviated on map are: B/RE--Bordas/Reynosa Escarpment; ECT--Eastern Cross Timbers; EFP--Eagle Ford Prairie; ER--Enchanted Rock; Ft. WP--Fort Worth Prairie; G Mts.--Glass Mts.; G/D Mts.--Guadalupe/Delaware Mts.; LCP--Lampasas Cut Plain; LF--Lipan Flat; M--Marathon Area; PDC--Palo Duro Canyon; SB--Salt Basin; SP--Stockton Plateau; STS--South Texas Salient; WCT--Western Cross Timbers.

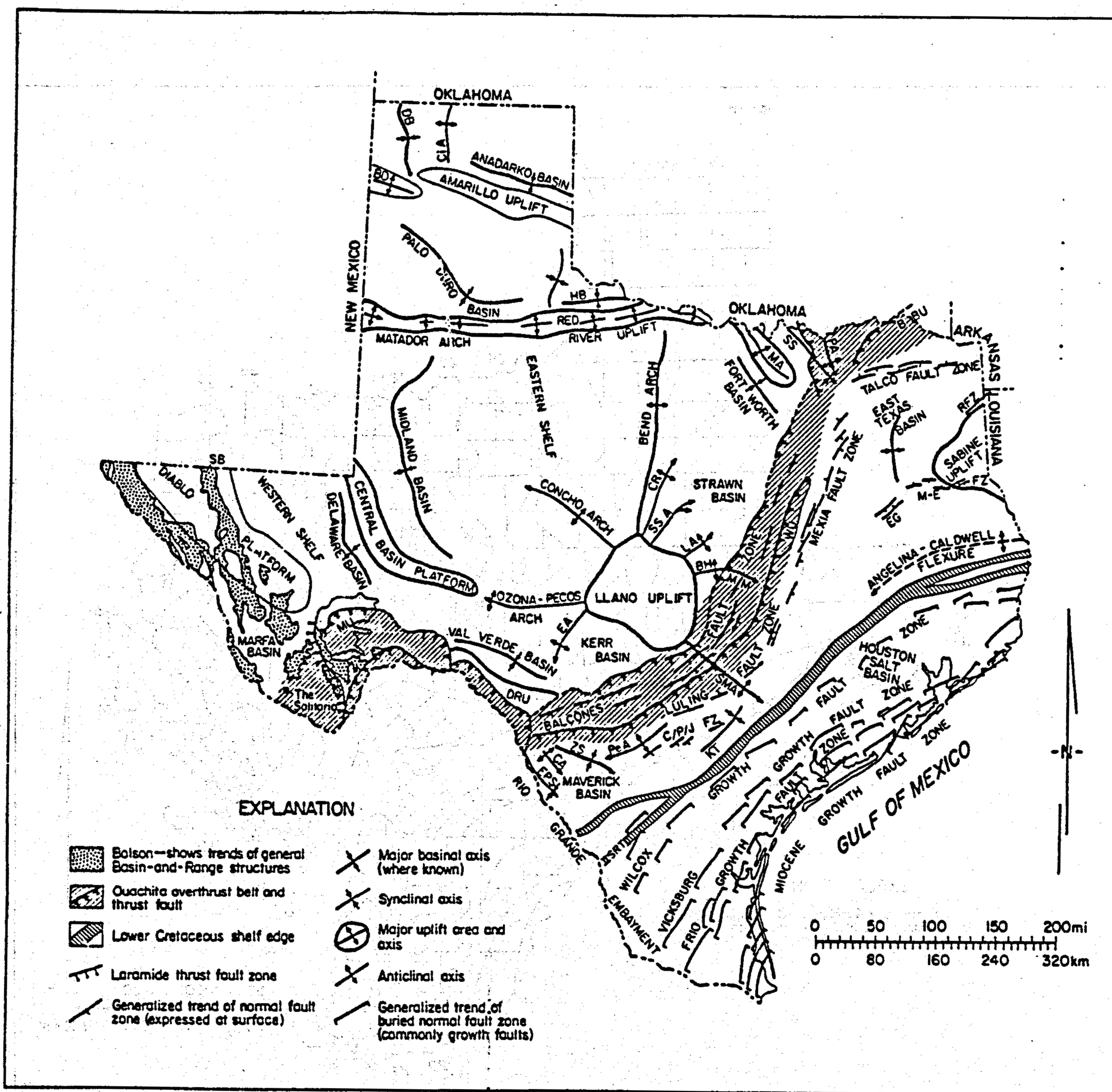

Figure 8. Generalized structural provinces of Texas. Selected areas abbreviated on map are: BBU--Broken Bow Uplift; BD--Bravo Dome; BH--Belton High; CA--Chittim Anticline; CiA--Cimarron Arch; C/P/JFZ--Charlotte/Pleasanton/Jourdanton Fault Zone; CR--Cavern Ridge; DB--Dalhart Basin; DRU--Devils River Uplift; EA--Edwards Arch; EG--Elkhart Graben; EPS--Eagle Pass Syncline; HB--Hardeman Basin; KT--Karnes Trough; LA--Lampasas Arch; MA--Muenster Arch; MEFZ--Mount Enterprise Fault Zone; MM--Moffat Mound; MU--Marathon Uplift; PA--Preston Anticline; PeA--Pearsall Arch; RFZ--Rodessa Fault Zone; SB--Salt Basin; SMA--San Marcos Arch; SRT--Sligo Reef Trend; SS--Sherman Syncline; SSA--San Saba Arch; WU--Waco Uplift; ZS--Zavala Syncline.

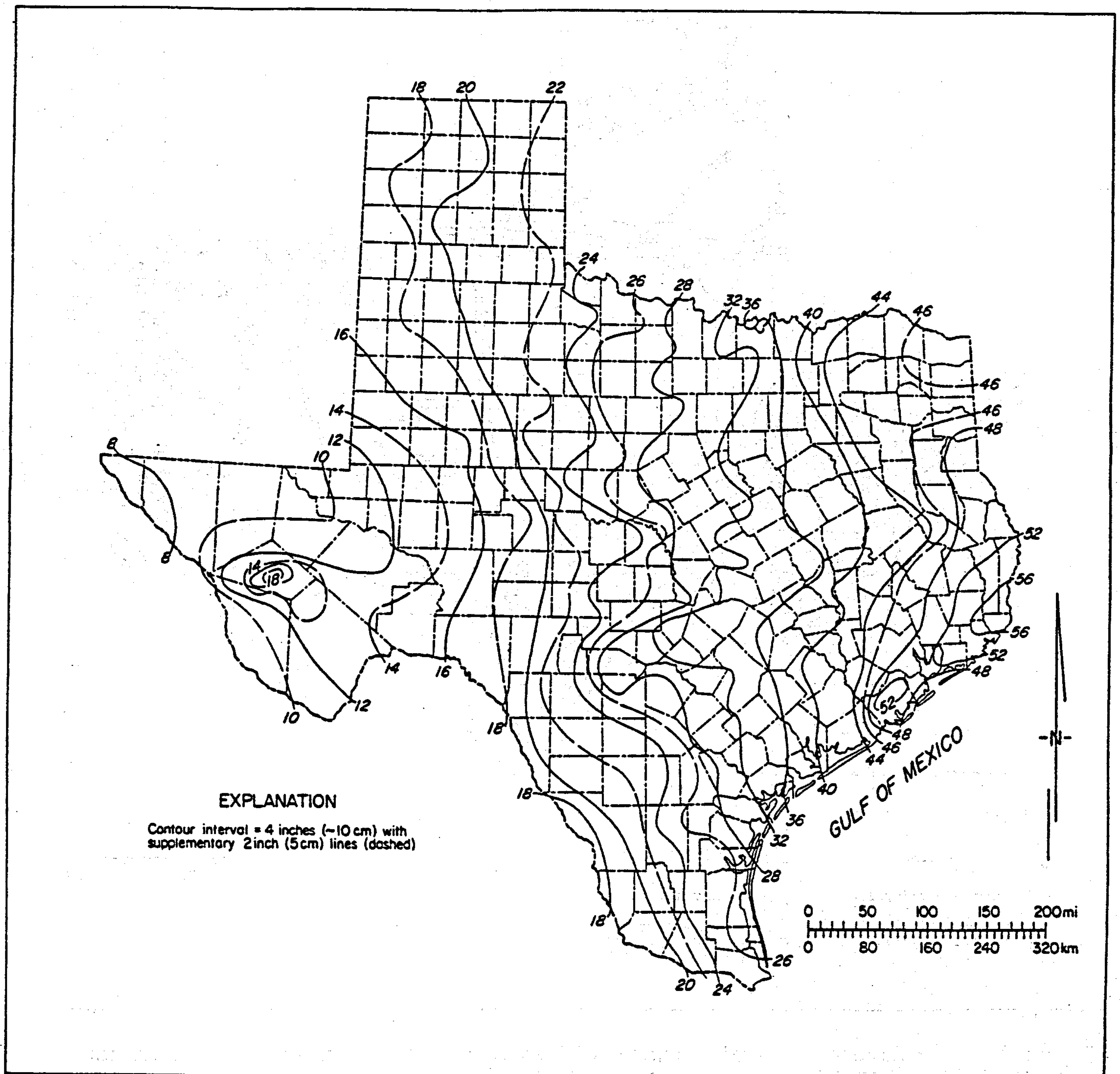

Figure 9. Mean annual precipitation (in inches) in Texas (Texas Department of Water Resources, personal communication, 1983).

Heretofore no distinction was made between the plateau proper and the dissected Hill Country west of the Balcones Escarpment. The distinction is certainly important to the degree of dissection and amount of soil retained and hence to the vegetative ground cover. Dissection and soil retention influence the amount and quality of lineament data that have been registered in the two subregions.

In addition to constructing a revised statewide physiographic map, we also prepared new generalized renderings of the state's topography and drainage based on 1:250,000-scale, 1° x 2° AMS Quadrangle sheets. On these original bases, we traced drainage nets and drew drainage basin boundaries for various stream orders. When these maps were photocopied and reduced to a scale of 1:500,000, topographic contour lines were smoothed and drawn showing a 500-ft (152 m) contour interval (with lesser intervals along parts of the Gulf Coastal Plain).

The two maps are, of course, complementary; drainage both shapes the landscape and is an expression of topography. From joint consideration of the two maps, certain motifs of regional grain may be seen. Both drainage and topography show aspects of the northwest-southeast--and less prominently at this scale of view--the northeast-southwest trends that constitute the respective secondary and primary azimuth quadrants for lineaments statewide.

The northwest motif is seen along the Pecos/Rio Grande drainage divide, which abruptly delineates the mountainous Trans-Pecos country from the plains and plateau country farther east. The overall topographic trend of the basins and ranges lies along this northwest-southeast grain, and the interior drainage of the Salt Basin lies along this same axis. The northeastern course of the Rio Grande in the Big Bend region marks a zone of high topographic relief approximately perpendicular to the overall basin/range grain throughout most of the remainder of the Trans-Pecos region. This indicates the influence of the cross-cutting Marathon structural belt. The northwestern motif is elsewhere expressed in drainage basins and draws coursing off the High Plains. Topographically a ragged edge of the eastern Caprock Escarpment lies roughly normal to the prevailing drainage trend. The northwest-southeast motif is further seen in the general trend of coastward-flowing rivers and many of the nearby major drainage divides, although there are prominent exceptions: in most of the main-stream course of the Red River, along the Colorado/Guadalupe drainage divide, within the upper part of the Nueces River, and along the main course and nearby drainage divide of the Nueces in South Texas where both stream and divide show a northeast to southwest trend.

Obviously, one major control on this northwest-southeast orientation of drainage is the configuration of the present Gulf shoreline--the baselevel for these southeastward-flowing river systems. But another control is the presence of a major topographic salient that is bounded on the south by the Rio Grande and on the north along a broad zone that extends from Palo Duro Canyon at the edge of the High Plains southeastward along the narrow topographic salient along the Colorado/Brazos divide at the southern edge of the Lampasas Cut Plain in Burnet and Williamson Counties. On the south, the topographic salient is bounded by the Balcones Escarpment. This major salient is partly structural, relating to the relative uplift north and west of the Balcones Fault Zone. But it is partly due to the resistance to erosion of Lower Cretaceous limestones that cap the Edwards Plateau region. The bounding area to the south of this major topographic salient is an embayed area along the Rio Grande. However, this feature is not well expressed topographically, probably owing to relatively recent (Neogene) uplift nearby in Mexico. However, the generalized topographic map shows much of north Texas to be an area of overall low relief; a vast embayment extends from the Brazos River northwest into Childress County at the edge of the High Plains. This embayment is asymmetrical owing to the nearby topographic influences in Oklahoma of the Wichita, Arbuckle, and Ouachita Mountains. In East Texas isolated topographic closures are common, which, at the generalized scale of presentation, indicates dissected rolling terrain. Erratic topography is probably influenced by salt tectonics and by the edge of a major buried crustal discontinuity along the Sabine Uplift.

Despite local anomalies, the salient and the adjacent embayed region have had marked effects on drainage development for river systems from the Brazos south. The Brazos and Colorado River systems show evidence of migration of the trunk streams off the topographic salient and into the embayment. This is especially true of the Colorado River: all its major tributaries west of the Balcones Escarpment enter the trunk stream from the west. Only Pecan Bayou enters the main stream from the north. For the Brazos, the same is true although the pattern is obscured by the major subbasin of the Lampasas-Little-San Gabriel Rivers that travel parallel to the Brazos along its prevailing southeastern course. It is further obscured west of the upstream extent of the Trinity River basin, where the Brazos and Red River basins are adjacent and where various headwater tributaries mingle with the main trunk stream. The response of the main stream courses to these overall topographic factors has been important in establishing northeastern trends of certain tributary streams, especially for parts of the Colorado system, as seen for the Concho, San Saba, Llano, and Pedernales Rivers. These tributary courses have contributed to the perception of many lineaments.

Trans-Pecos Region

The Trans-Pecos region is geologically complex. It has been deformed by at least three major tectonic events: the Ouachita orogeny of late Paleozoic age (affecting the Marathon area), the late Mesozoic Laramide orogeny (best seen along the Santiago Mountains in the Big Bend), and the Cenozoic Basin-and-Range faulting that has largely obscured the older structures in the region. In addition, there are local exposures of Precambrian rocks that have been deformed in complex ways by still older orogenic events; however, the limited exposure of these older structures reduces their direct influence on the regional surface grain. The more obvious regional grain is dominated by a series of northwest-southeast trending mountains with intervening structural basins (bolsons). The continuous linearity of these features is somewhat obscured by the widespread volcanic deposits that extend from the Davis Mountains southward to the Big Bend.

Lineaments are strongly correlative with the Basin-and-Range structures, that is, with the relatively recent extensional features having a northwest-to-southeast orientation. The highest densities of lineaments occur along the mountain fronts with prevailing azimuths along structural strike. A strong complementary alignment occurs roughly normal to strike, reflecting the presence of streams flowing along dip slopes. This secondary, strike-normal trend is especially evident along the dip slope east of the Guadalupe and Delaware Mountains. Here, a high density of east-west lineaments may be controlled by subsurface salt dissolution as well as by surface drainage. Surface drainage is probably controlled in part by this subsurface (solutional) phenomenon, which may be imprinted on the regional topographic gradient. Such subtle interactions occur throughout the state, for example, on the High Plains and Edwards Plateau, and they are important examples of polygenetic lineaments.

Whereas the block-faulted and volcanic mountains are the loci of greatest densities of lineaments in this region, the bolsons are areas having sparse lineament density. This is because of (a) low relief, (b) obscuring alluvial deposits that (unlike bedrock) do not readily display structural grain, and (c) the uniformly high reflectivity of the alluvial fill materials. These combine to cause poor contrast in Landsat images covering bolson areas. Poor contrast results in perception of few lineaments in these areas, yet the bedrock is surely deformed. Perhaps a more detailed resolution (such as large-scale photography) would disclose lineaments in these areas.

The topographic and drainage features align with Basin-and-Range structures because of relatively recent (and locally still active?) structural disturbances that control physiography directly. The Salt Basin is a manifestation of continuing structural control of modern drainage and topography; this large watershed with interior drainage indicates that structural processes have dominated the subsequent surface (geomorphic) processes. Relatively young tectonic controls persist as far east as a line extending from the Guadalupe/Delaware Mountains southeastward through the Davis and Santiago Mountains. To the east of the Santiago Mountains is the Marathon Uplift, where the topographic grain and drainage nets/drainage basins change to a northeasterly and easterly trend, as is reflected by lineament orientations conforming to the local structural grain of this part of the Ouachita deformed belt.

Major Paleozoic cratonic features such as the Diablo Platform, the Marfa Basin, and the Western Shelf of the Delaware Basin do not have a distinct surface expression except where the features have a northwest-southeast strike (Sellards and Hendricks, 1948). This orientation coincides with the younger Basin-and-Range grain, so our perception of the buried (cratonic) features is ambiguous. Except for the aforementioned salt-solution features east of the Guadalupe Mountains and the Glass Mountains/Marathon Uplift--areas little affected by Mesozoic or Cenozoic tectonic activity--there is little evidence of structural grain in the eastern half of the region. This is an area of vast deposition graded to the Pecos River. As with the bolsons, alluvial cover obscures bedrock structures, and lineaments are thus ill perceived.

The Trans-Pecos region is also the site of part of the "Texas Lineament," a major (and controversial) feature that supposedly extends from northern Mexico and South Texas through the Big Bend region and from there back into Mexico and possibly across New Mexico, Arizona, and California. First noted by Hill (1902), its boundaries are ambiguous, as noted by Albritton and Smith (1957). We have located parts of this (mega) lineament system as defined by Muehlberger (1980), but we do not see it as a single feature. It may be a major structural zone that would show up in a series of composite features at a smaller scale of view. However, the synoptic overview afforded by Landsat should present the best possible view of a large-scale feature of this kind. Gilluly (1976), for one, takes exception to the continuity of this trend as it has been extended into the ore districts of the southwestern United States.

High Plains

The Texas High Plains are here defined as the plateau terrain, largely held up by the Ogallala Formation and its resistant Caprock caliche that occurs in the Texas Panhandle and adjacent areas of West Texas. The High Plains Province includes two discontinuous areas, the Southern High Plains (or Llano Estacado) and the North Plains; the two areas are separated by the Canadian River Breaks, which is part of what we call the Caprock Breaks Province.

The High Plains Province is noteworthy among major physiographic regions of Texas in that it is a major aggradational highland area. That is, deposition has surpassed downwasting as the main process during most of the Quaternary. The only other areas where aggradation has dominated downwasting are the alluvial valleys and certain local adjacent areas (such as the Pecos River Plain), and the topographically low coastal plains (Pleistocene outcrop). Of course, individual sites within these other areas are also subject to erosion; they are all above baselevel, but, in contrast to the High Plains terrain, they are not highlands.

The High Plains Province also includes local areas in which surface downwasting does occur. These areas are the "draws," which are long drainage courses with highly elongate, extremely low-order drainage basins. The interfluvial areas that constitute most of the High Plains surface are not integrated into any surface drainage network. There, thousands of small playas and a few larger depressions (relict pluvial lakes) act as local baselevels. Unlike the Salt Basin, these interfluves are not areas of integrated interior drainage. Instead, they have an overall ground-surface slope of about 9 ft/mi toward the eastern caprock edge (fig. 6). The local baselevels of the small playas result in non-integrated interior drainage.

The High Plains are underlain by resistant strata, but across most of the region the ground surface consists of a veneer of eolian cover sands or loess (Barnes; project director 1965-1982). In some places, such as across Bailey and Lamb Counties, there are active dune fields. The High Plains thus would not appear to be a promising locality for viewing lineaments. It is a low-relief terrain with highly reflective eolian cover and intensive irrigation, which produces complex, man-made patterns on Landsat images. Yet it is an area with very prominent lineaments owing to the marked linearity of the draws and the playas. Various interpretations have been made regarding the alignment of these features (Woodruff and others, 1979; Finley and Gustavson, 1981). The draws trend mainly down the (southeast) topographic gradient, and many playas have lee dunes on their southeast (downwind) side, suggesting an eolian genesis. So it might be said that these features (and, hence, their associated lineaments) are merely the results of surface processes superimposed on the general regional topography. However, recent workers (Gustavson and Finley, in press) have noted a strong subsurface influence on this overall grain, owing to dissolution of soluble bedrock at depth. Dissolution at depth follows fracture systems that become expressed at the surface as subsidence troughs, draws, and alignments of playas (Finley and Gustavson, 1981).

The High Plains region is underlain by major uplifts and basins that are controlled by Precambrian basement structures and are characteristic of the continental interior (craton) of North America (fig. 8). The uplifts are commonly bounded by major faults that displace Precambrian basement (Ewing and others, in progress), and being structurally high, support a relatively thin column of sedimentary rocks compared to the basins.

Three major uplifts underlie the High Plains and adjacent areas: (1) the Amarillo Uplift, which mainly underlies and coincides with the Canadian River Breaks, and hence delimits the boundaries between the Breaks and both the Southern High Plains and the North Plains; (2) the Matador Arch, which trends east-west across the High Plains from Bailey to Floyd Counties, and from there farther east where it joins the Red River Uplift (fig. 8); and (3) the Central Basin Platform, whose northern edge almost exactly coincides with the southern limits of the High Plains.

The effects of basement structures on surface features of the High Plains are still open to question. Ongoing work at the Bureau of Economic Geology suggests that basement structures do control surface alignments (Budnik, 1983). The most obvious lineament trend is northwest-southeast (300° to 330° azimuth) parallel to drainage, and a complementary set (40° to 70° azimuth) is parallel to topographic contours. Certain minor flexures superimposed on the basins and uplifts align with the prevailing surface grain, but for the data presented here the High Plains area shows ambiguous basement control. Instead, salt dissolution may be a major subsurface control influencing the various surface alignments (Gustavson and Finley, in press). Salt dissolution, in turn, is apparently controlled by hydrodynamics imposed by thinning of the sedimentary column and structural disturbances across these uplifts.

Breaks of the Plains

The Breaks of the Plains region includes the escarpments and the topographically low areas that border the High Plains on all sides except the southeast, where the High Plains

Province merges with the Edwards Plateau. The Breaks of the Plains Province comprises three subprovinces: the Canadian River Breaks on the north, the Caprock Breaks Rolling Plains on the east, and the Pecos River Plain on the southwest. All three subprovinces are characterized by an abrupt topographic break with the High Plains, but the break is only minimally expressed at the edge of the Pecos River Plain in Texas, an area of eolian aggradation similar to the High Plains. The most dramatic topographic break occurs across the eastern edge of the Caprock where more than 1,000 ft (305 m) of elevation change occurs.

Except for the Pecos Plain the Breaks are intensely dissected owing either to the high relief or to the common occurrence of erodable substrate. There are also numerous areas of ongoing stream piracy resulting from abrupt changes in stream gradient. Moreover, stream-gradient changes have resulted in widespread alluviation that documents various periods of drainage adjustments. Many of the abrupt topographic changes and consequent drainage adjustments may be related to salt dissolution (Simpkins and others, 1981). The eastern limit of these Breaks aligns roughly with the 100th Meridian which, in turn, generally marks the eastern limit of broad, relict alluvial areas representing possible ongoing adjustment of drainage systems.

The 100th Meridian may also mark a major climatic break. It certainly exists as such in the popular mind; it is commonly cited (Heat Moon, 1982) as a dividing line. This meridian almost coincides with the 24-inch rainfall isohyet, and the eastern Caprock Escarpment of the Southern High Plains lies generally along the 21-inch isohyet (fig. 9). These precipitation values, coupled with evaporative losses, may closely approximate areas of maximum fluvial erosion predicted by Langbein and Schumm (1958). This maximum occurs where intense rainfall occurs sporadically and is so infrequent as to prevent the establishment of dense erosion-retarding ground cover. Because of maximum dissection along the borders of the Caprock, some of the highest densities of lineaments anywhere in the state occur east of this Escarpment.

As already mentioned in the discussion of the High Plains, major structurally high areas underlie part of the Pecos River Plain and most of the Canadian River Breaks. Hence, although the gross geometry of these two subprovinces seems to be at least indirectly controlled by basement uplifts, the more direct control may be salt solution in strata superjacent to these basement highs. Lineament patterns parallel the edge of part of the Central Basin Platform, which coincides at the surface with the low but continuous southern boundary between the High Plains and the Pecos Plain. A major normal fault marks the northern edge of the Central Basin Platform from Ector County to Crockett County. In Ector, Crane, and Upton Counties, the trace of this subsurface bounding fault is indicated by lineaments trending along a low escarpment made up of Lower Cretaceous strata that crop out along the edge of the Pecos River Plain. Elsewhere, the Pecos River parallels the axis of the Central Basin Platform only in its central part, so lineament expression of basement structure is not consistent everywhere across the region and in some place be only fortuitous. Lineaments across the Canadian Breaks do not generally reflect the structural grain (azimuth of 330°) of the Amarillo Uplift and associated faults, although there is an area in Hutchinson and Carson Counties that shows a high density of lineament azimuths in the range from 300° to 330° (secondary azimuth range). This coincides with the orientation of local buried structures, both faults and the axes of flexures.

The Caprock Breaks are not generally correlative with structures that are resolvable at our working scale (1:1,000,000). The province boundary parallels the strike of the Eastern Shelf of the Midland Basin. This shelf area, however, is not a distinct structural entity, as it has migrated through time. Lineament trends seen on the High Plains extend onto these Eastern Caprock Breaks, notably the concentration in the secondary azimuth mode seen in Kent, Scurry, and Fisher Counties. In this area, a correlation exists with the northern limb of the Horseshoe Atoll. The southern limb in Terry and Dawson Counties also lies along surface lineament trends. A broader and somewhat less pronounced trend of lineaments in the primary azimuth range (40° to 70°) occurs parallel to the Caprock Escarpment and along Palo Duro Canyon. The extension of azimuth trends from the High Plains to the Breaks suggests subsurface control on lineaments rather than effects of local ground slope with consequent surface drainage, or of prevailing wind direction with consequent deflation and lee dunes (Finley and Gustavson, 1981).

North-Central Texas Plains

The North-Central Texas (Low) Plains constitute a geological extension of the High Plains Breaks terrain on the eastern side of the Caprock. These two provinces make up the Rolling Plains region commonly depicted on physiographic maps of Texas. There is no inherent change in bedrock type that delineates the Low Plains Province from the Eastern Caprock Breaks farther west, but the discrimination of a different physiographic region is warranted because abrupt topographic changes characteristic of the Breaks are no longer seen east of the 100th Meridian. Neither are there the rapid changes in climate associated with the terrain breaks, nor the widespread relict alluvial features that are themselves characteristic of a landscape in disequilibrium. For these reasons fewer lineaments are perceived across the North-Central Texas Plains compared to the Caprock Breaks. In general, the province is part of a vast lowland or embayed area with local escarpments held up by resistant limestone and sandstone strata. It is an erosional terrain across which streams have adjusted their courses and gradients to a generally nonresistant substrate. The substrate is largely sandstones and shales of Pennsylvanian and Permian age, but the actual contact between Pennsylvanian and Permian units is poorly defined.

The North-Central Texas Plains Province extends north into Oklahoma, east to the continuous outcrops of Cretaceous strata (the Western Cross Timbers subprovince of the Grand Prairie Region), and south to the Edwards Plateau and Llano regions. It also includes part of the Cretaceous outliers that make up the Callahan Divide. In these areas of high relief, lineament density is the highest of any other place in the region. Along the Brazos-Colorado drainage divide, the Low Plains Province is constricted because of the geometry of the Cretaceous outliers that occur along the northeastern margin of the Edwards Plateau and along the western edge of the Grand Prairie region (fig. 7). There, also, are local areas of high lineament density.

A major subsurface structural feature extends through this province in a north-south direction (fig. 8); this is the Bend Arch, which marks a change in direction of dip involving Paleozoic strata, especially seen in the subsurface. On the west, the strata dip into the Midland Basin, and on the east they dip toward the Fort Worth and Strawn Basins. Drainage patterns within the Brazos watershed change across the surface projection of the Bend Arch. East of the Arch appears a persistent southeast trend, both of the trunk streams and of tributary basins. West of the Arch, elongate, northeastwardly trending tributary basins course into the general eastward trends of trunk streams. Colorado River drainage across this terrain is predominantly along an eastward course, and so are certain tributary basins (Brady Creek and San Saba River). Geophysical data indicate a basement discontinuity along this trend (Watkins, 1961) and streams in this area are probably influenced by these structural controls. In the southeastern corner of this province, the Colorado River, the Pecan Bayou watershed, and the Colorado/Brazos divide show a general northwest-southeast trend (azimuth of 310°) that generally parallels the overall alignment of Brazos drainage east of the Bend Arch. This trend probably aligns with the strike of possible basement faulting along the northern edge of the Llano Uplift. North of this line Watkins' geophysical data indicate an overriding of the craton by a salient of the Ouachita overthrust zone.

Lineament patterns across most of the Low Plains Province are generally nondescript. Their density is low, in accordance with the generally low surface relief. The few localities with a high density of lineaments correlate with topographic breaks such as along the Callahan Divide (fig. 8), near the continuous Cretaceous exposures to the east, and in an intensively dissected terrain in Throckmorton, Shackelford, and Haskell Counties. Lineament orientation generally aligns with the major trends of drainage, and this correlation indicate the underlying Bend Arch. The map showing azimuths in the primary mode shows a good correlation with the Bend Arch and Cavern Ridge as far north as Palo Pinto County. There the lineament trend veers to the east, where it may be influenced by southeast-trending features associated with the Red River Uplift and the Muenster Arch. Along the Texas-Oklahoma boundary, the Red River Uplift is not well expressed by lineament trends.

Grand Prairie Region

The Grand Prairie physiographic region was defined and extensively described by Hill (1899-1900). Nonetheless, there has been much confusion as to the names attributed to this region and to its subprovinces. We call the province the Grand Prairie region to be consistent with Hill but note inconsistencies with his other writings (see for example Hill, 1900). The Grand Prairie region comprises five subprovinces: (1) the Western Cross Timbers, underlain by Lower Cretaceous sandstone units (the Trinity Sands, including variously, the Sycamore, the Travis Peak, the Antlers, the Twin Mountains, and the Paluxy); (2) the Lampasas Cut Plain, underlain by limestones of the Trinity and Fredericksburg Groups; (3) the Fort Worth Prairie (or the Grand Prairie, proper) underlain by Washita-age strata; (4) the Eastern Cross Timbers, underlain by the Woodbine Sand; and (5) the Eagle Ford Prairie, underlain by the Eagle Ford Shale. The region is bounded on the west by the contact between Cretaceous and Paleozoic strata; on the north by the Red River alluvial valley; on the east, by the Whiterock Escarpment that marks the western limit of the Blacklands; and on the south (from near Burnet east to the Balcones Escarpment) by the Brazos-Colorado divide.

The Grand Prairie region has a remarkable northwest-southeast grain that is reflected in the river systems--both trunk streams and their tributaries (fig. 6). For example, this grain has already been mentioned with regard to the course of the Brazos River east of Palo Pinto County, but the same overall trend is seen in the orientations of the Bosque/Paluxy tributary system and the Leon/Lampasas/San Gabriel system, as well as in the headwater tributaries of the Trinity River. Topography also reflects this grain, as expected; there are linear southeast-trending interfluves superimposed on the same vast topographic embayment (fig. 5) that extends to the western edge of the Low Plains Province, and which is occupied in its lowest parts by the Red River.

Many lineaments align with this prevailing grain, although the density of features in the secondary (northwest) azimuth mode is not as great as one might expect from the prominent topographic and drainage alignment in that direction. This may result from scatter beyond the 30° of azimuth included in the secondary mode. Instead, the prevailing lineament orientation is northeast to southwest, and this trend aligns with subsurface faults within the Strawn Basin (Ewing and others, in preparation). Moreover, the continuation of this prevailing trend continues west onto the Low Plains, which indicates subsurface controls common to both provinces. There are several prominent subsurface structural features that exhibit this northwest-southeast orientation. These include the Muenster Arch, the Sherman Syncline, and the axis of the deep Fort Worth Basin. Lineaments mark the axes and edges of these structures. However, as mentioned, lineaments do not correlate well with the topographic linearity noted across most of the region--especially along the Lampasas Cut Plain south of Tarrant and Parker Counties where the northwest-southeast topographic and drainage trends are so evident. The northwest-southeast lineaments in areas farther south align with the general strike of strata dipping into the Strawn Basin. Instead, on the basis of geophysical data (Watkins, 1961), we have proposed a subsurface, cross-strike discontinuity between the Llano basement massif and the Ouachita overthrust belt (Caran and others, 1981). Such features are noted elsewhere along overthrust belts (Wheeler, 1980), and are commonly associated with unusual lineament patterns as well as with enhanced fracture porosity at depth.

Llano Region

The Llano region is the smallest major physiographic province in Texas. It, like the Trans-Pecos region, is structurally complex: a domal uplift that includes a Precambrian basement complex rimmed at the surface on all but one side by outcropping lower Paleozoic strata (mainly limestones). Although structurally domed, the Llano region is a topographic basin. Cretaceous strata that formerly covered the dome now rim uplands on the west, south, and east, but the Pennsylvanian strata composing the Low Plains form a broad, featureless lowland north of the apron of lower Paleozoic limestones that surrounds the Precambrian dome. The Precambrian rocks now mostly form lowlands surrounded by fault-bound Paleozoic "mountains," Cretaceous plateaulands, and the dissected Hill Country. There are, however, impressive highlands within the Precambrian terrain, such as Enchanted Rock and the metamorphic rock terrane near Lake Roy Inks.

The grain of the Llano region is largely dictated by the overall distribution of Precambrian and Paleozoic rocks, especially by the location of block-faulted Paleozoic uplands and the erosional edge of Cretaceous strata that almost everywhere marks the limits of this physiographic region. Overall, the region is roughly elliptical. Its major axis is about 80 mi (130 km) long and trends about 330°. The secondary axis is 50 mi (80 km) wide and lies along a 60° azimuth. Hence, the axes of this elliptical area lie within the minor and major azimuth modes, respectively, for lineaments statewide. This suggests a cratonic (basement) control on statewide lineament orientation.

On contour maps representing the frequency distributions of lineament azimuths, the Llano region is clearly defined (inset on Plate, in pocket). The primary mode probably includes numerous northeast-trending normal faults that are most prominently expressed within the lower Paleozoic limestone terranes. Tributaries flowing into the Colorado from the west and certain stream reaches of the Llano River and Sandy Creek probably constitute the features that make up lineaments of the secondary mode. Some long lineaments trend north-south and extend through the entire region, but there is no apparent surface or subsurface correlation for these intriguing features. Most of the normal faults mapped in the Llano Uplift have a northeast-southwest strike, parallel to the trend of Balcones faulting (Barnes, 1981). Most subsurface faults mapping into the Strawn Basin to the north and into the Kerr Basin to the south have this same orientation.

Edwards Plateau Region

The Edwards Plateau region comprises two subprovinces: the Plateau proper and the dissected Plateau Margins. Plateau Margin areas on the south and east sides of the Plateau region are popularly called the Hill Country. The principal rock units cropping out across the region are the Lower Cretaceous Edwards Limestone and the subjacent Glen Rose Limestone. The Edwards Plateau extends into the eastern part of Trans-Pecos Texas to include the Stockton Plateau that adjoins the Marathon Uplift. From the Terrell-Brewster county line south to the Big Bend, the Cretaceous strata exhibit evidence of Tertiary block faulting. These fault-bound alluvial basins align with the general trend of Basin-and-Range structures farther west and probably represent the southernmost extension of that fault system. Lineaments lie along this prevailing structural grain in that area. Farther north, the Plateau region is bordered by the Pecos River Plain, the High Plains, and the Eastern Caprock Breaks. Along the Breaks, extensive outliers of Lower Cretaceous strata make the regional boundary somewhat irregular. The northwestern boundary applied here extends along the valley of the Colorado River from Howard County to Tom Green County and from there eastward into McCulloch County, where it separates parts of the Low Plains from the Llano region farther east. The Edwards Plateau then curves around three sides of the Llano region and terminates at the Colorado/Brazos drainage divide that marks the boundary with the Grand Prairie region. The southern and eastern border of this region is the Balcones Escarpment, which delineates the boundary between the Hill Country and the Balcones/Blackland Province. Near the escarpment actual plateau terrain recurs where Edwards Limestone is downfaulted against less resistant rocks.

The rocks cropping out across the Edwards Plateau region are resistant limestones that support the prominent topographic salient between the moderately embayed areas along the Rio Grande/Pecos drainageways, and the major embayment noted across the North-Central Texas Plains. The Edwards Plateau highland has thin soils and a characteristic live oak/juniper woody assemblage that becomes progressively more scrubby toward the west. Ranching is the principal land use throughout the sparsely settled region, and except for fencelines and for pipelines or roads associated with petroleum development there is hardly any confusing human overprint on Landsat images of this area.

However, terrain conditions have markedly affected our ability to perceive lineaments. The Hill Country along the southwestern margin of the Edwards Plateau region provides ideal conditions for perceiving these features, owing to deep incision, high density of streams, and sparse vegetative cover. The Plateau proper, on the other hand, discloses very few lineaments, as low relief and low stream density are further compounded by poor resolution on most of the Landsat images covering this area (fig. 2). In short, the true Plateau lands, although of approximately the same slope as the High Plains, show almost no lineaments owing to the absence of resolvable surface features there.

The grain of this part of Texas consists of two major trends. These trends are best expressed in the orientation of surface drainage, and deep structural control may occur for some of these features. Major trunk streams and tributary drainage basins within the Colorado River watershed have a general west-to-east trend; basins and trunk streams in both the Nueces and Rio Grande systems are oriented north-to-south. Structural control of the north-south orientation is especially evident in the Nueces River basin. There, the streams trend roughly perpendicular to the prevailing structural grain associated with the Balcones Fault Zone and associated escarpment (which is also parallel to the subjacent Ouachita overthrust zone). Much of the physiographic development associated with this fault zone has been attributed to stream piracy, such as that which has affected the San Antonio and Guadalupe River systems (Woodruff and Abbott, 1979). The piracy hypothesis is further supported by the east-west grain of Colorado River tributaries. Drainage-basin geometry suggests that the ancestral Guadalupe (and perhaps the San Antonio, as well) might have been part of the Colorado drainage system. The fact that all present major tributaries--except for Pecan Bayou--flow into the Colorado from the west suggests either structural control or progressive northward migration of the Colorado with ongoing capture of Brazos headwaters. Or a combination of these factors may have controlled the drainage development. Irrespective of origin, structural grain is expressed by a conjugate set of lineaments: one trending northeast-southwest along Balcones Fault lines compared to prominent northwest-southeast lineaments in the San Antonio and Guadalupe watersheds.

In addition to the lineaments that are clearly influenced by the drainage and by faulting, certain long lineaments that are normal or oblique to strike extend into the Coastal Plain Province. Two sets of such features--one extending from Burnet through Travis County and into Hays County, and the other through Bandera and Medina Counties--seem to circumscribe the flanks of the San Marcos Arch. Again, this suggests the presence of "cross-strike discontinuities" (Wheeler, 1980), which have been used to predict loci of basement discontinuities and enhanced fracture porosity in the Appalachian overthrust belt. Watkins (1961) has shown that similar offsets may have affected the pre-Mesozoic complex underlying the San Marcos Arch and other structures. As already mentioned, major lineaments along the Brazos-Colorado divide may be a surface expression of such a discontinuity involving Precambrian Ouachita basement rocks.

Farther west, the Devils River Uplift, presumably an autocthonous basement massif that controlled a major break in the orientation of the Ouachita overthrust zone (Flawn and others, 1961), is roughly circumscribed by lineaments. A zone of lineaments within the secondary azimuth mode follows the southeastern end of the uplift in Kinney County. Another concentration of primary azimuth mode lineaments marks the northern edge of this structure in Val Verde County.

In Terrell County, long lineaments extend along an azimuth of approximately 10°; these features may represent an upward propagation of buried Marathon structures. This trend provides indirect evidence of the suspected (Flawn and others, 1961; Muehlberger, 1980) strike-slip dislocation of the Ouachita basement between the Marathon and Devils River Uplifts. The deviation in lineament strike between Terrell County and areas northeast of the Devils River Uplift suggests that the basement discontinuity may coincide with the general trend of the lower Pecos River. Cross-strike lineaments occur there, and this zone seems to separate two distinct areas of strike-parallel lineaments. In the area from Sutton to Tom Green Counties, some lineaments parallel the strike of the buried Fort Chadbourne Fault Zone, although there is no exact areal correlation with individual faults.

Balcones/Blackland Region

The Balcones/Blackland region is an arcuate belt across Central Texas from the Red River to the Rio Grande. It is made up of Upper Cretaceous strata that are mainly chalks, marls, and clays, and that commonly form black, clayey soils. The western limit of this province is the Balcones Escarpment, and farther north, the Eagle Ford Prairie of the Grand Prairie region. The eastern limit of the Blacklands is the western limit of Tertiary sandstone and mudstone outcrops that compose the sand hills of the inner Gulf Coastal Plain.

By this definition, the Blacklands include the basal Tertiary Midway Formation, which also forms similar low-relief terrain and fertile clayey soils. The Blacklands, as traditionally mapped (Johnson, 1931), extend only as far south as San Antonio. Yet the broad alluvial plains with black soils that occur as far west as Uvalde are an extension of this province. From Uvalde west, we also include the upper (Upper Cretaceous outcrop) Rio Grande Embayment as a subprovince of the Balcones/Blackland Belt.

The grain of this region is largely obscured owing to several factors. Thick soils cover the bedrock, and since much of the bedrock is soft clay or marl, structural features are generally inconspicuous. Moreover, cultural overprinting, in the form of intensive agricultural activity, has further obscured the natural grain. The presence of several major cities along this trend also reduces the number of lineaments.

However, the Balcones/Blackland region encompasses parts of the Balcones and Luling-Mexia-Talco Fault Zones, and these impose a generally northeast-southwest grain. The region is also the locus of a buried structural hinge defined by the interior zone and eastern limits of the foundered Ouachita overthrust belt. The hinge marks the boundary between (1) the stable continental interior (Texas Craton) that clearly shows local Precambrian control of uplifts and (2) the downwarping Gulf Coast Basin (Flawn and others, 1961). Differential movement across the hinge has controlled sedimentation throughout the Mesozoic and Cenozoic, has probably controlled faulting and igneous activity along the Balcones and Luling-Mexia-Talco Fault Zones, and, through depositional patterns and faults, has influenced migration of fluids including hydrocarbons and hot waters. Locally, geothermal gradients are anomalously high and many wells tap warm ground waters. The relation of geothermal anomalies and resources to lineament patterns in this region has been addressed by Caran and others (1981) and by Woodruff and others (1982b).

In spite of various obscuring factors, remarkable linear features have been noted across this terrain, and some have demonstrated structural counterparts in the subsurface (Caran and others, 1981). For example, in the Rio Grande Embayment, lineaments parallel to strike of exposed formations extend from the Hill Country onto alluvial plains near Brackettville, in Kinney County; this suggests that there is a mechanism for expressing subsurface structural trends through a surficial veneer. Cross-strike and strike-oblique features extend from the Edwards Plateau across the Balcones/Blackland region. These are noted in Medina, Hays, Caldwell, Travis, and Bell Counties. Some of the strike-oblique features suggest possible lateral continuations of fault traces into the Coastal Plain. One such example is the apparent extension of lineaments projecting from the Balcones Escarpment at San Marcos northeastward into Milam County. This is the general trend of the Brushy Creek Lineament zone, which is also a locus of buried volcanic centers and their associated oil fields (Woodruff and Caran, 1981).

Another set of lineaments trending oblique to known regional structures extends from eastern McLennan County northeastward through Navarro County. This alignment is prominently reflected in the contour pattern of lineament density in the primary azimuth mode (inset on Plate, in pocket). It also coincides with the Waco Uplift, a basement feature beneath the buried Ouachita thrust belt (Nicholas and Rozendal, 1975). Farther north near the Red River, where the structural and stratigraphic strike changes to a roughly east-to-west orientation, the lineament grain falls within the secondary azimuth mode. Some of these features coincide with the axes and flanks of major buried structures, especially the Sherman Syncline and the Preston Anticline.

Gulf Coastal Plain Province

The Gulf Coastal Plain is by far the largest physiographic province in Texas. It extends from the Gulf Coast to the eastern edge of Cretaceous and lower Tertiary marine mud outcrops on the west and north. This region is the outcrop of mostly terrigenous Tertiary and Quaternary sedimentary units whose strike generally parallels the present Gulf Coast, although strike changes near the Sabine Uplift in East Texas. Strata within the region are gently dipping and are generally undeformed except near growth faults or salt structures. However, dips increase downward through the section, and numerous zones of normal faulting occur. The sedimentary rocks underlying this region are largely sandstones and mudstones. Although the substrate and structure are similar throughout the region, there are tremendous contrasts in landscape, owing mainly to regional climatic differences. Rainfall varies from less than 18 inches (45.7 cm) in Webb and Zapata Counties in South Texas to more than 56 inches (142.2 cm) in Jasper, Newton, and Orange Counties in deep East Texas. Vegetative assemblages include chaparral in the west and south and vast stands of hardwoods and pines in East Texas. Vegetation also changes across strike, from the post oak stands of the sandstone outcrops, to the intervening "string prairies," to the broad low coastal prairies that border the marshlands and other modern coastal environments. Obviously, the type and extent of vegetative cover have influenced our ability to perceive lineaments. Southeast Texas and deep East Texas both have a very low lineament density as a result of the dense, obscuring forest cover there.

Several subareas compose the Coastal Plain region. These divisions impose an overly fragmented view of the region, which--despite climatic and associated terrain variations--has a similar structural framework overall. The subregions include (1) the Inner Gulf Coastal Plain and its components, the East Texas Embayment and the Rio Grande/Nueces Plain, and (2) the Lower Coastal Plain with its component Coastal Prairies and Tideland/Barrier areas.

As mentioned, the grain throughout the Gulf Coastal Plain is dominated by topographic contours and major stream courses. Topographic contours generally parallel the coastline, except in northeast Texas where they form an embayed area adjacent to the Sabine Uplift. The rivers generally flow coastward, perpendicular to prevailing topographic contours (figs. 5 and 6). However, variations occur in both the northeast and the southwest parts of this region. The northeast part (East Texas subprovince) composes a major part of the topographic embayment that extends almost to the 1,500-ft contour at the edge of the Texas Panhandle. Local topographic high areas within Cherokee, Smith, and Anderson Counties have moderate relief as a result of local stream dissection. But overall, East Texas is a topographically low area, with the general course of the Sabine River bisecting the arc of this embayment. The embayment is well expressed by the generalized trend of the 500-ft (150-m) contour line where it extends north from Limestone County (fig. 5). This contour follows a salient only into northern Henderson County, or 220 straight-line mi (350 km) from the coast. On the southwest, quite a different situation occurs: a major salient exists, and the 500-ft (150-m) contour occurs along a line through Starr, Jim Hogg, and Duval Counties, only 75 mi (120 km) from the Gulf shoreline. This South Texas salient has a prominent northwest-facing escarpment (the Bordas/Reynosa Escarpment) that also marks the drainage divide between the Nueces River and streams that flow into Baffin Bay.

Major riverine courses are affected by both the embayed and salient areas (fig. 6). In East Texas the river courses radiate like spokes from the axis of this embayment. The Sabine has generally axial flow, with the Brazos River forming one limb and the Red River the other. The Trinity parallels the southern margin of the embayment. The Red River forms the northern limb of this embayment, and it has an asymmetrical watershed encompassing Ouachita/Arbuckle highlands in Oklahoma. This northern part of the embayment in East Texas is paralleled by the course of the Sulphur River. In the salient area of South Texas, the Nueces

River flows abruptly northeastward (approximately along an azimuth of 40°) west of the Bordas/Reynosa Escarpment for about 50 straight-line mi (80 km), thus interrupting an otherwise southeastward course.

Between these topographic aberrations general regional trends of topographic contours parallel to the coast continue and drainage flows down the topographic gradient. For most of the Lower Coastal Plain, drainage consists of consequent streams on an inclined depositional surface. Major trunk streams (the Trinity, the Brazos, the Colorado, the Guadalupe/San Antonio, the Nueces, and the Rio Grande) have constricted drainage basins but wide alluvial valleys incised into nonresistant strata of the Coastal Prairies. Most tributary development occurs within the coastal basins that occupy most of this terrain. These tributary basins have a somewhat higher slope and thus a higher density of relatively low-order streams compared to nearby major rivers with their alluvial valleys.

The grain of the Lower Coastal Plain has two main orientations: one is normal to the coast and the other parallels it. Major distinctions between "strike-parallel" and "strike-normal" trends have diminished in this kind of terrain since the Coastal Prairies are largely an undissected depositional surface that comprises both strike- and dip-oriented components (Brown, project director, 1972-1980). That is, both trends expose recognizable depositional conditions; no subsequent structural dislocation is needed to produce cross-strike linear features. In the Coastal Zone, the trend lying normal to the present coastline may correspond either to present drainage or to Pleistocene dip-oriented depositional features. The other orientation, parallel to the Gulf shoreline, corresponds to presumed surface expressions of growth faults that occur all along the Coastal Zone (Brown, project director, 1972-1980) or to local strike-fed relict depositional features. Some of the straight headlands and shorelines seen along the bay margins are probably surface expressions of faulting. Also, certain coastal drainage courses show this parallel-to-the-coast trend. Examples include Buffalo Bayou and Pine Island Bayou, both of which occur in the northeastern part of the Texas Coastal Zone (fig. 6). Elsewhere within the Coastal Plain, the grain is defined by the local strike of stratigraphic units (and of normal faults) or by the courses of through-flowing streams. In several areas topographic escarpments accentuate this grain.

Lineaments express subsurface structure at several localities throughout the Coastal Plain. Major examples in South Texas include lineaments that trend across the Nueces/Rio Grande divide northeast from Laredo and that delineate the surface projection of the Sligo Reef Trend. Landward of the continuation of this reef trend in McMullen County, a circular set of lineaments centering on the town of Tilden indicates the location of the Dilworth Dome. The lineament expression of the Stuart City Reef Trend extends from Webb County northeast as far as De Witt County. In East Texas, the exceptionally high lineament density for an area of relatively low relief probably indicates structures associated with salt tectonics (Dix and Jackson, 1981). The same is true for the high lineament density in the Houston salt basin, but there the issue is further complicated by the presence of growth faults (described by Kreitler, 1976) and of relict barrier systems with a pronounced linear grain along depositional strike (Fisher and others, 1972). In East Texas, a series of northeast-trending lineaments marks the edge of the Sabine Uplift, and one particular set aligns with the subsurface Rodessa Fault Zone.

The Grain of Texas

In this region-by-region discourse, we have demonstrated the various attributes of the grain of Texas. The linear grain of the state and the associated pattern of lineaments represent the net effect of a variety of geologic influences, both at the outcrop and in the subsurface. In brief, lineaments are polygenetic. But in certain instances subsurface structural control of lineaments is documented. A statewide overview is too generalized for denoting precise correlation among landforms and geologic structures. However, the alignment of lineaments and physiographic and structural features seems well supported in local instances. This survey has also corrected some initial misconceptions in the underlying causes of lineaments.

At the outset, it appeared that the bimodal orientation of lineaments across Texas merely reconfirmed the observations that the predominant stratigraphic and structural strike of units is northeast-southwest (consistent with the primary azimuth mode of our lineaments), and that most rivers of Texas flow southeastward (secondary azimuth mode). To test these observations, we determined the general azimuths of map-unit boundaries on geologic maps of Texas at a scale of 1:250,000 and found that the primary (northeast) and secondary (northwest) azimuths of lineaments encompass less than 25 percent of the strike directions of sedimentary rocks in Texas. A similar review of straight reaches of major drainages showed that less than 30 percent of the principal stream reaches lie within the combined primary and secondary azimuth modes. Thus, lineaments reflect a broader range of surface affinities; they are not merely streams and outcrops by another name. Still, individual lineaments do often correspond to many straight stream channels as well as to outcrop (strike) patterns of exposed bedrock. And the preferred northwest-southeast and northeast-southwest components of the lineament population as a whole do conform to general trends of the state's rivers and the strikes of major stratigraphic units. The level of agreement between these trends and the dominant lineament modes is sufficient to suggest the existence of a common fabric of controls on drainage, outcrop patterns, and lineaments. Presumably the controls are structural, but with the regional resolution applied in this study, all controls could not be identified.

A general fabric is also evident when we compare maps of lineament density and physiographic provinces. Regional variation of ground cover (soils and vegetation) affects the visibility of geologic or physiographic features to which lineaments may correspond. Ground cover also influences settlement patterns and land use, in turn significantly affecting our perception of lineaments (for example, note the near absence of lineaments from the intensely developed area around Dallas and Fort Worth). But since soils and vegetation (and ultimately cultural features) broadly reflect the same kinds of underlying geologic controls that presumably cause lineaments, multiple phenomena can produce valid lineaments, irrespective of ground cover and human overprint. It is not surprising that both the general and derivative lineament maps correspond so closely to the patterns of surface geology and physiography.

Another widely held generalization that has proven to be only partially true is that lineament density is a direct function of topographic relief: that is, the higher the relief the more incision of low-order streams, and hence the more lineaments recognized. There are, however, notable exceptions. As mentioned, the area of highest lineament density (57) in any unit cell statewide is along the Canadian River. This is a highly eroded area, but relief is relatively low. The second, third, and fourth highest lineament densities (55, 48, and 46) occur in the Davis Mountains, along Palo Duro Canyon, and in the Solitario area--all of which have high relief. The fifth highest density (43) occurs near Palestine in Anderson County in East Texas. This is rolling terrain, but one wherein relief is very low, particularly if compared to that of either the Chinati Mountains or the area between Guadalupe/Delaware Mountains and the Salt Basin, in neither of which is the lineament density as high. Other relatively high-relief areas also have very low lineament densities, for example, the area draining into the Nueces River from the Bordas/Reynosa Escarpment. But these negative correlations may be due in part to poor image quality, biasing human overprint, or a number of other causes.

In sum, there certainly is not a simple grain of Texas. Instead, there are several persistent trends that vary among different geographic areas, each with its own characteristic lineament patterns. How our perception and analysis of these trends may be applied to assessments of geothermal potential will be addressed next.

LINEAMENTS AND GEOTHERMICS

The region-by-region discussion of lineaments shows that, in at least certain areas, these features correlate to structural grain. However, many lineaments have no apparent structural connotations. Nonetheless, even given the influence of purely surficial phenomena, the statewide lineament map may be used to discriminate major areas of like structure and the boundaries between different--but adjacent--structural provinces. This hypothesis has a corollary: topography (especially large-scale, diffuse features) may reflect subsurface structure in ways that are not fully appreciated, and these relations, in themselves, warrant further study.

A critical assessment of the lineament map and its derivatives indicates that--in certain areas--one may make general predictions on the location of structural discontinuities and on areas having abnormally high fracture porosity. Either of these factors may influence geothermal potential, but there is no sure correlation. Lineaments do not, however, stand alone as an assessment method. They must be compared with other geological or geophysical data to be very meaningful.

To have a viable geothermal resource, certain conditions are necessary to allow heat generated deep in the earth to be conveyed relatively close to the earth's surface. These conditions may be met in two different (but often complementary) ways: one involves the transfer of heat by conduction; the other involves the upward transfer of water (classically thought to result from convection). The first mechanism involves the heat-flow equation; the second involves Darcy's Law. Both equations have the general form:

$$Q = -\kappa G$$

where Q is the flow in question; κ is a coefficient of conductivity (either thermal or hydraulic) and reflects properties of the local host rock; and G is a gradient (either thermal or pressure); the minus sign indicates a negative slope on a Cartesian graph.

The heat-flow equation and Darcy's Law provide information on phenomena that are interrelated. Temperature regimes influence ground-water flow, and subsurface waters clearly influence local earth temperatures at depth. However, because data on the two phenomena have generally been collected for different purposes by different specialists, much of the interconnection has escaped notice. In Texas, there has been little work with heat flow except in the Trans-Pecos region. Instead, most information on geothermics that bears on the heat-flow equation is obtained from the oil industry through geophysical well logging. For most regions of Texas (the major exception being the Trans-Pecos region) work on ground water temperature has been ancillary to general hydrologic (and especially water-quality) studies. Systematic studies of anomalous water temperatures had not been undertaken prior to current efforts at the Bureau of Economic Geology. Thus, we have two data bases that are fragmentary and often incompatible.

We therefore have two depictions of geothermal potential in Texas: geothermal gradients derived from temperatures cited on electric logs (see inset on Plate, in pocket); and the loci of thermal aquifers based on measured water temperatures. Of the two, the thermal ground-water map is more useful because it actually delineates a usable resource whose qualities are known at a well or spring. The geothermal gradient map may indicate a geothermally anomalous area, but there is ambiguity as to what causes the anomaly because of the three variables noted in the heat-flow equation. Geothermal gradient is a direct function of heat flow and an inverse function of thermal conductivity; hence, a relatively high anomaly may be caused by high heat flow, by low thermal conductivity, or by a combination of both. Such a depiction does not necessarily indicate where hot water may be extracted at depth. However, many of the high geothermal anomalies may, in fact, be due to the hydrologic effects of upwelling (warm) basinal waters, just as some of the low anomalies may indicate areas of recharging (cool) waters.

Lineaments and Geothermal Gradient

The geothermal gradient map presented on the enclosed Plate is a modification of that published by the American Association of Petroleum Geologists and the U.S. Geological Survey (1976). It consists of contour lines constructed on gradient values from an essentially random array of wells (Kehle and others, 1970). These wells have BHT measurements in a variety of rock types--hence the gradient values obtained are presented irrespective of thermal conductivity. However, the gradient patterns often correlate with areas of major structural discontinuities. In other words, such maps should provide a view of the same type of subsurface structural information that we sought to acquire in the lineament study.

The statewide geothermal gradient map (Plate, in pocket) shows grain similar to the major structural trends in certain areas. Of these correlations between geothermics and structure the most prominent are the Balcones/Ouachita trend, the Central Basin Platform, and the basinal slope on the coastward side of the Stuart City/Sligo Reef Trends. Other features may also be present, but their resolution is unclear.

In general, basinal areas have lower gradients than do uplifts, but the absolute magnitude of the anomaly is probably meaningless unless one has corrected for thermal conductivity by comparing only those gradients that penetrate like rock types. Such information was not provided in the previously constructed statewide geothermal gradient map (AAPG and USGS, 1976). Also, any discussion of anomalous geothermal gradients has meaning only if a norm is established. This entails plotting geothermal gradient with respect to depth, and this was done only in Central Texas (Woodruff, 1982).

The Balcones/Ouachita trend provides the best locality for describing the correlation between lineaments and geothermal gradients; these correlations have been discussed in detail by Caran and others (1981). Because of sparse data north and west of the Balcones Escarpment, we do not see the low thermal gradients characteristic of the recharging waters there. However, at several places along strike we note relatively high gradients. For example, the area of high (2.0° F/100 ft or 36° C/km) gradient closure in Maverick County is parallel to the axis of the Rio Grande Embayment and is delineated by two lineament sets that intersect at approximately right angles.

In southern Bexar County there is another closure of 2.0° F/100 ft, and data suggest the upwelling of basinal brines there. This anomalous gradient area is bisected by a zone of lineaments trending normal to strike from Medina County southeast into Atascosa County. The closure of the 2.0° F/100 ft (36° C/km) contours that extend from near San Marcos to the Lake Walter Long area in eastern Travis County lies along the extension of the Brushy Creek lineament zone (Woodruff and Caran, 1981). The highest geothermal gradient closure in the state (2.5° F/100 ft or 45.6° C/km) centers on Belton, in Bell County, and an associated 2.5° F/100 ft (46° C/km) contour extends from near Walburg in Williamson County northeast to Waco. This trend lies along a major alignment of strike-parallel lineaments in the south and it is bisected by features that strike oblique to the local Balcones trend and that mark the northern edge of the Belton High/Moffat Mound area. The 2.0° F/100 ft closure in eastern Tarrant County is not expressed on the lineament map, probably owing to the obscuring urban overprint on the Landsat scene there. The closure farther north in Cooke and Denton Counties lies along the axis of the Muenster Arch. Farther west another relatively high gradient area lies along the Ouachita structural high area that may be a subsurface extension of the Broken Bow Uplift.

Elsewhere in the state, correlations between lineaments and geothermal gradient anomalies are less evident. As mentioned, generalized trends may be discerned, but the ambiguous patterns within both lineaments and geothermal gradient data sets obscure interpretations and correlations.

Lineaments and Hydrocarbons

Hydrocarbon formation, migration, and entrapment are associated with geothermal processes, and often reflect structural controls. Hence, a comparison of lineaments to locations of oil and gas fields might reveal relations between structures and geothermics that were not heretofore recognized.

Certainly a regional map of oil and gas fields in Texas is another depiction of the grain of Texas. As expected, this depiction of grain correlates well with that derived from structural information (St. Clair and others, 1976). For example, most fields in the Gulf Coast region lie along the strike of major structures or related features such as buried reef trends. Examples include fields along the Wilcox and Vicksburg zones of growth faults; along the Miocene growth fault trend in the upper coastal area; along the Stuart City Reef Trend, the Chittim Anticline, and the Pearsall Arch in South Texas; across the Sabine Uplift in East Texas; and associated with salt structures and with the major fault zones of the inner Gulf Coast Basin, including the Luling-Mexia-Talco trends and the Elkhart Graben/Mt. Enterprise Fault Zone. Elsewhere, structural orientations are reflected in locations of oil fields along the axis of the Central Basin

Platform, although the parallel pattern of fields (stratigraphic traps) that occur in adjacent areas of the Delaware and Midland Basins show less obvious (more complex) relations to structures. No clear trend is seen in the Eastern Shelf area except for a general orientation of oil fields along the roughly north-south strike trend. Farther south, deep gas fields roughly align with the axis of the Ozona-Pecos Arch and along similar trends into the adjacent Val Verde Basin. In the Panhandle, major gas fields align with the Amarillo Uplift and the Cimarron Arch, but no major structural control is evident in the Anadarko Basin. Similarly, gross control tied to basinal geometry is apparent in the Fort Worth Basin/Muenster Arch areas, but the trends are somewhat diffuse. Farther south, the few gas fields in the Strawn Basin occur along the axis of the San Saba Arch.

Given the limited resolution from our regional perspective, there appears to be only a very general relation between lineaments and oil fields. Correlation is through structures: in places where lineaments indicate structural grain and those structures either provide traps for hydrocarbons or contribute to the development of stratigraphic traps, there lineaments are indicators of oil and gas accumulations. Admittedly, applications of lineament analysis to petroleum exploration are limited at this scale. Perhaps the greater detail afforded by an assessment based on maps and images of a larger scale would yield more meaningful correlations. Some of these correlations have, in fact, been noted along the eastern part of the Balcones/Blacklands region where oil is associated with buried volcanic complexes. These features occur along major lineament trends that indicate previously unmapped subsurface (and perhaps surface) fault zones. The correlation among lineaments, buried faults, igneous features, and oil fields is discussed in more detail by Woodruff and Caran (1981).

Certain stratigraphic traps are controlled by structures. Lineaments may indicate the presence of these traps owing to the surface expression of controlling structures. An example is in the East Texas Basin, where an early assessment of the thermal characteristics of the Woodbine Sand in effect independently discovered the East Texas Field as well as the older, structurally controlled Powell and Mexia Fields and other Woodbine production associated with salt domes (Plummer and Sargent, 1931). This work anticipated our hypothesis of the importance of hydrodynamics (upwelling waters) as major controls on geothermal-gradient anomalies. Lineaments indicate enhanced fracture porosity that allows preferential upwelling in some areas. In the vicinity of the East Texas Field, we note a high geothermal anomaly with closure of 1.75° F/100 ft (31.9° C/km) immediately updip from the producing zone (the Woodbine pinch-out). A group of lineaments lies both along the northern part of this pinch-out field, and farther east, along the edge of the Sabine Uplift which provides structural control for the depositional offlap that created on the stratigraphic trap for oil in the East Texas Field. Usually, however, lineaments at 1:1,000,000-scale show many lineaments that do not correlate with oil-producing structures. Where any correlation does exist, it is through the aforementioned subtle structural expressions at the ground surface. Clearly, structures may be expressed in this way with or without hydrocarbon entrapment.

Geothermal gradient anomalies are commonly related to structures, and using our conceptual model based on the upwelling of underground fluids channelled by fracture-controlled porosity (inferred from lineaments), an integrated exploration program may be devised in local areas. Upwelling fluids, of course, may affect the distribution of several types of resources: hydrocarbons, hydrothermal minerals, and waters whose temperature partly reflects that of environments at greater depth.

Lineaments and Thermal Waters

The most direct expression of geothermal potential anywhere is the occurrence of a hot spring. In Texas, hot springs occur only in the Trans-Pecos Basin-and-Range province (fig. 10). Warm springs--those whose waters are only slightly above mean ambient air temperature--also occur within the dissected parts of the Edwards Plateau region along the Rio Grande and the Pecos River in Val Verde and Terrell Counties. Lineaments do not show a unique signature at springs in the Basin-and-Range, but there is a high density of intersections of lineament trends

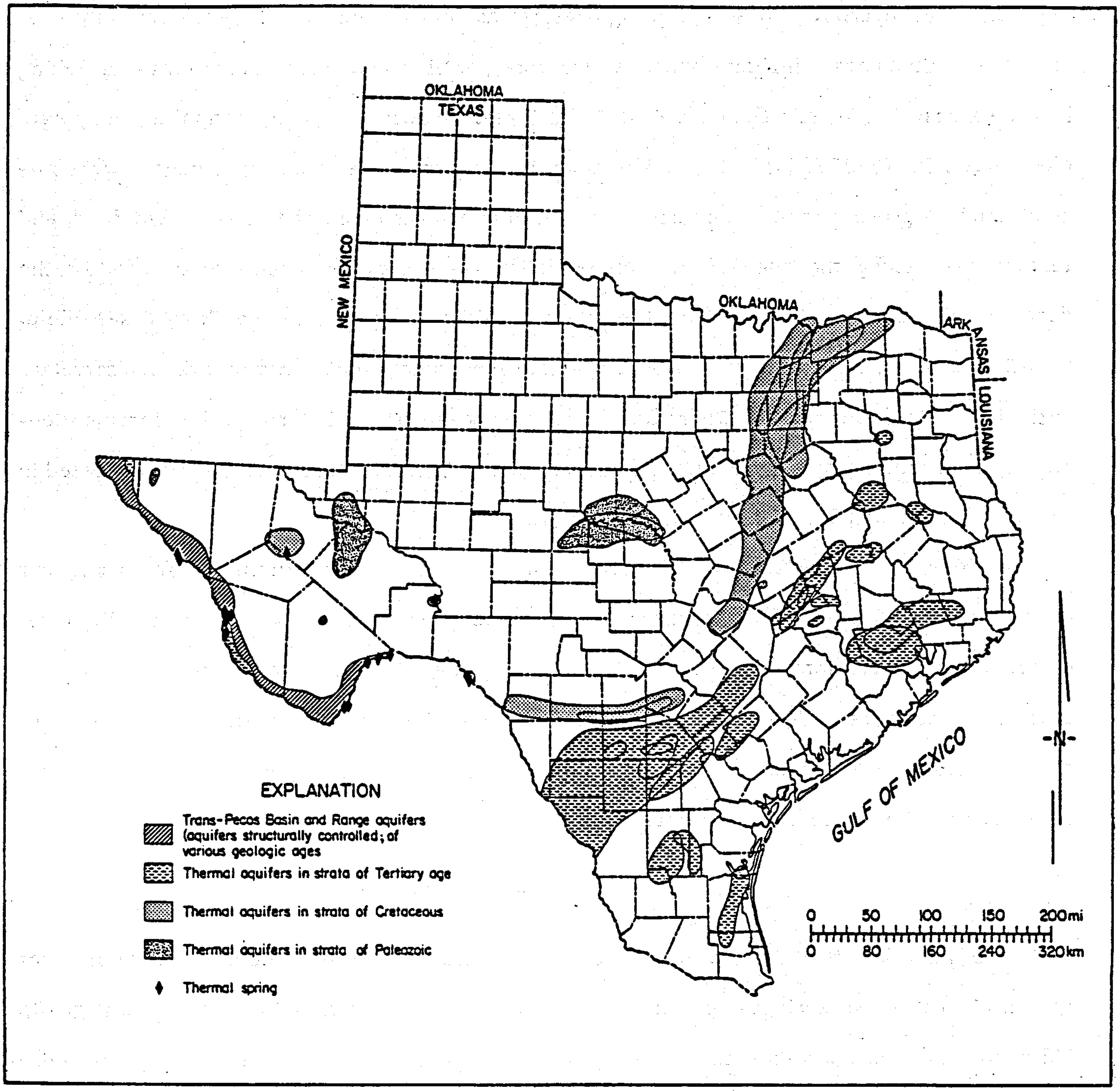

Figure 10. Simplified map showing extent of major geothermal aquifers and selected thermal springs in Texas.

near warm springs in the Edwards Plateau province, which suggests fracture control of porosity at these localities.

Elsewhere in Texas, there are no direct surface expressions of geothermal resources; there are only wells that produce warm to hot waters. The well sites themselves may not bear obvious relations to lineament patterns any more than individual oil and gas wells are indicated by lineaments. Lineaments may indicate the presence of previously unrecognized or hidden geothermal resources, but they do so only indirectly--through the surface expression of buried structures, or as previously pointed out, by indicating enhanced fracture porosity.

The Balcones/Ouachita trend of Central Texas is an area in which geothermal resources seem to be indicated by lineaments. Even allowing for the variable data quality, certain areas stand out as anomalous lineament traces even at a scale of 1:1,000,000. One of these is along the major cross-strike lineament zone that extends from Bandera and Medina Counties southeastward into Atascosa County. This cross-strike zone--where it intersects the lineaments associated with the axis of the Pearsall Arch--is the locus of optimum geothermal potential from the Edwards Limestone. There water temperature is moderately high, up to 120° F (50° C), and water of fairly good quality (less than 1,000 mg/L total dissolved solids) flows under an artesian head. Farther north, the lineament trend that extends northeast from the Balcones fault-line scarp at San Marcos to the Cameron area in Milam County includes the site of an Edwards (brackish) geothermal well at Thorndale, and municipal wells producing potable water from the Hosston Sand at Granger and Rogers in Williamson County. Another lineament trend, extending northeast along strike of the Balcones Fault Zone from eastern McLennan County through the southeastern corner of Hill County, delineates the boundary between warm water wells (90° to 150° F, or 32° to 65° C) and those with temperatures greater than 120° F (50° C). Corsicana, which has a long history of oil production, incidental withdrawal of geothermal waters, and two geothermal test wells, lies along a major strike-parallel lineament trend. The regional trend of one of the large-scale cross-strike linear features can also be extended through the Corsicana area.

Elsewhere in the Gulf Coast Basin, correlation of lineament and geothermal resources is less easily demonstrated because the known distribution of geothermal waters is an artifact of petroleum exploration. Drill deep enough in this region and a sand producing hot water will probably be penetrated. Many of these hot-water wells have supported spas and health resorts, but there is no reason to suppose that there is anything unique about any specific area where these wells are located. However, further work is needed to establish an accurate representation of the geothermal regime--that is, one in which rock type, and hence, thermal conductivities, could be properly accounted for. Once this is done, areas of true water-temperature anomalies (presumably owing to upwelling) may be seen. As mentioned, lineament analysis may play a key role in this process.

CONCLUSIONS

Lineaments are correlative locally with structures that in turn control the depth and continuity of suitable aquifers and may provide pathways for deep circulation of ground water. Thus, lineaments can be useful indicators of geothermal resources in some areas. But many factors influence the actual resource potential of warm ground waters. In addition to water temperature, the transmissivity of the aquifer, salinity of the water, deliverable yield of the well, and even the proximity of the intended user all affect the degree to which the waters constitute a resource. Clearly, lineament analyses provide little information on these factors. One certainly should not locate a prospective drilling site using lineament analysis alone, but in conjunction with other techniques a lineament survey may prove very useful. An appropriate strategy for lineament-based exploration recognizes that structural grain may be subtly expressed at the ground surface and that lineaments, seen in the aggregate, are one such form of structural expression.

For the purposes here, one should pay careful attention to areas that have anomalous lineament expressions. Examples include areas having high density of lineaments in areas of moderate to low relief, or areas where lineaments trend along azimuths that deviate markedly from the prevailing structural and stratigraphic strike. Either of these phenomena may indicate areas of enhanced fracture porosity or some kind of subsurface discontinuity through which upwelling waters may flow. In certain areas there may be few lineaments (but lacking obvious cultural or vegetative ground cover) may be areas of known structural complexity there may be few lineaments; examples include intermontane bolsons or broad topographic depressions produced by active tectonism or salt solution at depth. In all these settings, rapid alluviation occurs and obscures surface expression of structures and, hence, lineaments. Yet such areas often have geothermal-resource potential. The key to use of lineaments for regional exploration is recognition of the proper structural setting and expected "norm" for lineaments, and having acknowledged the norm, to closely inspect discontinuities in lineament patterns.

In summary, lineaments provide little information by themselves. They are inherently ambiguous features and have been misused--touted to show features that they could not possibly show. For this reason, lineament surveys have fallen into disrepute in the minds of some investigators (see, for example, Gilluly, 1976). This is unfortunate because lineaments can provide a valuable overview of the structural grain of a region. If one is rigorous with the method and is careful not to extend interpretations beyond the support of corroborative data, lineament analysis is a useful tool in exploration for any resource that requires underground movement of fluids. The lineaments may indicate the general loci of upwelling owing to structural control, or they may provide a clue to fracture-induced plumbing.

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APPENDIX A
Landsat images used in compiling map of lineaments of Texas

Black-and-white positive prints (standard products) at 1:250,000-scale, prepared from band 5 reflectance data collected during winter months.

BEG scene number (see fig. 2)	EROS Data Center image identification number	Image date	Comment
01*	8591415400500	10/19/77	Poor contrast in central part of image (corresponds to area of reflective salt flats and bolsons). Southwestern two-thirds of scene lies in Mexico.
02*	83029716541X0	12/27/78	Obtrusive scan-line stripes. Poor contrast in northeastern corner of image.
03*	83027916544X0	12/09/78	Excellent image but for prominent scan-line stripes. Southwestern two-thirds of scene lies in Mexico.
04*	8593015253500	11/04/77	Poor resolution in western half of image. Intense cultivation in northeastern and southeastern corners of scene.
05*	8229116450500	11/09/75	Dune field extends across central part of scene. Intense cultivation in virtually the entire scene.
06*	83022416481X0	10/15/78	Dune and oil fields extend across northwestern and southeastern quarters of scene. Intense cultivation in northeastern quarter of scene. Western half of scene lies in New Mexico.
07*	82147916354X0	02/09/79	Dune and oil fields extend across northeastern and north-central parts of scene.
08*	82108316174X0	01/09/78	Excellent image.
09*	82108316181X0	01/09/78	Moderate resolution in southwestern quarter of image. All of scene except northeastern corner lies in Mexico.
10*	8225416391500	10/03/75	Excellent image. Intense cultivation in northwestern and southwestern quarters of scene.
11	8591115222500	10/16/77	Excellent image. Intense cultivation in virtually the entire western half of scene.

Appendix A (cont.)

BEG scene number (see fig. 2)	EROS Data Center image identification number	Image date	Comment
12	82111816123X0	02/13/78	Poor contrast and resolution in southwestern third of image. Intense cultivation in western two-thirds of scene.
13	8592915211500	11/03/77	Moderate contrast and resolution in southwestern corner of image. Dune fields cover small area in west-central part of scene. Northwestern and southwestern quarters of scene depict irrigated and intensively cultivated areas.
14*	82110016122X0	01/26/78	Excellent image.
15*	82110016125X0	01/26/78	Excellent image. All of scene except northwestern corner lies in Mexico.
16*	82138716194X0	11/09/78	Obtrusive scan-line stripes. Northeastern third of scene in Oklahoma.
17	83063616330X0	12/01/79	Small area of intense cultivation in northeastern quarter of scene.
18	82138716203X0	11/09/78	Poor contrast in southern third of image. Oil fields extend across west-central part of scene. Small areas in northwestern corner and east-central part of scene are intensively cultivated.
19*	82138716205X0	11/09/78	Moderate contrast and resolution in southwestern and north-central parts of image, respectively. Oil fields cover central part of scene.
20*	83000516345X0	03/10/78	Poor resolution in southeastern corner of image. Rectilinear pattern of agricultural lands in northeastern half of scene impairs geologic interpretation. All of scene except northeastern corner lies in Mexico.
21*	83023916304X0	10/31/78	Moderate resolution across entire image. Intense cultivation in virtually the entire scene. Northern two-thirds of scene lies in Oklahoma.
22	82138616142X0	11/08/78	Intense cultivation in western and eastern thirds of scene.

Appendix A (cont.)

BEG scene number (see fig. 2)	EROS Data Center image identification number	Image date	Comment
23	82136816140X0	10/21/78	Intense cultivation in northeastern corner of scene. Narrow band of hazy clouds across northwestern quarter of scene.
24	8227016292500	10/19/75	Poor resolution across entire scene. Oil fields and intense cultivation obscure small areas in west-central, east-central, and southeastern parts of scene.
25*	8227016294500	10/19/75	Diffuse pattern of oil fields and agricultural lands across virtually the entire scene.
26*	83067116275X0	01/05/80	All of scene except northeastern corner lies in Mexico.
27*	8226916224500	10/18/75	Intense urbanization of large area in east-central part of scene. Cultivation of broad areas in western and eastern thirds of scene.
28	8226916231500	10/18/75	Cultivation and urban development in eastern third and south-central part of scene, respectively.
29	8226916233500	10/18/75	Intense cultivation in eastern third of scene.
30	8226916240500	10/18/75	Intense urbanization and cultivation in northern third of scene.
31*	83067016221X0	01/04/80	Moderate contrast and resolution across northeastern three-fourths of image. Diffuse dune fields across east-central part of scene. Oil fields and cultivated lands cover southeastern and central parts.
32*	83067016224X0	01/04/80	All of scene except northeastern corner lies in Mexico.
33	8129016303500	05/09/73	Poor contrast and resolution across entire image, particularly the southeastern corner. Intense urbanization in southwestern corner of scene. Broken cloud cover across northeastern quarter of scene.

Appendix A (cont.)

BEG scene number (see fig. 2)	EROS Data Center image identification number	Image date	Comment
34	83063316162X0	11/28/79	Diffuse pattern of urbanization and cultivation across entire scene.
35	8145216284500	10/18/73	Poor resolution across entire image.
36*	8111016313500	11/10/72	Moderate contrast and resolution across entire image. Wispy clouds and coastal waters cover central and southeastern parts of scene.
37*	8203416202500	02/25/75	Dune fields and coastal waters cover southeastern half of scene.
38*	8203416205500	02/25/75	Dune fields and irrigated croplands extend across central third of scene. Coastal waters cover eastern fourth of scene. Southern half of scene lies in Mexico.
39*	82120315484X0	05/09/78	Poor contrast and resolution across entire image. Mixed agricultural and forested lands cover most of scene. Northern and eastern thirds of scene lie in Oklahoma, Arkansas, and Louisiana.
40*	8268116012500	12/03/76	Poor contrast (corresponding to virtually unbroken forested lands) in southeastern third of image. Forested and cultivated lands cover the northwestern two-thirds of scene.
41*	82136515570X0	10/18/78	Poor contrast (corresponding to virtually unbroken forested lands) in northeastern third of image. Intense urbanization and cultivation in southwestern and east-central half of scene.
42*	8239316105500	02/19/76	Diffuse (concentrated locally) pattern of urbanization and cultivation across northwestern half of scene. Coastal waters cover southeastern half of scene.
43*	8268015553500	12/02/76	Moderate contrast and resolution across entire image. Eastern half of scene lies in Louisiana.

Appendix A (cont.)

BEG scene number (see fig. 2)	EROS Data Center image identification number	Image date	Comment
44*	8280615504500	04/07/77	Poor contrast across entire image. Coastal waters cover southeastern fourth of scene. Northeastern third of scene lies in Louisiana.
45*	83022516540X0	10/16/78	Oil fields extend across northeastern third of scene. Scene lies entirely within New Mexico, immediately adjacent to Texas border.
46*	82151616421X0	03/18/79	Croplands, oil fields, and clouds cover eastern half of scene. Southwestern two-thirds of scene lies in New Mexico.
47*	83029216244X0	12/22/78	Poor contrast and resolution across entire image. All of scene except narrow strip along southern boundary lies in Oklahoma.
48*	82142016035X0	12/12/78	Poor contrast and resolution across entire image. All of scene except narrow strip along southern boundary lies in Oklahoma.
49*	8607715420500	01/03/78	Excellent image. Silvicultural practices impart "patchwork" pattern across central half of scene. All of scene except southwestern corner lies in Oklahoma and Arkansas.
50*	8280615511500	04/07/77	Intense urbanization and cultivation in northwestern quarter of scene. Coastal waters cover southeastern three-fourths of scene.
51*	8593115311500	11/05/77	Poor contrast and resolution (corresponding to low-relief areas) across image except northwestern and southwestern quarters. All of scene except northeastern corner lies in New Mexico.

*Scene extends beyond the borders of Texas into adjacent states of the United States or Mexico, or coastal waters of the Gulf of Mexico. If one-third or more of the scene lies outside the terrestrial boundary of Texas, the contiguous area is identified in the comment.

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LINEAMENTS OF TEXAS

1981

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY

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Prepared for the U.S. Department of Energy, Division of Geothermal Energy. Under Contract No. DE-AS07-79-ID12057, Geothermal Resource Assessment for the State of Texas

NOTE: Lineaments presented on this map were originally perceived on 51 Landsat images (Band 5, 1:250,000 scale) of Texas and adjacent areas.

SCALE 1:1,000,000

20 0 20 40 60 80 Miles

20 0 20 40 60 80 100 Kilometers

Cartography by R. L. Dillon under the supervision of D. F. Scranton

Base map modified from United States Geological Survey, State of Texas, Scale 1:500,000.