Geological Circular 81-5

LINEAMENT ANALYSIS BASED ON LANDSAT IMAGERY, TEXAS PANHANDLE

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Bureau of Economic Geology W. L. Fisher, Director • 1981
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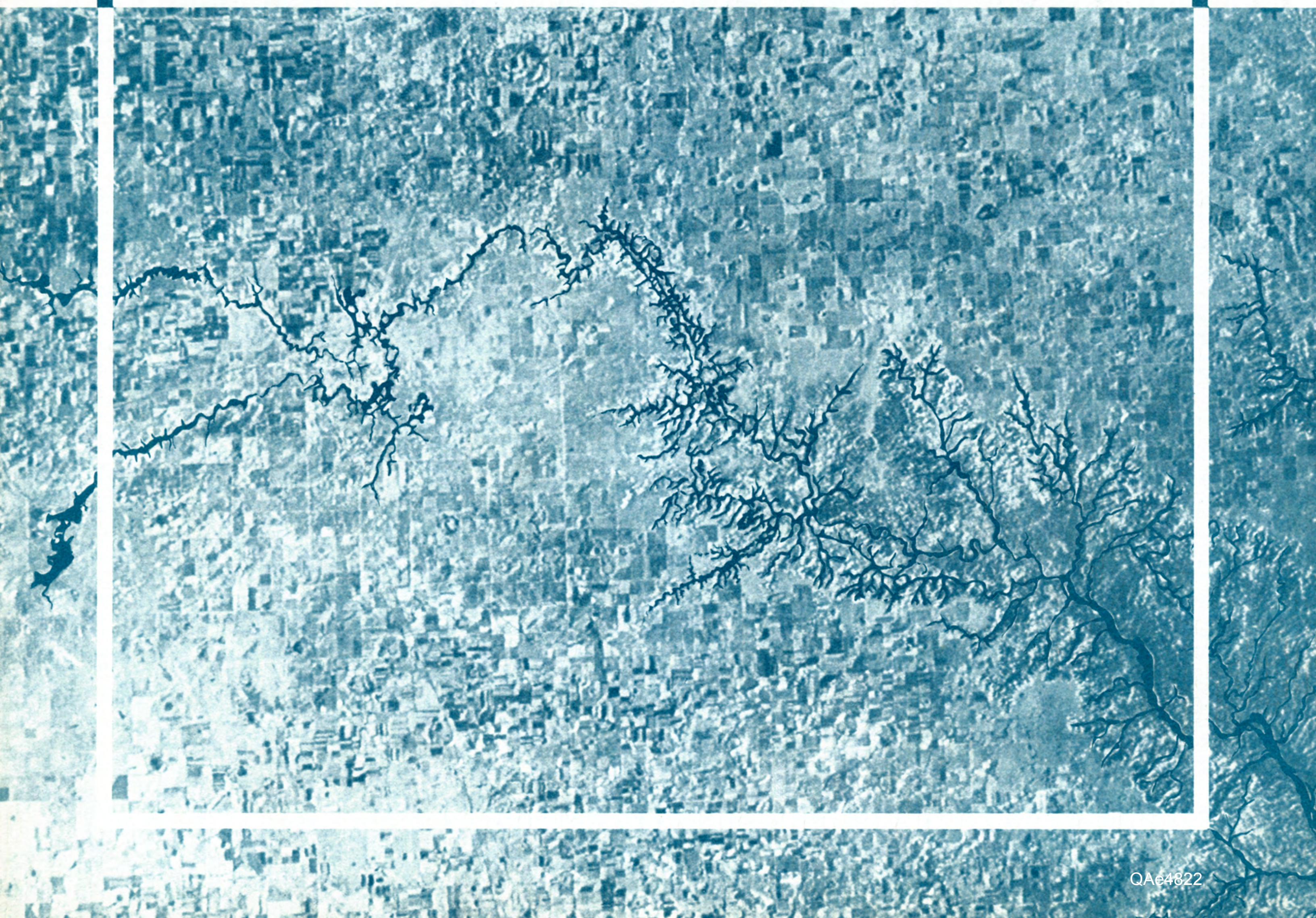

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Cover photograph: Landsat image showing an area of the Texas Panhandle that includes (from left to right) parts of Tierra Blanca Creek, Palo Duro Creek, Palo Duro Canyon, and Prairie Dog Town Fork of the Red River. The linearity of some stream valleys in the Texas Panhandle, typified by sections of the streams shown here, is a major subject of this report. Part of Landsat image no. 1672-16455, taken May 26, 1974, by the National Aeronautics and Space Administration.

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ABSTRACT

Analysis of seven frames of Landsat imagery covering the Texas Panhandle and adjacent areas revealed linear physiographic features including stream channels, stream valleys, scarps, and aligned playa-lake depressions. These lineaments show preferred orientations of 300^{o}-320^{o}, 030^{o}-050^{o}, and 0^{o}-020^{o}. The 300^{o}-320^{o} orientation of aligned playas and shallow surface drainage is best developed on the surface of the Southern High Plains. The orthogonal 030^{o}-050^{o} orientation is less well represented. Lineaments oriented 0^{o}-020^{o} are most readily detected in the dissected terrain of the Rolling Plains in the eastern Texas Panhandle; a secondary orthogonal trend oriented 270^{o}-280^{o} is also present.

Lineament orientations are similar to orientations of joints measured in the field and to regional structural trends, which suggests that development of physiographic lineaments is controlled or influenced by geologic structure. Few surface faults are mapped in the region; therefore, joints rather than widespread faults are a likely structural geologic control. Joints may provide paths of weakness along which surface drainage might develop preferentially. Joint intersections provide potential sites for downward percolation of water, possibly enhancing playa development, as suggested by dissolution of caliche beneath playas. Thus, joints probably exert an important control on the geomorphology of the region.

INTRODUCTION

An examination of 1:250,000-scale geologic maps (Barnes, 1967, 1968, 1974, 1977) of the Texas Panhandle reveals a notable linearity of stream segments and scarps and an alignment of playa-lake depressions. The recent availability of specially enhanced satellite imagery has permitted a comprehensive study of these linear elements within a 237,000-km^2 (91,500-mi^2) area centered over the Palo Duro Basin and including the High Plains of Texas and eastern New Mexico (fig. 1). More than 4,600 linear features have been delineated from the Landsat imagery.

This study was undertaken to examine the prevalent orientations of linear physiographic trends and the relationship between these trends and structural geologic elements of the Texas Panhandle and adjacent areas (fig. 1). The extent to which

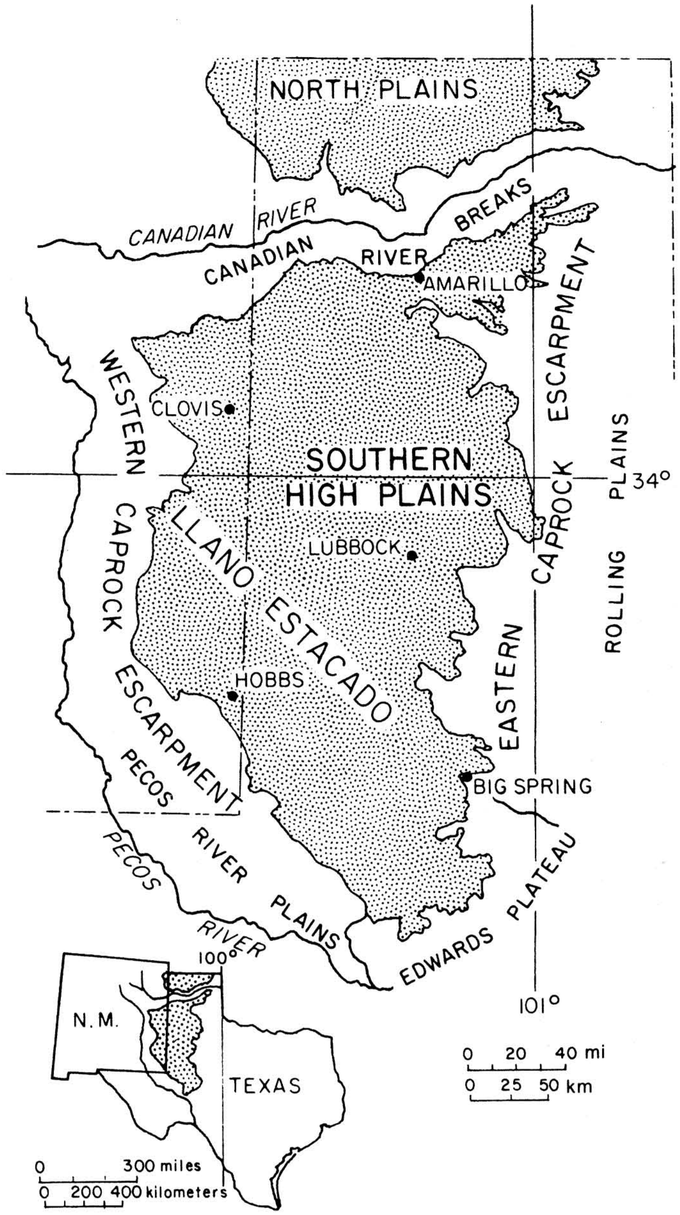


Figure 1. Physiographic units in the Texas Panhandle and adjacent areas of Texas and eastern New Mexico.

these trends coincide in orientation with structural features may indicate the degree of control exerted by geologic structure on present geomorphology. Some correlation exists between the orientation of linear physiographic features and linear structural elements ranging from joints to basement structures, suggesting that physiographic features in the Panhandle are controlled or influenced by geologic structure.

The term "lineament" defines a "straight physiographic element" (E. S. Hills, 1963), and, as suggested by O'Leary and others (1976) and Hobbs and others (1976), it is preferred to the terms "linear" and "lineation." Lineaments defined from Landsat imagery of the Texas Panhandle range in length from 2 to 40 km. Although these physiographic features may be shorter than implied in E. S. Hills' (1963) definition, the use of the term "lineament" remains appropriate. Where the word "lineament" applies to a larger tectonic element, such as a major boundary between contrasting structural features, the term "tectonic lineament" is generally used (Kelley, 1955).

PREVIOUS WORK

Reeves (1970) considered the regional drainage pattern in the Southern High Plains to be influenced by the global regmatic fracture pattern. Generalized lineament orientations of northwest, north, and northeast correspond to worldwide tectonic patterns, but whether these lineaments represent joints or faults was not known (Reeves, 1972). Reeves (1970) also suggested that the trends and locations of large lake basins are influenced by "intersections of the regional lineaments or the lineaments themselves."

Finch and Wright (1970) observed the northwest-trending Running Water Draw - White River lineament along those drainages, and the Double Mountain Fork lineament, trending northwest from Garza County to Lamb County, Texas. Both were identified on the basis of aligned depressions and linear drainage segments on 1:250,000-scale maps. The "approximate restored post-Ogallala surface of the High Plains appears to be faulted" along the Running Water Draw - White River lineament, as evident from a contour restoration using 1:250,000-scale maps (Finch and Wright, 1970). Finch and Wright conclude that control by structural elements, such as joints and faults, is a likely cause of these lineaments.

Long (1975), in an analysis of High Plains topography, suggested that continued isostatic adjustment of intersecting tectonic elements in the deep basement has affected the Ogallala surface. Basement features and younger structures have therefore been examined to obtain a better understanding of regional lineament orientation.

GEOLOGY AND STRUCTURE

The general geology of the Texas Panhandle has been summarized by Roth (1955), Totten (1956), Nicholson (1960), Dutton and others (1979), and Gustavson and others (1980b). The Panhandle region (fig. 2) contains three major basins--the

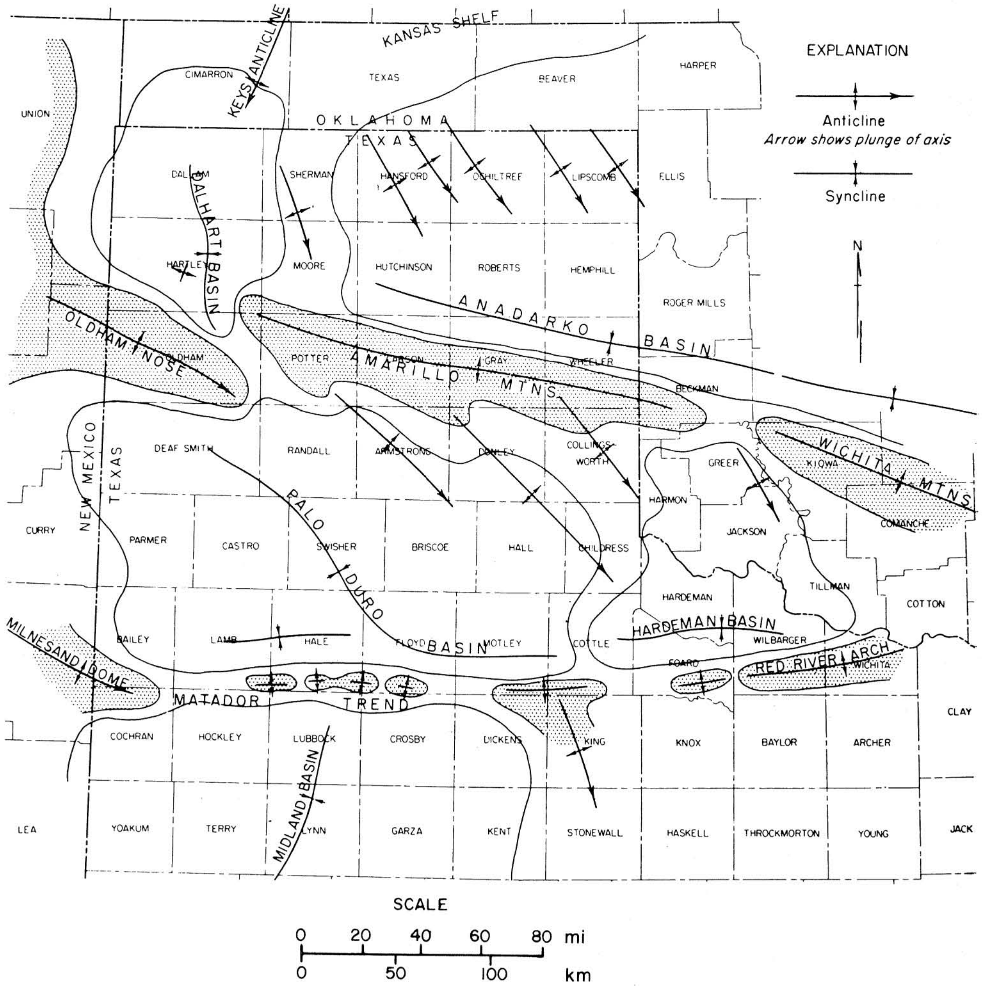


Figure 2. Subsurface structural features of the Texas Panhandle (from Nicholson, 1960).

Anadarko, the Dalhart, and the Palo Duro. The Palo Duro Basin occurs between two major uplifts, the Amarillo Uplift and the Matador Arch. The Amarillo Uplift trends west-northwest, as do the subsidiary en echelon anticlines both north and south of the Amarillo trend. The isolated structural domes of the Matador Arch are bounded by a major east-west-trending fault (Flawn, 1956).

The stratigraphic section in the Panhandle of Texas can be divided into three parts (Nicholson, 1960; Dutton and others, 1979): (1) the pre-Pennsylvanian sequence, including all sediments deposited before the development of the present structural pattern, (2) the Pennsylvanian-Permian sequence, which was deposited during growth and burial of the present structure, and (3) the post-Permian sequence (fig. 3).

The area coinciding with the later Palo Duro Basin was a stable shelf during the early Paleozoic when Cambrian and Ordovician carbonates were deposited. Late in the Ordovician Period a broad northwest-southeast-trending positive feature

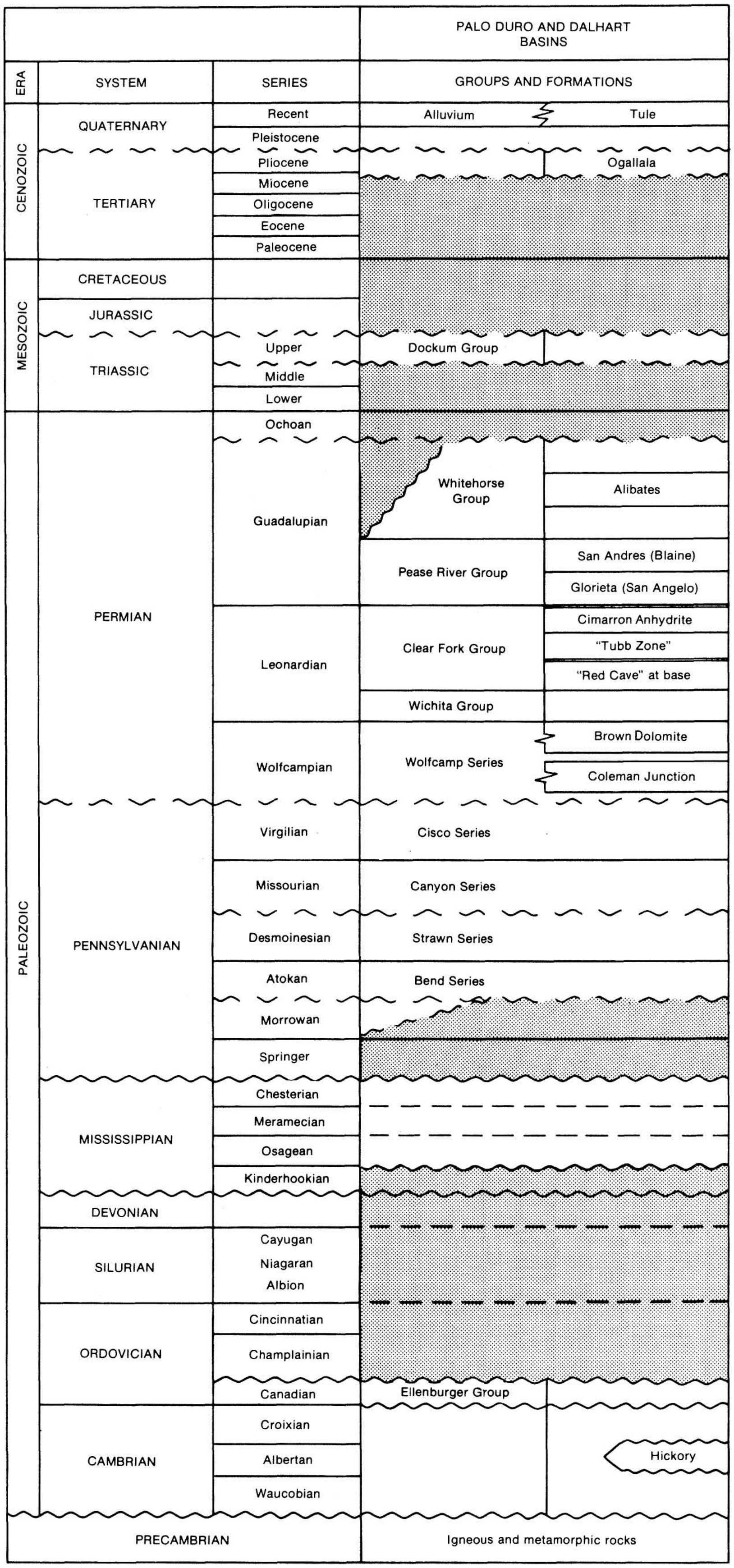


Figure 3. Stratigraphic column of the Palo Duro and Dalhart Basins in the Texas Panhandle (after Nicholson, 1960). Periods represented by stippled pattern indicate strata that were not deposited or have eroded.

developed, followed by erosion of lower Paleozoic deposits. Not until the Early Mississippian did deposition resume, and by the Late Mississippian, basinal development was well established.

Pennsylvanian rocks were deposited while the major positive structures were developing; Permian sediments were deposited after the principal structural development of the basin was completed. These deposits vary from granite wash of the Pennsylvanian Strawn Group (fig. 3), near the margins of major uplifts, to Upper Permian dolomite, anhydrite, and salt interbedded with shales. The latter strata represent deposition under the restricted marine conditions that prevailed throughout the Panhandle during deposition of the Leonardian and Guadalupian Series.

By the end of the Permian Period, basin development had ceased; erosion intervened, and the Triassic Dockum Group was subsequently deposited under continental conditions. The Dockum Group is composed of three progradational genetic sequences containing lacustrine, deltaic, and fluvial facies (McGowen and others, 1979). Cretaceous marine limestones and shales were deposited, as evidenced by scattered erosional remnants preserved in the southwestern part of the basin. Finally, sands and silts of the Pliocene Ogallala Formation, eroded from the Rocky Mountains to the west, were laid down over an eroded surface of Cretaceous, Triassic, and Permian strata. A carbonate-cemented zone, or caliche, which subsequently developed in the upper part of the Ogallala Formation, forms the prominent erosion-resistant scarp around the margin of the High Plains. This escarpment is locally known as the Caprock. Pleistocene and Recent windblown sands and silts mantle the Ogallala Formation on the High Plains surface.

METHODOLOGY FOR LINEAMENT ANALYSIS

Types of Lineaments

Seven Landsat scenes (fig. 4 and table 1), in the format of 1:250,000-scale paper prints, were examined, and six categories of lineaments were noted.

1. *Stream segment* designates relatively short, straight channel reaches commonly connecting at sharp, angular junctions. Stream segments include the shortest lineaments recognized, as short as 2 km (1.2 mi) long. Stream segments were delineated only if they were part of a distinctive sequence of linear channels. All stream segments counted are within recognizable floodplain or valley trends, whether or not that valley trend is itself linear or somewhat curvilinear. Stream

segments correspond to the nonvegetated, high-albedo active channel of fluvial features, especially the ephemeral streams in the Rolling Plains east of the Caprock Escarpment.

2. *Drainage line* designates linear valley trends independent of the orientation or linearity of channel segments within the trend. Included are valleys where no high-albedo channel is evident. Vegetation, topographic scarps, and the overall drainage pattern are used in recognizing drainage lines, particularly for the lower order streams in the Rolling Plains.
3. *Scarp* designates a prominent topographic break evident because of changes in land cover or land use, changes in drainage pattern, variations in outcropping rock units, or the presence of shadows on the imagery. The high reflectance of calichified Ogallala Formation produces a distinct white band along some scarps. In dividing lineaments between the High Plains and Rolling Plains categories, the scarps of the Caprock Escarpment boundary feature are considered separately as a unique physiographic category.
4. *Playa alignment* designates a lineament consisting of playa lakes located so that they tend to define a straight line. This alignment must be defined solely on the basis of playa-lake depressions, although playa alignments seem to be enhanced by poorly defined stream channels that connect playas on the High Plains surface (Woodruff and others, 1979). These are seen as slight color or tonal differences on the Landsat imagery.
5. *Geologic contact* designates linear contacts between surficial materials with different reflectivity, for example those between the colluvium and windblown sands and the Ogallala Formation. This lineament category was only applicable in Lea County, New Mexico, near the western margin of the Southern High Plains.
6. *Tonal anomaly* designates a linear feature that cannot be clearly recognized as a member of any of the previous categories. The feature may be a composite physiographic feature that becomes evident because several geomorphic elements, such as scarps and stream courses, combine to produce a discernible pattern on the Landsat image. Playa alignments on the High Plains grade into tonal anomalies, some of which may indeed be shallow draws that carry drainage between playas.

Analytical Procedures

Each Landsat image (table 1) was studied in conjunction with 1:250,000-scale topographic and geologic maps of the same area. This was necessary to become

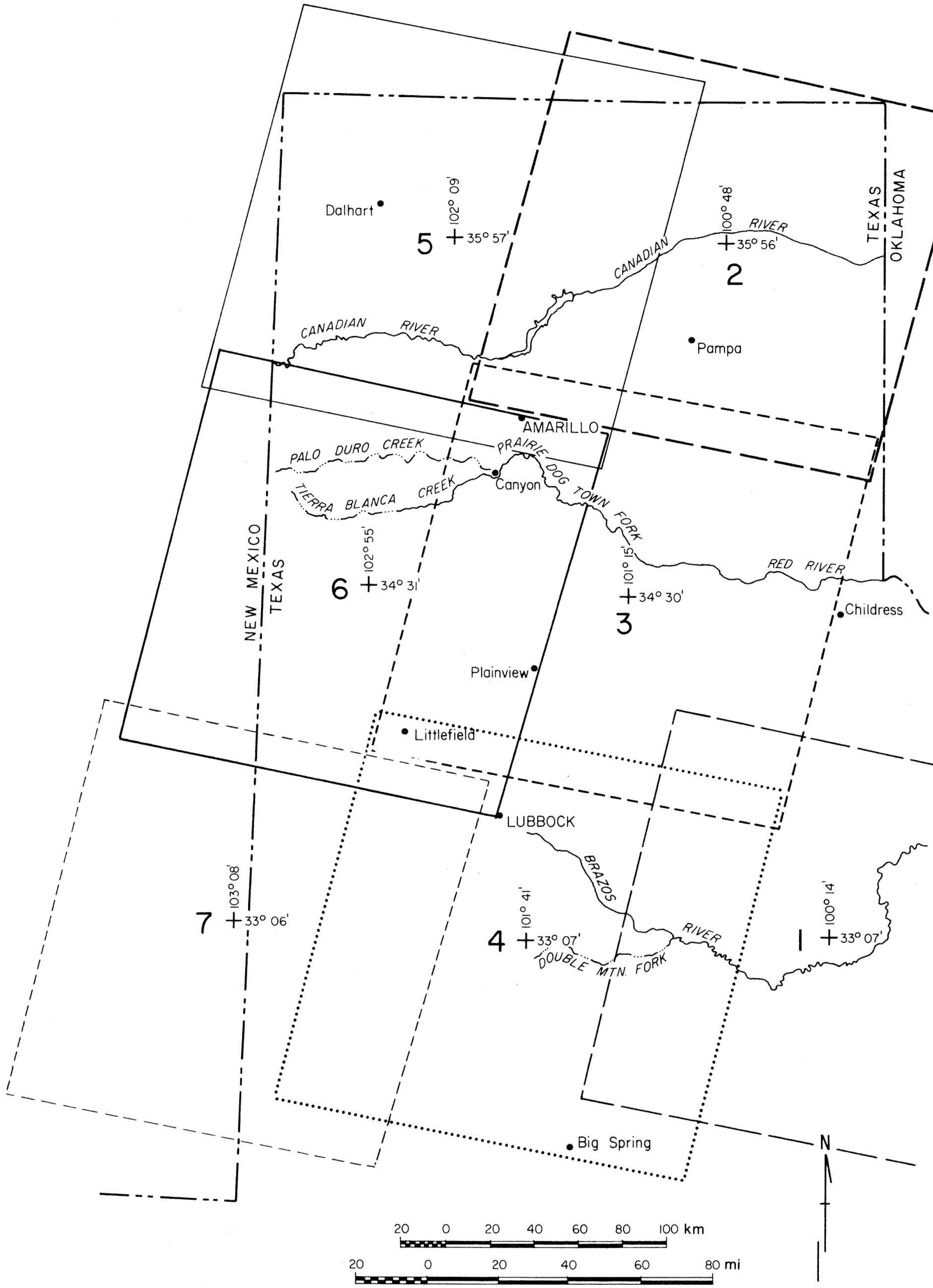


Figure 4. Generalized frame boundaries and approximate center points for Landsat coverage of the Texas Panhandle. Numbers refer to text discussion and to table 1.

Table 1. Analyzed Landsat scenes of the Texas Panhandle.
Block number refers to location in figure 4.

Block	Scene identification no.	Date	Approximate center point lat. and long.	Product type
1	2757-16205	Feb. 17, 1977	$33^{o}07'$-$100^{o}14'$	black-and-white, band 5
2	2704-16274	Dec. 26, 1976	$35^{o}56'$-$100^{o}48'$	black-and-white, band 5
3	1672-16455	May 26, 1974	$34^{o}30'$-$101^{o}15'$	enhanced false-color composite
4	2200-16404	Aug. 10, 1975	$33^{o}07'$-$101^{o}41'$	enhanced false-color composite
5	2759-16312	Feb. 19, 1977	$35^{o}57'$-$102^{o}09'$	black-and-white, band 5
6	2759-16315	Feb. 19, 1977	$34^{o}31'$-$102^{o}35'$	enhanced false-color composite
7	2741-16325	Feb. 1, 1977	$33^{o}06'$-$103^{o}08'$	standard false-color composite

acquainted with the region under study, to help develop the lineament categories, and to avoid the inclusion of man-made features in the analysis. A particular effort was made to exclude roads and field boundaries, which are primarily oriented north-south and east-west, to detect apparent alignments resulting from agricultural practices, and to avoid the influence of scan lines present in the standard Landsat products.

Interpretations were made exclusively from 74-cm (29-inch) wide, 1:250,000-scale paper prints. All imagery was studied using both reflected light and transmitted light from a standard light table. False-color composite prints, with distinctive hues of red representing vegetation, contain color subtleties that are more evident in transmitted light than in reflected light. A clear plastic film was placed over the print, and the ends of lineaments were marked with arrows. The identified lineaments were inked on tracing paper once the analysis of each scene was complete. Each lineament was designated as one of the six types, and its orientation measured to within 10^{o}-increments of arc. Total lineament length was measured. The density of lineaments was interpreted for variability throughout the study area, and azimuth frequency diagrams were prepared.

Each Landsat image depicts an area of 34,225 km^2 (13,255 mi^2), and viewing times of 2 hours by one interpreter and 20 minutes by a second interpreter were initially allocated for study of each 1:250,000-scale print. Duplicate data resulting from overlapping adjacent images were excluded from analysis. It became evident that the initial interpreter required up to 6 hours to study each image adequately, primarily because of the time required to review supplementary map data and exclude cultural features. Any feature that was suspected of being man-made was not mapped. Ultimately the study time by the first interpreter was considered unlimited, and a 30-minute independent review by a second interpreter was conducted. Some lineaments were added by the second interpreter, and a few lineaments were deleted where cultural features may have been involved.

Guidelines for Imagery Selection

Both an analysis and a comparison of two black-and-white Landsat scenes, using band 5 data, were made before interpreting the data listed in table 1. A summer scene (June 6, 1977; No. 2866-16204) and a winter scene (December 26, 1977; No. 2704-16281) covering block 3 (table 1) were selected for variation in sun elevation angle (56° summer, 23° winter). Differences in the ease with which scarps, drainage patterns, and playas could be delineated were related to the presence of shadows at the lower sun angle, to the availability of moisture, and to the growth stage of vegetation (table 2). Experience with the black-and-white data suggested the importance of varying tonal patterns; hence false-color composite images were acquired for the central section of the Texas Panhandle (blocks 3, 4, 6, and 7, table 1) overlying the primary area of interest, the Palo Duro Basin.

Three of the four false-color composite images acquired had been specially processed and enhanced at the Earth Resources Observation Systems (EROS) Data Center, Sioux Falls, South Dakota. Processes used to improve image quality include reduction in detector striping, contrast enhancement, edge enhancement, and geometric corrections that reduce distortion resulting from orbit, sensor, and platform variables. Such processes make the resulting image easier to interpret by conventional photointerpretation procedures. When enhanced data are used, the differences in detectability of lineaments on summer and winter images become less significant, and a mix of images from different seasons was ultimately used (table 1).

Guidelines on data use in areas of image overlap and at the boundaries of physiographic provinces were established as part of the analytical procedure. The entire image for block 3 (fig. 4) was used, and the areas duplicated on surrounding

Table 2. Characteristics of physiographic features on winter and summer Landsat images.

Winter (low sun angle)	Summer (high sun angle)
Scarps	
Scarps stand out extremely well because of shadowing; however, the shadows obscure detail in the valley bottoms. The contrast between highly dissected terrain and nondissected terrain in areas off the High Plains is apparent. Relative relief is easy to judge, and reentrants into the High Plains are well defined.	Shadows resulting from topography are negligible, and it is more difficult to delineate topographic scarps. More reliance must be placed on drainage patterns when interpreting topography. Relative relief is more difficult to judge.
Drainage	
Minor drainage lines in dissected terrain are in shadow, which aids delineation, especially in the Rolling Plains. More detail of the low-order stream network is evident. On the low-relief High Plains, surface shadows do not facilitate drainage detection.	Shadows are minimal. In dissected terrain the high reflectivity of the barren streambed is much more evident. Stream patterns in Rolling Plains agricultural areas are more evident because of lush vegetation along the streams. Vegetation on sloping banks used for grazing makes drainage features on the High Plains somewhat clearer.
Playas	
Playas on the High Plains are difficult to interpret because they resemble the background tone of the agricultural areas.	Playas are easier to discern because they are distinctly less reflective than surrounding fields, and many stand out because they contain water. In some areas playas that are barely detectable in winter are evident on the summer image.

Table 3. Criteria for defining physiographic provinces within the study area.

High Plains	That part of the Great Plains Shortgrass Prairie (Bailey, 1976) within Texas and eastern New Mexico, bounded by (1) the Caprock Escarpment, (2) the limits of the Pleistocene windblown cover sand (based on land use interpretation) where an escarpment is not present (northeastern part of the study area), (3) a relatively gentle slope break and eroded Ogallala Formation (interpretable from land use, northeastern part of study area), (4) the Canadian Breaks region along the Canadian River, and (5) by arbitrary extension of topographic breaks (western part of study area in New Mexico).
Caprock Escarpment	The boundary between the High Plains and a general "off High Plains" category where the boundary is defined by a sharp topographic break. This break can be delineated from Landsat imagery on the basis of land use and drainage patterns in conjunction with supplementary topographic data and geologic mapping. Where the High Plains surface gently breaks over into dissected or "stripped" Ogallala Formation, an escarpment category is considered to be absent. Pronounced scarps bounding Ogallala-capped mesas in the western part of the study area are included in this category.
Off High Plains	Includes (1) the Red River Rolling Plains (Johnson, 1931) east of the Caprock Escarpment in Texas, (2) the Canadian Breaks dissected terrain along the Canadian River, and (3) the Pecos Plains in eastern New Mexico (fig. 1), which lie west of the High Plains and the pronounced topographic break termed the "Mescalero Escarpment." A section of the Edwards Plateau is included in the southeastern part of the study area.

images were excluded from analysis. Wherever a false-color composite image overlapped black-and-white images, the color data were used preferentially.

The extent of the High Plains, Caprock Escarpment, the Red River Rolling Plains, and other "off High Plains" categories were delineated (table 3) to place lineament data within a physiographic framework (fig. 1). Variations in the geomorphology of the region required that a single definition of the boundary of the High Plains not be applied along all margins of the entire province.

DISTRIBUTION OF LINEAMENTS

The distribution of lineaments can be described in terms of orientation, length, and density; a series of azimuth frequency diagrams can be prepared using both the number of lineaments and the total lineament length in each category.

Orientation

High Plains and Caprock Escarpment

Lineaments on the High Plains show maximum frequency at an orientation of 300°-320° and a subordinate, orthogonal frequency peak at 030°-050° orientation (fig. 5). Drainage lines and playa alignments make up most of the features with these orientations. Rainfall in the 48 hours preceding the Landsat overpass of block 3 (table 1; fig. 4), plus excellent image quality, made lineaments on this part of the High Plains particularly easy to define (fig. 6). Soil colors were darker where precipitation occurred; therefore, drainage lines and playas were easy to discriminate. Many playas contained standing water. Tonal anomalies between playas that appear on this image most likely are low swales that may subsequently develop into draws (Woodruff and others, 1979) and that retain greater soil moisture than surrounding areas.

Palo Duro Creek and segments of Tierra Blanca Creek show rectilinear offsets (fig. 7), which typically indicate structural control of drainage orientation (Zernitz, 1932). Similar northwest-trending lineaments in Dawson County include numerous closely spaced and parallel playa alignments and linear drainage segments (pl. I). Sulphur Springs Draw exhibits some of the most distinctive rectilinear offsets in the study area; these offsets trend obliquely to the regional southeastern slope of the High Plains surface (fig. 8).

A succession of northwest- and northeast-trending linear scarps makes up the Caprock Escarpment in Quay County, New Mexico, and Deaf Smith County, Texas (fig. 9). The escarpment in Quay County is in part faulted (Barnes, project director, 1977), and a lineament 21.5 km (13.2 mi) long oriented 040° marks the fault trace. Parts of the Mescalero Ridge, the southwest-facing escarpment in Lea County, New Mexico, trend northwest (300°-310°). However, data for all escarpment areas taken together (fig. 5) do not show the same generalized northwest and northeast orientations of escarpment segments in Quay County. This may be related to greater stream dissection of the Eastern Caprock Escarpment, hence more irregular topography at the heads of drainage basins, in a less arid climate (510 mm [20.1 inches] mean annual

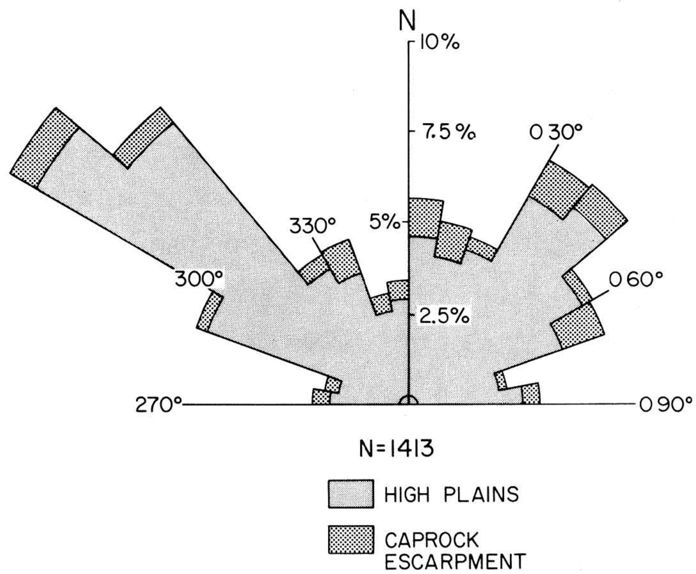


Figure 5. Lineament trends for the surface and margins of the Southern High Plains and North Plains, Texas Panhandle.

precipitation) than that of the Western Caprock Escarpment (380 mm [15.0 inches] mean annual precipitation).

Other Physiographic Provinces

The Rolling Plains, Canadian Breaks, Pecos Plains, and a small part of the Edwards Plateau physiographic provinces surround the High Plains within the study area (fig. 1). These areas have been aggregated in an "off High Plains" category. Lineaments in these provinces show a peak frequency at 0°-020° and subordinate frequency peaks at 030°-040° and 060°-070° (fig. 10). A minor peak is present at 300°-320°. Drainage lines are the primary lineament type, and stream segments the second most frequent lineament type delineated in areas off the High Plains. Comparison of areas east and west of the High Plains (fig. 11) shows greater lineament frequency at 300°-330° in the Rolling Plains, the eastern Canadian Breaks, and a part of the Edwards Plateau than in the Pecos Plains and the western Canadian Breaks. In the western area the 0°-020° trend has narrowed to a distinct 010°-020° peak, and an orthogonal, subordinate frequency peak is evident at 270°- 290°. Lineaments oriented toward the northeast at 050°-060° are also prominent.

The primary difference in lineament orientation between the High Plains and surrounding areas is the presence of the 0°-020° and 270°-280° frequency peaks off the High Plains (compare figs. 5 and 11). More lineaments having these orientations

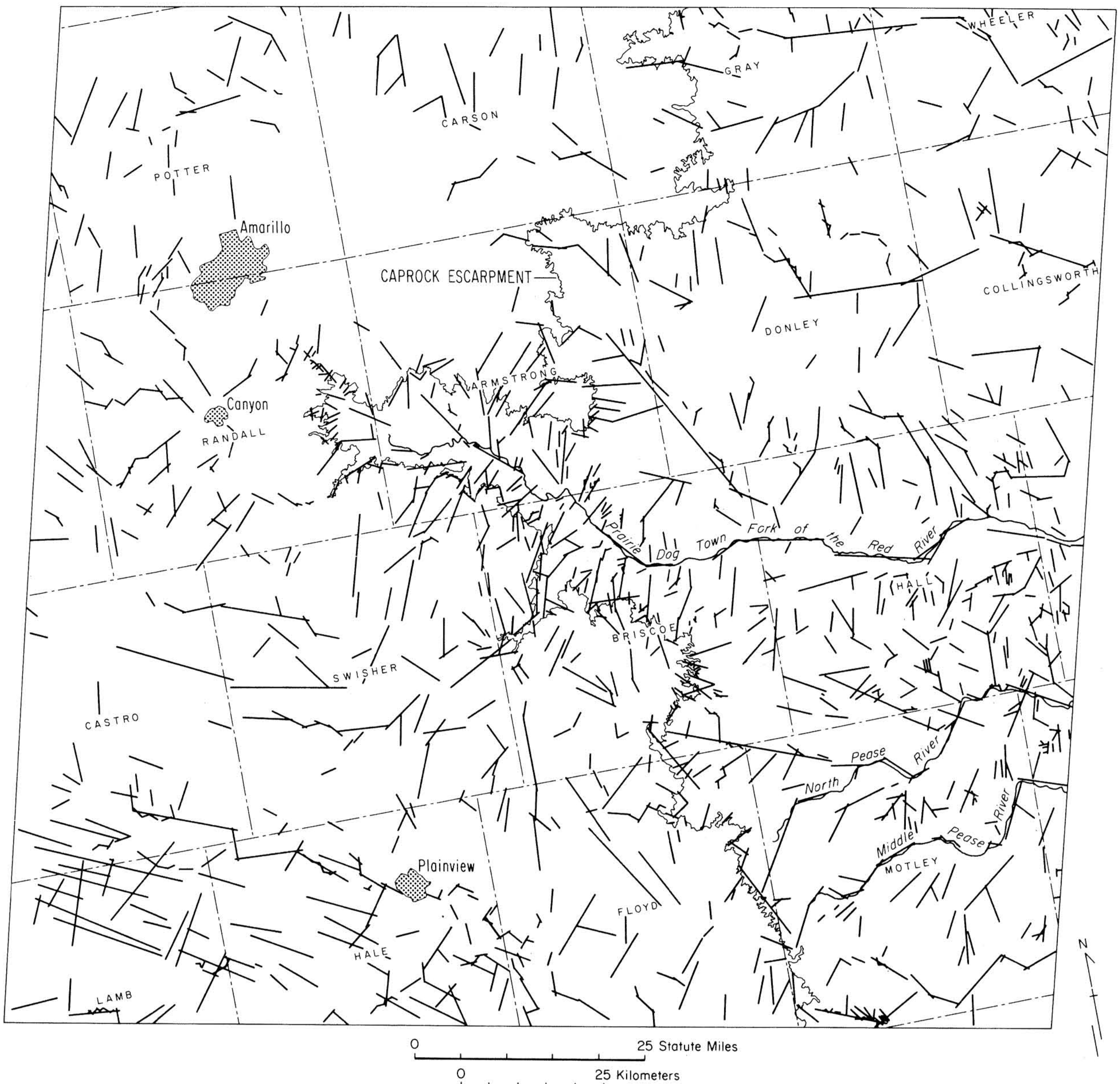


Figure 6. Lineaments derived from Landsat imagery, block 3 (fig. 4), Texas Panhandle region (Scene 1672-16455, May 26, 1974). Original imagery is at a scale of 1:250,000.

may be present on the High Plains than were detected in this analysis, but these may have been excluded because of similar orientation to cultural features. The High Plains is covered by a north-south and east-west grid of field boundaries and unpaved county roads at a 1.6-km (1-mi) spacing, which obscures lineaments of these orientations. Wermund and others (1978) identified fewer north-south and east-west fractures on aerial photographs than were verified in the field in the Edwards Plateau of Central Texas. North-south orientation of playa lakes is not evident.

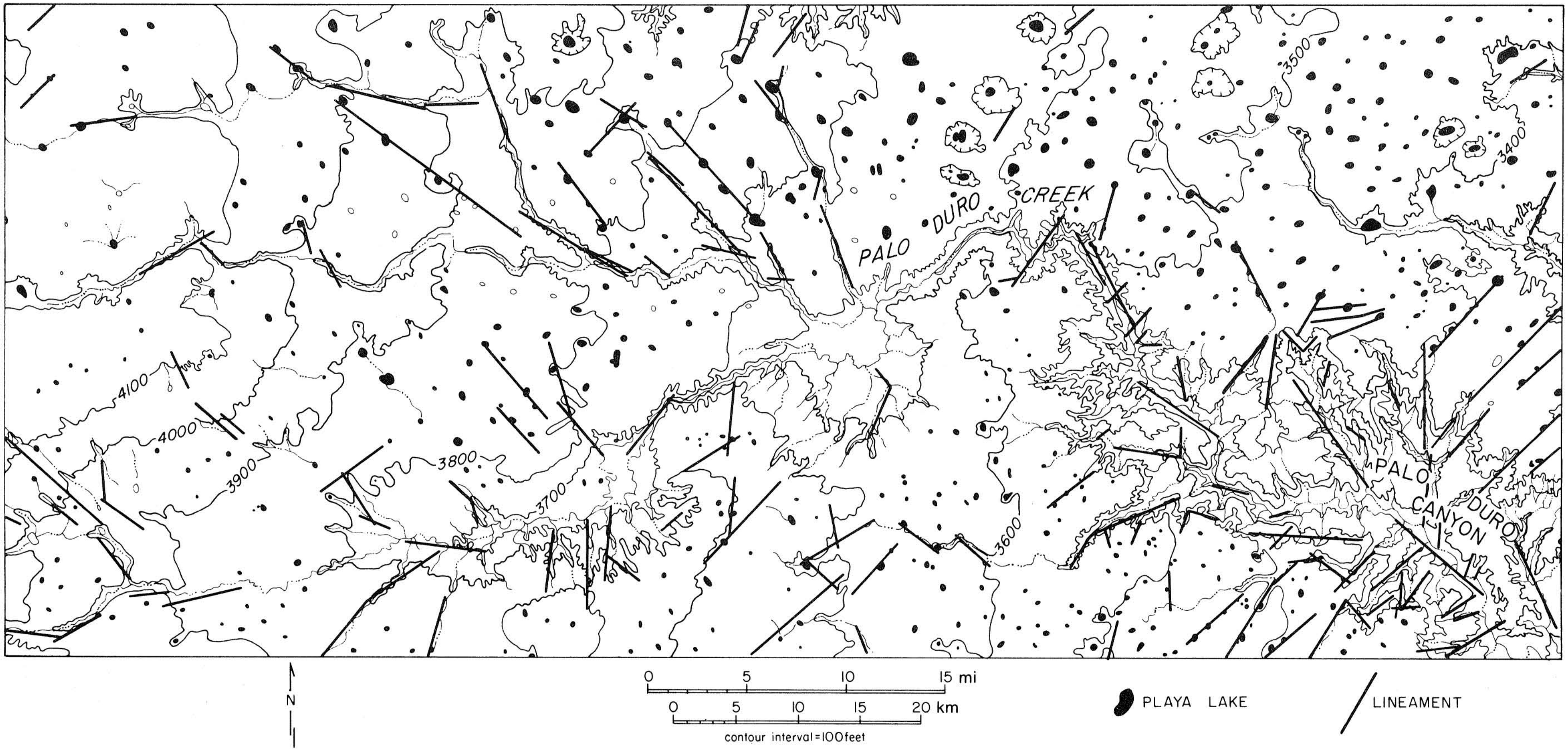


Figure 7. Detail of lineaments mapped on Landsat imagery in the vicinity of Palo Duro Creek and Palo Duro Canyon. Linear stream segments and escarpments form many of the lineaments. Area shown is A in figure 12. Original imagery is at a scale of 1:250,000.

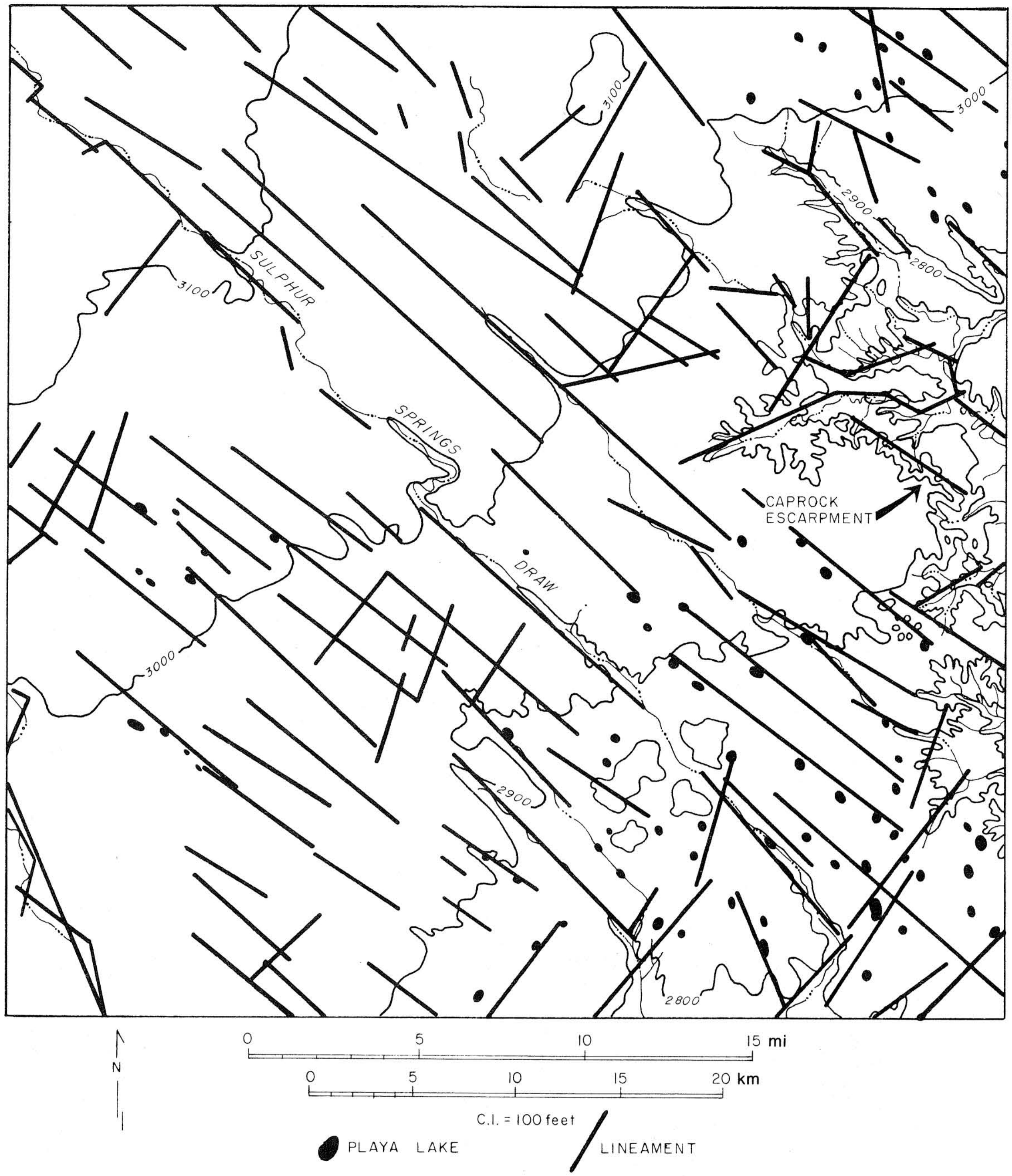


Figure 8. Detail of lineaments mapped on Landsat imagery in Dawson County, Texas, showing prominent northwest orientations derived primarily from playa alignments on the High Plains. Area shown is B in figure 12. Original imagery at a scale of 1:250,000.

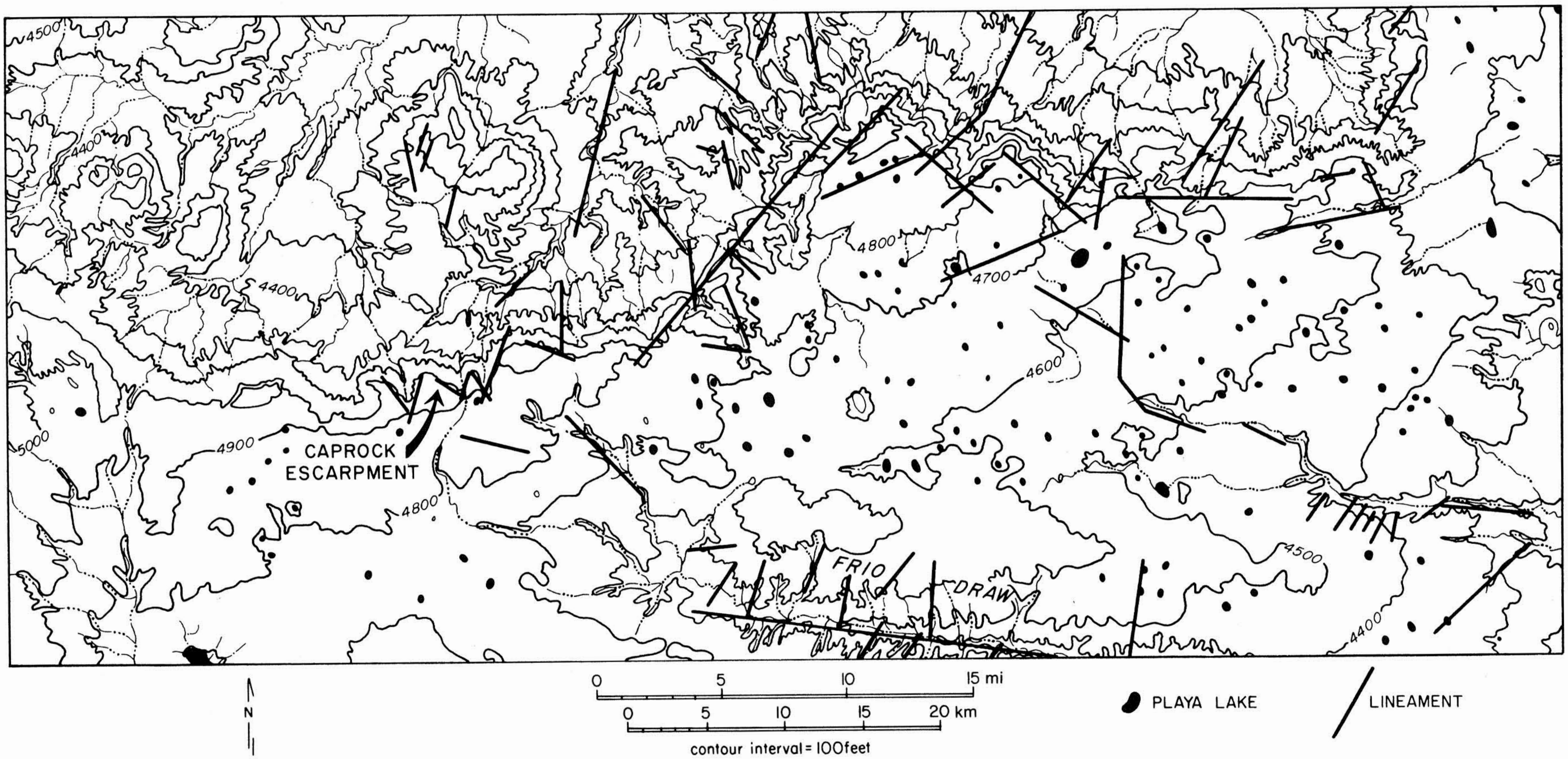
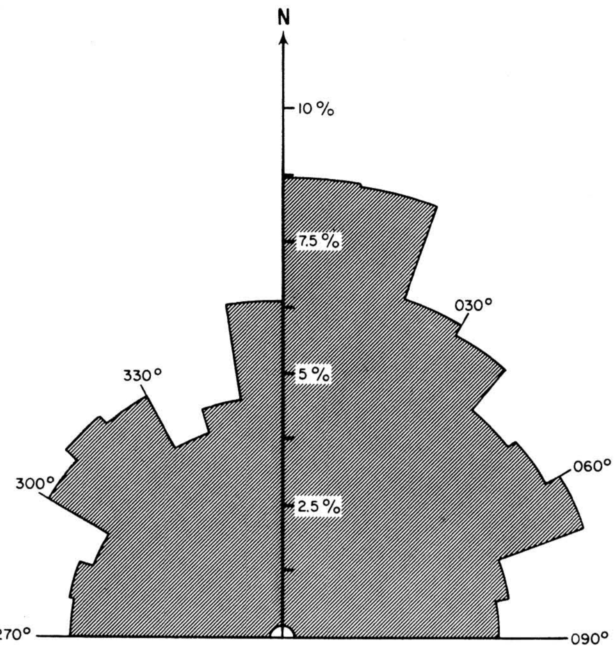


Figure 9. Detail of lineaments mapped on Landsat imagery in Quay County, New Mexico, showing linear escarpment segments and linear drainage lines on the south-eastward-sloping High Plains. Area shown is C in figure 12. Original imagery is at a scale of 1:250,000.



N=3065

Figure 10. Lineament trends in the physiographic provinces surrounding the High Plains. These trends, primarily from the Rolling Plains area, make up the "off High Plains" category.

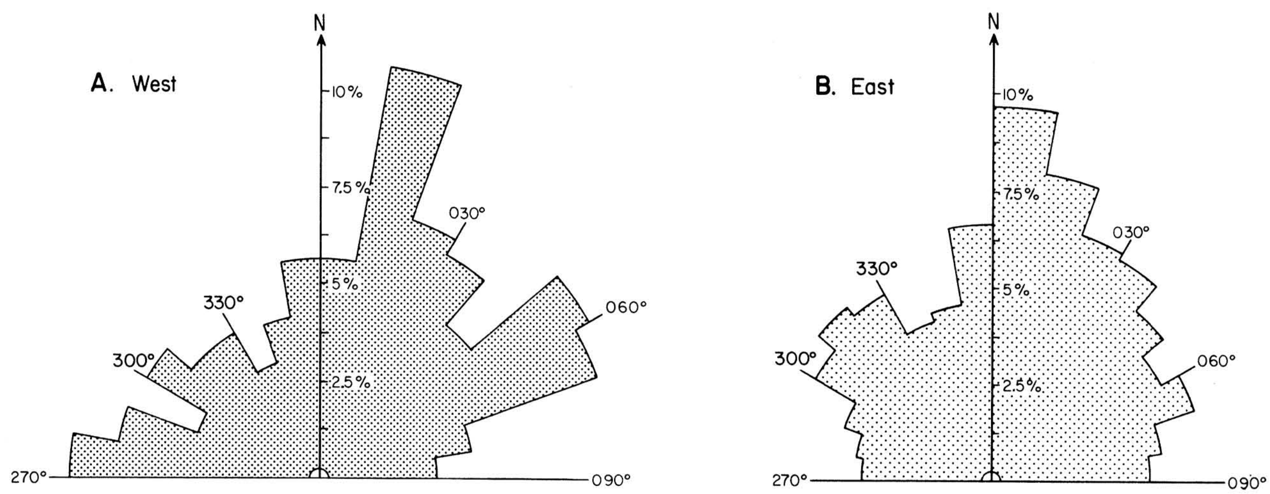


Figure 11. Comparison of lineament orientations for the western and eastern parts of the "off High Plains" category.

Comparison of Lineament Length and Orientation

The distribution of lineament length by azimuth frequency was computed for areas on and off the High Plains within each sheet of the 1:250,000-scale National Map Series covering the study area. A series of rose diagrams (fig. 12) was prepared by

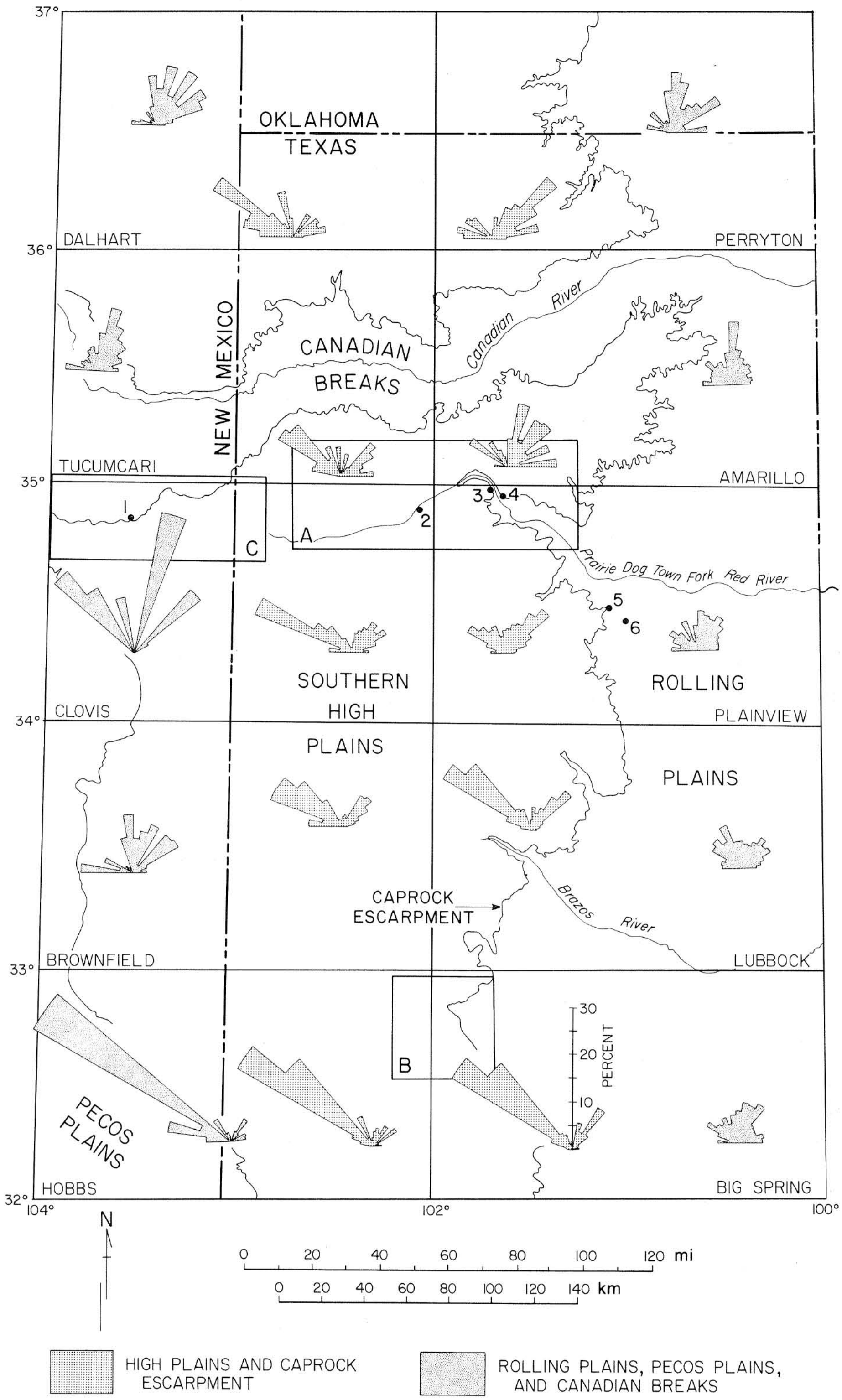


Figure 12. Summary of lineament length by 10° azimuth category within each named $1^{\circ} \times 2^{\circ}$ National Map Series sheet. Areas A, B, and C correspond to figures 7, 8, and 9. Localities 1 through 6 are sources of joint data for figure 14.

summing data within each physiographic province defined by the boundaries given in table 3. Data from the High Plains show least scatter; playa alignments and shallow drainage lines retain the same 300^{o}-320^{o} and 030^{o}-050^{o} orientations across most of the High Plains. Exceptions are the High Plains data from the Amarillo, Tucumcari, and Perryton sheets, the lineaments of which show greater diversity in orientation. This diversity may be related to dissolution of bedded Permian salts in the subsurface of these areas. Processes of deflation and localized dissolution of the caprock caliche have probably influenced the development of playa lakes across all the High Plains. Throughout these areas of greater lineament diversity, examples of playa lakes overlying salt dissolution at depths of 240 to 300 m (800 to 1,000 ft) have been documented (Gustavson and others, 1980a). The diverse orientation of lineaments and the greater frequency of larger playas (more than 2,400 m or 8,000 ft in diameter) in the northeastern part of the Texas Panhandle may be one consequence of regional salt dissolution (Gustavson and Finley, 1979).

Lineament orientations vary more off the High Plains than on the High Plains but there are common trends throughout the region. Total lineament lengths in each 10^{o} sector for areas off the High Plains show a northerly peak trend for data plotted on the Perryton, Amarillo, and Plainview $1^{o} \times 2^{o}$ topographic sheets (fig. 12). This trend is less well defined on the Plainview sheet, and may merge with a 010^{o}-040^{o} trend, as on the Big Spring sheet, or may be subordinate to the 030^{o}-060^{o} trend, as on the Lubbock sheet. Northwest and east-west lineament orientations also occur in the Rolling Plains, Pecos Plains, and Canadian Breaks. The greater amount of lineament data from stream segments and drainage lines results from the much greater drainage density in these physiographic provinces. The influences of variable bedrock stratigraphy, development of integrated drainage systems, slope aspect, and development of pronounced local relief contribute directional scatter to these data.

Longer lineaments occur particularly within the High Plains of the Hobbs and Big Spring map sheets and parts of the Brownfield and Lubbock sheets (fig. 12; pl. I). These lineaments consist of aligned playas and linear drainage segments (fig. 8) that are orthogonal to the regional dip of the High Plains surface. It is possible that a coincidence of joint direction and consequent drainage direction has led to a more frequent occurrence of long lineaments in the 300^{o}-320^{o} direction. Data are not available to test this hypothesis because windblown sands and silts mantle the bedrock beneath the High Plains and prevent study of joints.

Lineament Density over the Palo Duro Basin

Lineament density (expressed as total lineament length in kilometers per 7.5-minute U.S. Geological Survey quadrangle) was contoured for a $2^{\circ} \times 4^{\circ}$ block of the study area. High densities overlie the Caprock Escarpment, the fluvial systems east of the escarpment, and the topographic scarps and drainage of Palo Duro Canyon in northern Briscoe and southern Armstrong Counties (fig. 13). A prominent belt of lineaments trends northwestward over the Palo Duro Basin (pl. I) and has a peak density of 86 km per 7.5-minute quadrangle in the Dodd SE quadrangle in southern Castro County (fig. 13). The lineament belt, first noted by Finch and Wright (1970) and termed the "Running Water Draw - White River Lineament," is 26 to 29 km (16 to 18 mi) wide and extends 240 km (150 mi) from Crosby County, Texas, to Curry County, New Mexico. Aligned playas, some with incipient drainage between playas, and linear draws form individual lineaments within the trend. This study shows that (1) lineaments are more numerous than mapped by Finch and Wright (1970), (2) lineaments not noted by the latter authors have a northeast orientation, orthogonal to the major trend and within the lineament belt, and (3) faulting along the lineament trend, as indicated by Finch and Wright (1970) has probably not occurred, as no evidence of faulting was found during extensive stratigraphic studies of the Palo Duro Basin using all available geophysical well logs (Dutton and others, 1979). The suggestion of Finch and Wright (1970) that joints probably are involved in the development of lineaments is supported herein, but major control by subsurface faults seems unlikely. Few major faults have been mapped at the surface in the Southern High Plains (Barnes, 1967, 1968, 1974, and 1977). Two major faults, both in east-central New Mexico, may be related to local subsurface salt dissolution (Gustavson and others, 1980a) rather than to regional structural development.

RELATIONSHIPS OF LINEAMENTS TO REGIONAL GEOLOGY

The orientations of lineaments delineated and measured from remotely sensed data have in some areas shown parallelism with bedrock joints measured in the field (Lattman and Nickelsen, 1958; Lattman and Matzke, 1961; Wermund and others, 1978). To evaluate this potential relationship in the Texas Panhandle, joint trends were measured, primarily along the margins of the Southern High Plains where bedrock is accessible. Also, similarities between the peak frequency of lineament orientation and

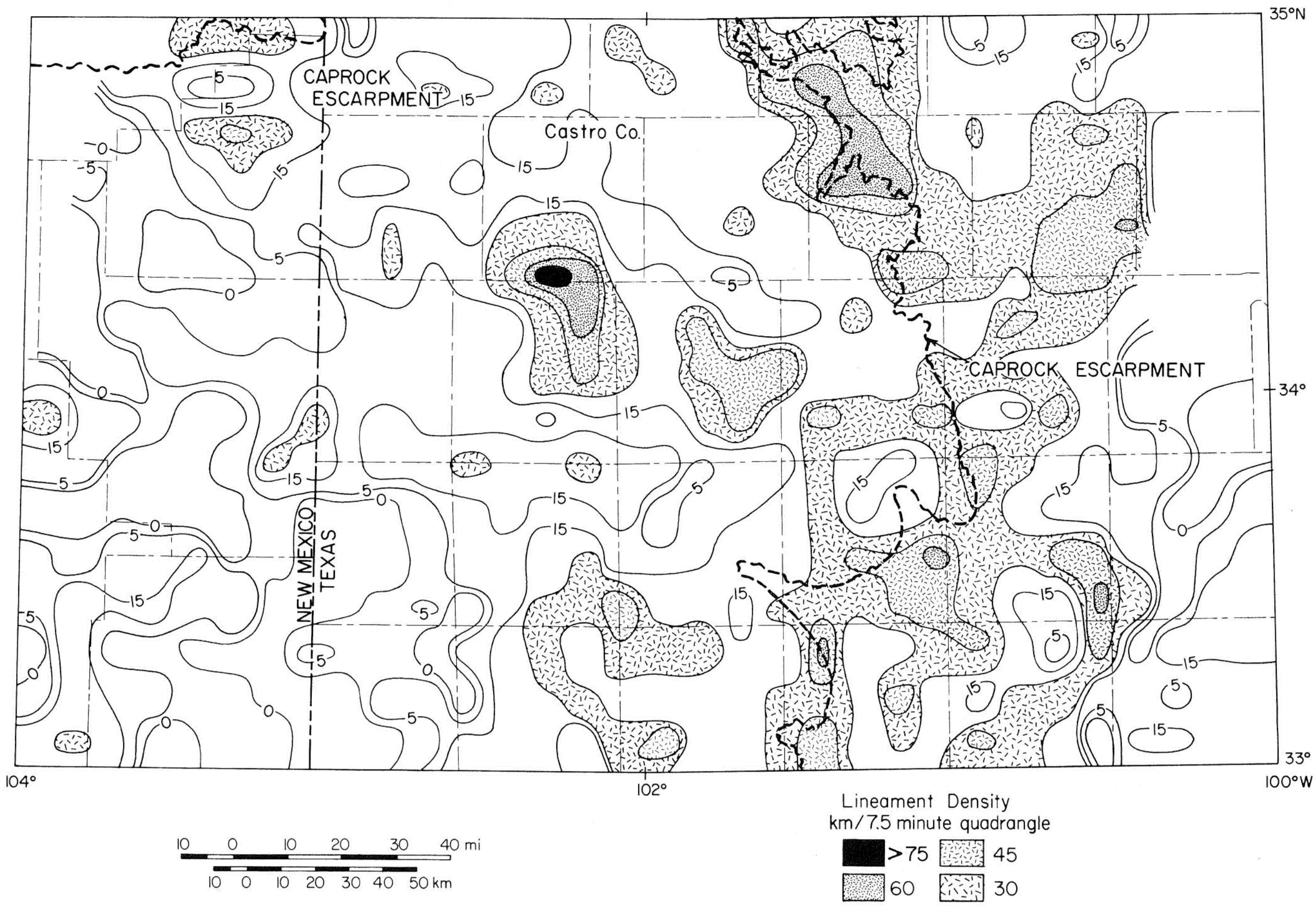


Figure 13. Lineament density within a 2° latitude by 4° longitude area over the Palo Duro Basin, within the central part of the Texas Panhandle.

major subsurface structural trends of southwestern Oklahoma, the Texas Panhandle, West Texas, and eastern New Mexico were investigated.

Comparison of Lineaments and Joints

Joints are narrow, approximately planar surfaces of discontinuity, or fractures, along which displacement has not occurred or is too small to be apparent to the unaided eye (Hobbs and others, 1976). Joints are evidence of the brittle behavior of rock, and are most evident in the sandstones of the Triassic and Permian formations of the Rolling Plains. The poorly consolidated silts, sands, and gravels of the Ogallala Formation do not show well-developed jointing in outcrop, but the caliche caprock within the Ogallala may show an irregular pattern of nearly orthogonal surfaces. Linear caves within the caprock caliche indicate possible joint control of dissolution of the caprock itself. Roughly cubic blocks of caliche on scree slopes suggest that jointing in the Ogallala Formation provides a locus for enhanced weathering. Rather than well-developed fracture planes, the joints in the Ogallala could be a response to reduced cohesion between grains.

Joint Orientation

Orientations of more than 1,100 near-vertical joints have been recorded from the Quartermaster Formation, Dockum Group, and Ogallala Formation. Regionally, joints exhibit fair to poor development in outcrops of moderately to poorly consolidated fine-grained sandstones and siltstones. Joints are best developed in sandstones of the Triassic Dockum Group and Permian Quartermaster Formation, and these units are the source of most data. Outcrops suitable for joint studies are restricted to the escarpments along the boundary of the High Plains, to the Rolling Plains, and to canyons incised into the margins of the High Plains. Obvious expansion joints, or rim joints parallel to canyon walls, were avoided.

Azimuth frequency plots of joints show trends that vary geographically (fig. 14). These orientations parallel major lineament trends and suggest that jointing influences the orientation of streams, valley segments, and escarpments in the High Plains and surrounding physiographic provinces. The 300°-320° lineament orientation is not well represented in the compiled joint data (only one of six groups, fig. 14), but in some outcrops of the Dockum Group this orientation is dominant (fig. 15). This orientation may not be adequately sampled because available outcrops are primarily within the Rolling Plains and Caprock Escarpment physiographic units, while the 300°-320° lineament orientation is prevalent over the High Plains where outcrops are absent.

Joint Control of Drainage

Joints influence physiographic features because they represent surfaces of decreased resistance along which surficial processes of weathering and erosion can act more effectively. Rectangular or angulate patterns result from joint or fault control of drainage development (Howard, 1967). Solution-widening by ground water of joints in limestone has been noted (Lattman and Olive, 1955), and Reeves (1970) suggests that solution of Ogallala caliche along fractures may be controlling the location of some playa-lake depressions, thus producing lineaments. In the Rolling Plains of Briscoe County, Texas, water seeping from joints in Permian bedrock indicates that joints can act as preferential pathways for ground-water flow. The water probably originated from a man-made lake located above the outcrop. Some joints had clearly been widened by sapping of the saturated rock.

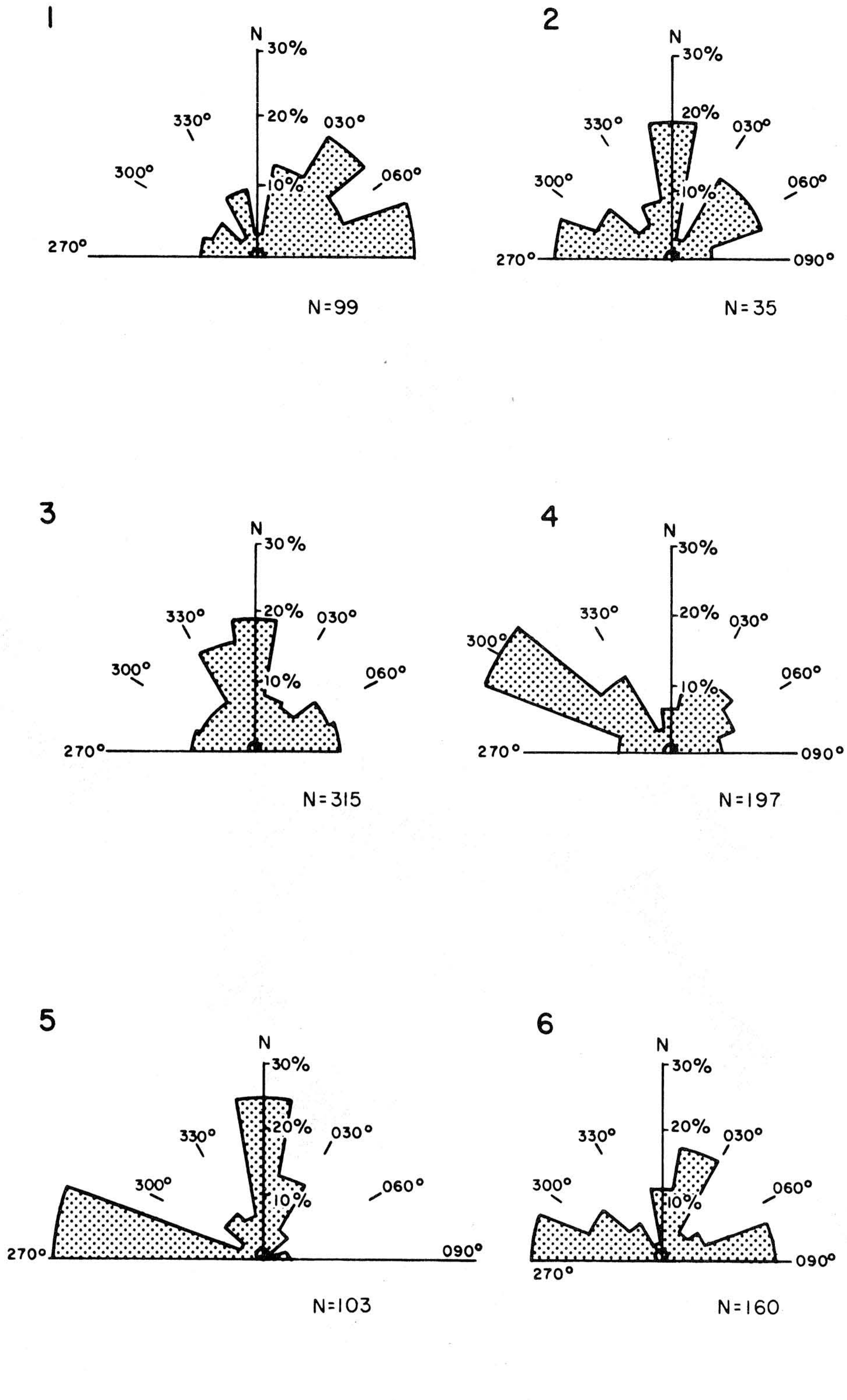


Figure 14. Joint orientations from localities in the Texas Panhandle and eastern New Mexico. Localities 1 and 2 are within the Clovis sheet, and localities 3 through 6 are within the Plainview sheet (fig. 12).

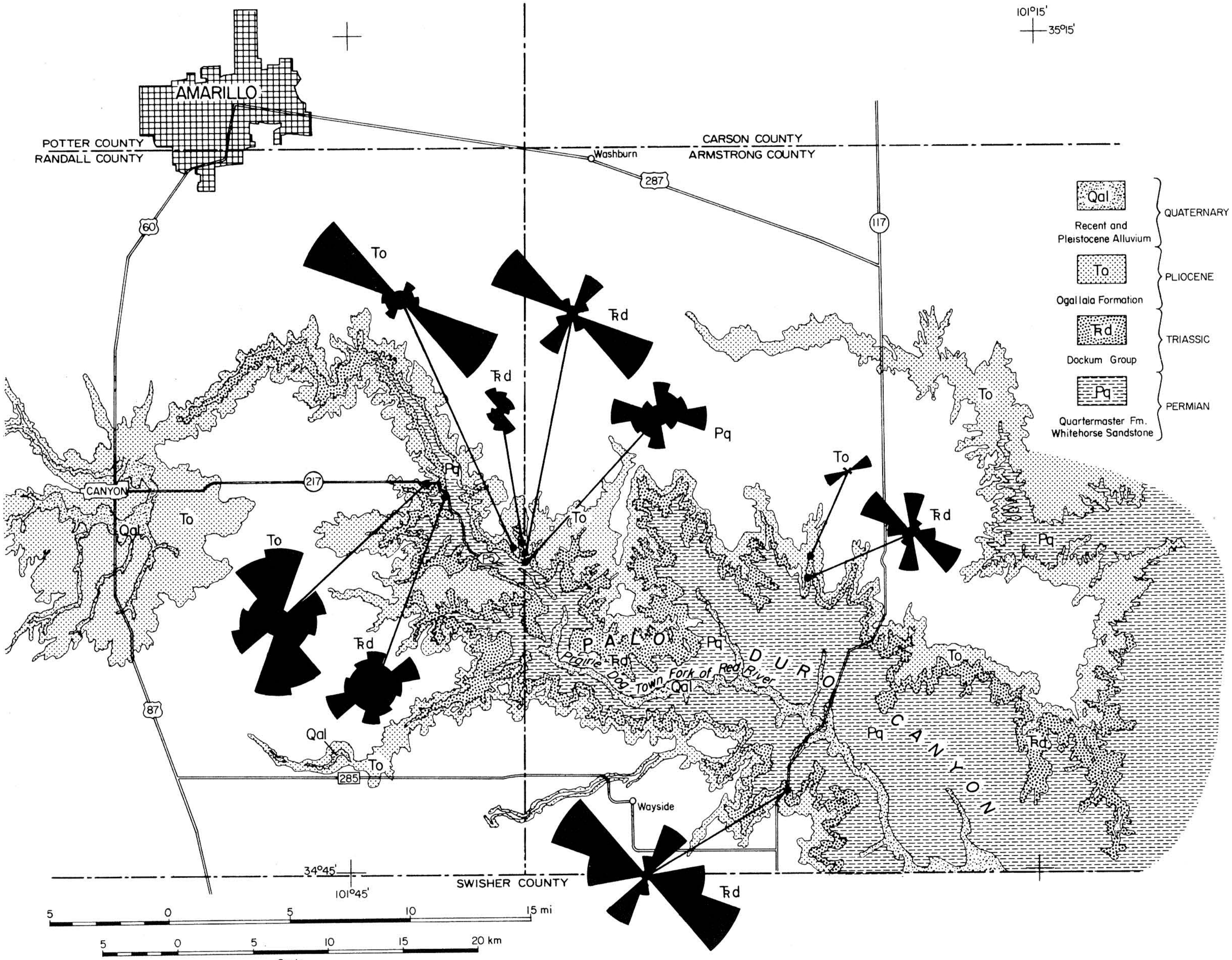


Figure 15. Joint orientations in the rocks of Palo Duro Canyon.

Joint control of drainage should be best developed where streams flow on obviously jointed bedrock, as on the Permian formations of the Rolling Plains. Other factors, such as bed thickness and degree of induration, may also influence locations of stream development. In previous work along the eastern margin of the Rolling Plains and in the North-Central Prairie physiographic provinces of North-Central Texas, Brown (1961) found that 66 percent of approximately 13,000 lineaments coincided in orientation with joint sets. Brown measured more than 2,100 joints in areas of limestone outcrop.

In the Quartermaster Formation exposed in the Rolling Plains of eastern Briscoe County, a tributary of the Little Red River is incised into a 3- to 4-m-wide, bedrock-walled gorge over a 30- to 35-m distance. Joints in the bedrock channel floor are parallel to the 5.8-m-deep gorge and probably controlled its development. Another tributary has cut through the crest of a gentle flexure where the Permian bedrock is highly jointed. This suggests joint control of a stream that otherwise may have tended to enter the higher order stream at a low point away from the crest of the flexure. Gypsum beds within the Quartermaster Formation are up to 2.4 m thick and provide local resistant ledges through which streams are preferentially downcutting along joints. Small tributaries (45 cm wide) on sloping, eroded gypsum surfaces clearly follow single joints that are also evident in the gypsum-floored streambed of the mainstream, beyond the mouth of the tributary. The 29 joints measured in gypsum bedrock at one locality, representing all joints present, show preferred orientations of 280°, 320°, and 020°, similar to some regional lineament patterns (fig. 12).

There is evidence to support joint control of linear drainage even where developed on poorly consolidated Ogallala sediments. The High Plains surface of the Lubbock, Hobbs, and Big Spring map sheets shows many lineaments oriented 300°-320° (fig. 12). The High Plains surface in this region slopes 120°-140° at 1.9 to 2.7 m/km (10 to 14 ft/mi); therefore, coincidence of joints and consequent drainage direction may have enhanced the development of lineaments (pl. I). The possibility that all lineaments are solely related to consequent drainage on the High Plains is unlikely, however, because (1) rectilinear offsets resulting in drainage parallel to slope contours are frequent, (2) playa alignments perpendicular to the dominant trend of 300°-320° occur as though developed along an intersecting joint zone, and (3) surface slopes of the High Plains change from 110° to 090° in direction on the Plainview, Amarillo, and Tucumcari map sheets while a lineament frequency peak remains at 300°-320° (fig. 12). Those joints nearest in orientation to the consequent drainage direction probably exerted the strongest influence on lineament development where coincidence of these factors would provide a path of least resistance for surface drainage. Similarly, Stone (1963), during a study of glacial drift in the Midwest, noted that the joint set "oriented most nearly parallel to initial land slope exerted the greatest control in the early stages of (postglacial) drainage development."

Joint Propagation

An analogy can be drawn between a layer of glacial drift that overlies bedrock and the poorly consolidated Ogallala Formation that overlies more highly indurated Permian and Triassic strata. Cox and Harrison (1979) noted a statistically significant correlation between the orientation of streams flowing over glacial drift and the orientation of joints in the underlying bedrock. The apparent influence of jointing on stream orientation did not appear to decrease with increasing thickness (up to 152 m [500 ft]) of drift. This thickness is similar to, or thicker than, the Ogallala Formation in most areas of the Texas Panhandle, where the Ogallala reaches a thickness of more than 250 m (820 ft) only in limited areas (Seni, 1979). Because streams developing after deglaciation appear to be influenced by fracture orientation, Cox and Harrison (1979) suggest that joints may propagate upward relatively quickly in a geologic time frame.

In the Texas Panhandle, surfaces resembling joints are poorly developed in the alluvium of the Little Red River basin in Briscoe County. At one locality the alluvium is probably no older than 8,200 to 9,500 years, the maximum ages of radiocarbon-dated bison bones (Harrison and Killen, 1978) contained in an alluvial deposit 0.3 km (0.2 mi) from the jointed alluvium. Poorly developed joint planes in the alluvium are marked by accumulations of calcium carbonate, indicating preferred fluid pathways along these surfaces. The presence of possible joints in Holocene alluvium and the weathering of Plio-Pleistocene Ogallala caliches into roughly rectangular blocks suggest that development of joint-controlled lineaments is possible even in poorly consolidated sediments. Other evidence of the existence of joints in geologically young, poorly consolidated sediment comes from "post-Glacial" lakebeds in Utah exhibiting complementary joint sets with the predominant sets parallel to adjacent mountain ridges (Gilbert, 1882). In addition, glacial-drift-covered terrain in southeastern Saskatchewan, Canada, exhibits systematic lineament patterns that appear to be controlled by joints in bedrock and are unrelated to glacial processes (Mollard, 1958).

Mollard (1958), Price (1966), and Hobbs and others (1976) describe multiple possible origins for jointing; a single origin is clearly unlikely. Shrinkage and differential compaction following deposition of silty and muddy sediments may be a part of the joint-development process in alluvium.

Price (1966) relates the formation of joints to residual compressive tectonic stresses and also to tensile stresses that develop during uplift. Field evidence in support of this theory comes from the Colorado Plateau, where widely persistent joint trends in Pennsylvanian- to Triassic-age rocks suggest that joints formed in reponse to homogeneous forces acting over the area (Hodgson, 1961). The theory of upward propagation of joints may be difficult to support for the entire sedimentary section of the Palo Duro Basin, where highly ductile salt units occur. However, jointing may accompany regional deformation that is in the form of barely perceptible regional flexures (Hobbs and others, 1976) and thus develop over a wide area and throughout a stratigraphic section such as that of the Palo Duro Basin. Similar joint orientations even extend through as wide an area as the entire Colorado Plateau (Kelley and Clinton, 1960).

Comparison of Lineaments and Regional Geologic Structure

A notable similarity exists between the prominent northwesterly lineament trend and the structural geology of the Texas Panhandle and adjoining areas. Numerous structural elements of the Texas Panhandle exhibit northwest orientation (fig. 2). A major structural element, the Amarillo Uplift, extends into southwestern Oklahoma as the Wichita Uplift along a 290^{o}-300^{o} trend. Other positive features of southern Oklahoma, such as the Waurika-Muenster Arch, Wichita-Criner Arch, and intervening basins, trend 300^{o}-310^{o} (Ham and others, 1964). Lineaments and structural folds of the southern Permian Basin (Midland and Delaware Basins) and of eastern New Mexico also show orientations in the 290^{o}-310^{o} range (Hills, 1963, 1970).

Five faults oriented between 315^{o} and 290^{o} were mapped in subsurface Precambrian metamorphic, granitic, and volcanic rocks of Quay, Guadalupe, San Miguel, and Harding Counties, in east-central New Mexico (Foster and others, 1972). One fault is oriented 060^{o}, and others are oriented nearly north-south. This area includes the western part of the Clovis and Tucumcari map sheets, where similar lineament trends are evident (fig. 12). Foster and others (1972) suggest that the Precambrian surface may be block faulted and that minor structural features appear to follow the trends of subsurface uplifts, possibly as a result of continued sediment compaction. The mechanism of differential sediment compaction and uneven loading caused by varying thicknesses of sediment has been suggested as a possible cause for jointing (Kelley and Clinton, 1960). If such joints were parallel to the margins of the faulted basement blocks and were transmitted to the surface, the parallelism with lineaments would naturally follow.

While it is likely that there are several modes of origin and possibly different periods of joint development, which in turn control lineaments, a regularity is exhibited in basement structure, lineament orientation, and some elements of the joint pattern within the Texas Panhandle region. This may result from tectonic stresses applied to the entire region, such as stresses related to plate convergence or the subsequent pulling apart of plates that formed the present Gulf of Mexico during the Mesozoic Era (165 to 150 m.y. B.P.) (Pilger, 1980). The orientations of lineaments may also be influenced by very slight reactivation of basement faults and joint patterns (A. G. Goldstein, personal communication, 1981). Flawn (1956) and Muehlberger and others (1967) have documented the complex tectonic and petrographic relationships within the Precambrian of the Texas Panhandle that may influence the joint patterns within the sedimentary sequences of the Palo Duro Basin.

IMPLICATIONS OF LINEAMENT ANALYSIS

Lineaments are linear physiographic features that suggest structural control of geomorphic development. Analyzing lineaments and defining their preferred orientation utilizing products of remote sensing is an indirect means of evaluating this structural control. Joints are the most likely control of lineaments in the Texas Panhandle because only a limited number of faults have been recognized by surface mapping (Barnes, 1967, 1968, 1974, 1977) and from subsurface studies (Dutton and others, 1979). Correlation of lineament orientation with the orientation of major joint systems strongly supports the hypothesis that joints can provide a path of lower resistance along which linear surface drainage preferentially develops. The alignment of canyons near the margin of the Rolling Plains with playas on the High Plains surface beyond the heads of the canyons suggests structural geologic control extending across major physiographic boundaries (fig. 16). Joints extending across this boundary could reasonably provide a locus for both incised canyons and playas to follow as they develop.

Joints may serve as preferred pathways for the movement of ground water; in carbonate terranes, joints have developed into cavernous solution zones, especially at joint intersections. Water wells drilled at joint intersections marked by lineaments often have greater yields than wells drilled at other localities (Lattman and Parizek, 1964). Reeves (1970) suggested that some of the large pluvial lake basins on the High Plains may have been localized at the intersections of lineaments; he also notes the

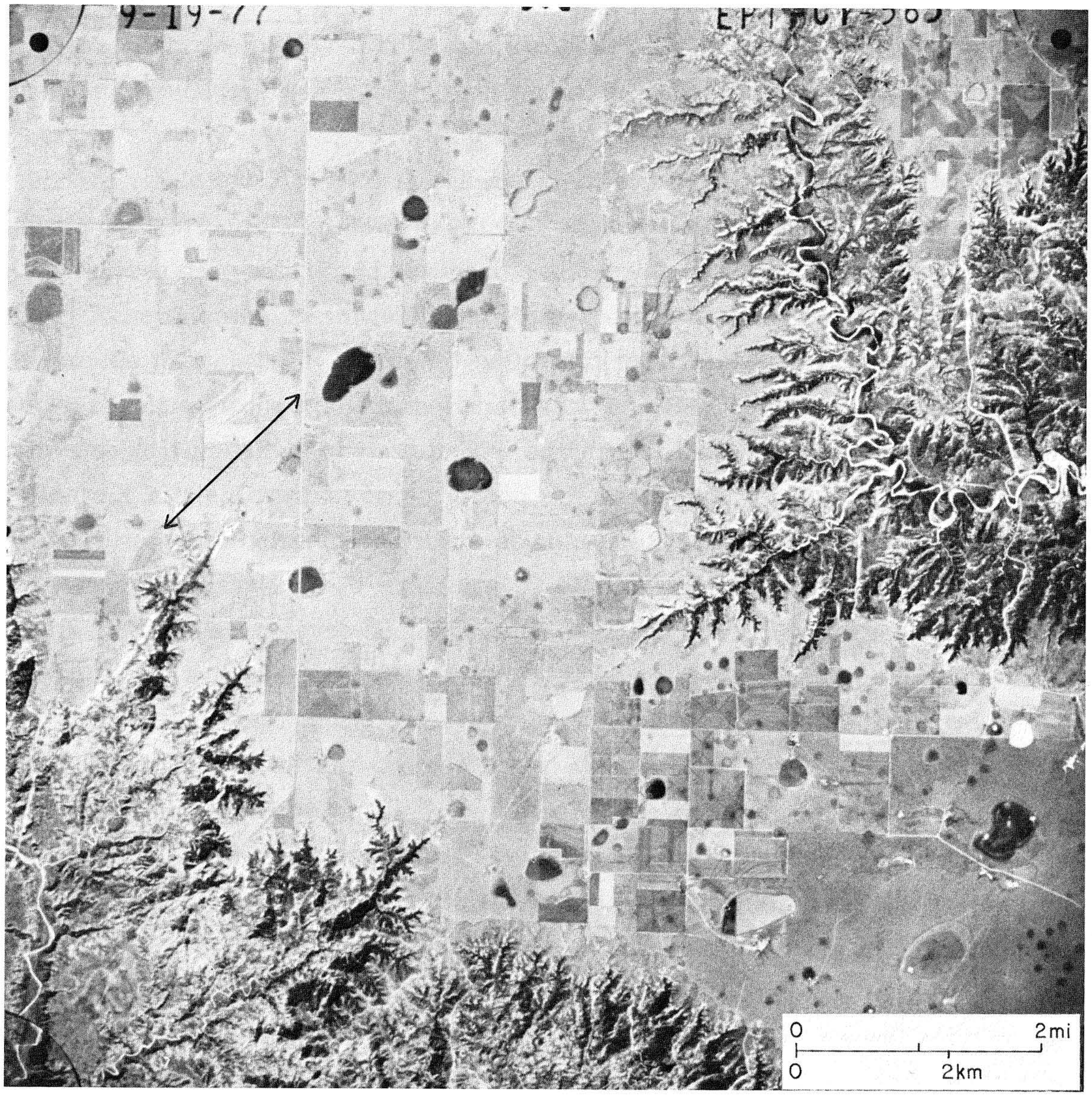


Figure 16. Reproduction of 1:80,000-scale color-infrared aerial photograph showing alignment of linear tributaries in Palo Duro Canyon (lower left) and aligned playas on the adjacent High Plains surface (parallel to arrow). North is toward the top of the figure.

absence of caprock caliche in the Ogallala Formation beneath smaller playa-lake depressions in eastern New Mexico, suggesting dissolution by downward percolating water. The numerous lineaments consisting of aligned playa-lake depressions oriented northwest across the High Plains may therefore, in part, be the product of enhanced dissolution of caliche at the intersection of northwesterly and northeasterly oriented joint sets.

An area of increased joint density of the two orientations may tend to localize a single playa-lake depression. A wider zone of preferred joint development could result in major lineament trends, such as the Running Water Draw - White River lineament, where playa alignments are very well developed.

The Running Water Draw - White River lineament parallels and partly overlies a generalized net sand thick in the Ogallala Formation (Seni, 1980). This coincidence may suggest that joints may be more readily propagated in the sand-rich section of the Ogallala due to enhanced permeability and more rapid downward percolation of ground water at points of playa development controlled by joints. Certainly in outcrop the moderately consolidated sandstones of Triassic and Permian age show better developed jointing than do the associated siltstones and mudstones. It is difficult to determine whether this same tendency applies to the poorly consolidated Ogallala Formation, whose outcrops are highly eroded. Regarding downward percolation of water in a more permeable sand-rich section of the Ogallala, it is possible that downward ground-water movement into joints in underlying units may have helped develop a system of aligned depressions on the surface. Mollard's (1958) studies in Manitoba and Saskatchewan suggest that such long-term ground-water movement can cause loss of soluble constituents and may be one mechanism whereby joints help to define linear swales and aligned depressions. Detailed subsurface studies of a playa approximately 600 m (2,000 ft) in diameter near Amarillo in the Texas Panhandle identified bleached sands and no caprock caliche at the stratigraphic level of caliche present outside the playa, thus indicating solution by ground water (Lotspeich and others, 1971). A recent excavation through a playa, also near Amarillo, revealed that caliche in the Ogallala Formation thins toward the center of the playa. Open holes occur within the thin part of the caliche zone, and the altered appearance of the caliche suggests that leaching by ground water has occurred.

The mechanisms required for joint development and propagation to produce lineaments do not necessitate major rejuvenation of shear zones or renewed tectonic activity to influence the Pliocene Ogallala Formation and younger sediments. This is evident from review of the literature. Price (1966) suggests that stresses that produce joints "are residual and are not replenished by tectonic processes." Jointing, although poorly developed in Holocene alluvium of the Texas Panhandle, could, at most, be aided by minor earthquake shock, microseismic activity, or small stresses caused by cyclic semidiurnal earth tides. Otherwise, sediment compaction and joint propagation from underlying materials are likely methods of joint development, but it remains difficult to ascribe a unique cause for joint systems.

CONCLUSIONS

Landsat multispectral scanner data, including specially enhanced false-color composite imagery, have been used to define lineaments in the Texas Panhandle and part of eastern New Mexico. On the Southern High Plains a 300°-320° lineament orientation is most prominent and is defined by aligned playa-lake depressions and surface drainage in low-relief swales. A 030°-050° frequency peak also occurs, represented primarily by short rectilinear offsets in surface drainage and by playa alignments. Along the High Plains margin, linear segments of the Caprock Escarpment show similar orientations. Included is one of only two major faults intersecting the surface in the region, located in Quay County, New Mexico.

The Rolling Plains, Canadian Breaks, Pecos Plains, and a small part of the Edwards Plateau physiographic provinces exhibit a peak lineament orientation of 010°-020°. Subordinate peaks are present at orientations of 030°-040°, 060°-070°, and 300°-320°; the overall lineament pattern for these areas off the High Plains is not as well defined as those on the High Plains surface. These areas have a greater drainage density than does the High Plains surface, and lineaments consist predominantly of stream segments and drainage lines.

The similarity in orientation of lineaments, major joint trends, and subsurface structural trends points to structural control of linear physiographic features. Joints provide a preferential pathway for surface drainage development as well as potential sites for enhanced downward percolation of meteoric waters that may foster playa development through dissolution of caliche caprock. These are mechanisms by which joints might control the development of lineaments. Because the local orientation of regional joint trends can vary as a result of bed thickness, lithologic variations, and localized structural features, joint-controlled lineaments can be expected to show the same degree of variation. Changes of 10° to 20° in orientation of lineament frequency peaks between map areas are, therefore, not likely to represent differences requiring separate mechanisms for development.

A variety of mechanisms may account for joint propagation into geologically young sediments, hence the control of lineaments by joints in Pliocene, Pleistocene, and Holocene substrates. Poorly developed joints were observed in Holocene alluvium. Lineaments defined from remotely sensed data can therefore be ascribed to structural geologic controls even where not developed on exposed bedrock surfaces.

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