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A New Methodology for Oil and Gas Exploration Using Remote Sensing Data
and Surface Fracture Analysis

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ABSTRACT

A systematic methodology for oil and gas exploration using remote-sensing information and surface fracture analysis has been developed. This methodology consists of (1) acquisition of satellite images and aerial photographs, (2) photogeological interpretation of these images and photographs for mapping surface lineaments, fracture traces, drainage patterns, and circular and arcuate anomalies, and (3) surface fracture analysis. The techniques for acquisition and photogeological interpretation of remote-sensing data were obtained from a literature search. The techniques for surface fracture analysis were developed through an integration of geological and mathematical analyses.

The new techniques of using surface fracture analysis for delineating subsurface hydrocarbon traps are based on five criteria which were developed in a case study in Osage County, Oklahoma. The five criteria were in turn developed using five indicators of subsurface structural complications. The five indicators identified in the case study are surface lineaments, surface fracture orientation, local residual surface-fracture frequency, local residual surface-fracture density, and surface circular and arcuate anomalies. The correlation between these indicators and subsurface structures was quantitatively evaluated, as was the relative effectiveness of these indicators in locating subsurface structures.

The methodology was used to develop new exploration leads in Osage County, Oklahoma. Areas along and adjacent to surface major lineaments, or of high values in residual surface-fracture frequency and density, or with surface fractures of multiple orientations are identified as anomalous locations. The anomalous locations which have not yet been explored are delineated as priority locations for potential new reserves in this mature region.

The methodology was also applied to oil and gas exploration in northeastern Arizona. After remote-sensing data were acquired and interpreted for mapping surface lineaments, fracture traces, drainage patterns, and circular and arcuate anomalies in northeastern Arizona, analyses of surface lineaments and fracture traces were performed, and preliminary priority locations are suggested for exploratory drilling and/or for further geophysical and geochemical surveys in this frontier region.

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1.0 INTRODUCTION

This study investigates the applicability of surface fracture analysis for hydrocarbon exploration. The word "fracture" in this report is used as a general term for surface fracture zones, lineaments, and fracture traces. Lineaments refer to larger-scale surface linear features mapped from satellite images. Fracture traces refer to small-scale surface linear features interpreted from aerial photographs. Surface fracture zones are defined as major linear features interpreted as reflections of subsurface weakness zones.

In structural geology, fractures are classified into regional and tectonic. Regional fractures may appear as surface lineaments on satellite images, whereas tectonic fractures are more likely to appear as surface fracture traces on aerial photographs. Unrelated to local geological structures, regional fractures tend to be orthogonal in pattern, persistent in orientation, and pervasive in large areas.^{2,8,31} Although they may also appear in large scale, tectonic fractures are acutely intersecting shear and extension fractures and directly associated with local geological structures such as folding, faulting, and draping, which are favorable geological mechanisms for the formation of potential oil and gas entrapments in the subsurface. Hence, surface fracture analysis may be a potential tool for hydrocarbon exploration if the subtle relationship between the structures of subsurface hydrocarbon traps and their expressions as surface fracture patterns can be recognized.

The use of fracture analysis for hydrocarbon exploration is not a new concept. Throughout the history of the oil industry, various approaches have been tried to infer subsurface oil and gas accumulations and to analyze production performance using surface fracture information.^{1,2,9-20} The purpose of this study was to review and evaluate existing techniques in the literature and to develop a more comprehensive and more quantitative methodology through statistical, geological, and computer analyses. The significance and validity of using surface-fracture pattern analysis for locating subsurface features were first reviewed, followed by techniques for surface fracture mapping using different types of remote sensing data. Also reviewed were techniques for geological interpretation and statistical analysis of surface fracture traces for identifying subsurface oil and gas traps.

A case study in Osage County, Oklahoma, is presented to provide concrete evidence to the significance and effectiveness of using remote sensing data and surface fracture analysis for hydrocarbon exploration purposes. The surface and subsurface features in Osage County, Oklahoma, were mapped and digitized, and the correlation between them investigated. The effectiveness of using surface fracture characteristics as indicators of subsurface features was analyzed. Criteria were developed for delineating potential subsurface traps by integrating surface lineaments, fracture traces, and circular and arcuate anomalies. Priority locations were then identified for potential new reserves in Osage County, Oklahoma. The result is an

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integrated methodology for mapping surface features using remote sensing information and for systematically analyzing and interpreting surface fracture patterns for oil and gas exploration.

The methodology was also applied to oil and gas exploration in northeastern Arizona. Landsat images and color-infrared aerial photographs were used to map the surface lineaments, fracture traces, drainage patterns, and circular and arcuate anomalies in the region. The basic structural styles and the basement structures of the area were investigated, as was the correlation between the oil shows and the surface fracture zones and basement fault systems. Preliminary priority locations were delineated for exploratory drilling and for further geophysical and geochemical surveys in northeastern Arizona.

2.0 LITERATURE REVIEW

2.1 Origin of Surface Fractures

The validity of using surface-fracture mapping and pattern analysis for oil and gas exploration hinges on whether fractures observed at surface can be projected into the subsurface, and whether surface fracture anomalies, if properly identified, are indicative of geological features in the subsurface. Many field observations and engineering analyses have concluded that at least surface fracture orientations are very consistent with those in the subsurface,^{1,3-14} and subsurface structures are generally aligned with the locations of surface fracture or curvilinear anomalies.^{15-23,26,29}

Field studies in the Colorado Plateau, Wyoming, and New York, found, by observing sedimentary systems exposed in succession on deep canyon walls, that the systematic fracture patterns observed in earlier rocks are essentially repeated within each of the younger sedimentary systems all the way to the surface.^{3-6,8-10} When viewed over a large region, the areal pattern of folds in central Wyoming is remarkably regular.⁴ The regional fold pattern can be compared favorably with a fracture pattern of similar extent.⁴

The consistency between surface and subsurface fractures was also observed by comparing various aerial-photograph analyses and production monitoring of petroleum reservoirs.¹¹⁻¹⁴ A photogeological study of the North Burbank unit in Osage and Kay counties, Oklahoma, showed that the orientation of the primary fracture set mapped from aerial photos is approximately parallel to the direction of early water breakthrough of the waterflooding operations in the field.¹¹ The congruence of fracture orientations from well logging with those of surface fractures from aerial photo mapping was also observed in the Midland basin area after analyzing data from eight reservoirs.¹² A correlation between subsurface hydraulic-fracture azimuths and surface fracture orientations was observed in Appalachian areas.^{13,14}

Based on these observations, researchers have proposed that regional fracture patterns are first established in basement and/or deep subsurface rocks due to large-scale tectonic activities. Some of the fractures, if not the whole fracture patterns, are then propagated upward into the overlying sedimentary strata (as the sediments accumulate and become capable of fracturing) through an oscillatory mechanism caused by earth tides, microseisms, plate tectonic compressional and tensional stresses, the rotation of the earth, recurrent glacial loading and unloading, and groundwater-related processes, or all of them.^{3,4,7,8,11,15,19,23,28} As discontinuities in rocks, regional fractures provide lines or zones of weakness along which other structures later develop. Hence, deformation other than fracturing in sedimentary rocks is concentrated along, and largely confined to, narrow linear zones.

Similar to regional fractures, tectonic fractures associated with geological structures at depth can also be propagated upward to the surface. Unlike regional fractures, however, tectonic fractures

can originate from geological structures in more than one zone, from that immediately below the surface down to the basement.⁷ That is, some of the tectonic fractures observed at surface can also be caused by surface or near-surface structures. What is observed at the surface are combinations of regional and tectonic fractures. Although the tectonic fractures are more likely to produce surface fracture anomalies which may be associated with subsurface geological structures, the uncertainties associated with the classification and origin of surface fractures make it a challenging task to use surface-fracture mapping and pattern analysis as a tool for hydrocarbon exploration. Nevertheless, various attempts have been made to identify the surface fracture signatures of subsurface oil and gas traps through statistical, mathematical, and geological analyses.^{15,17-23,29}

2.2 Surface-Fracture Mapping Techniques

The effectiveness of using surface fracture analysis for hydrocarbon exploration is directly affected by the accuracy in mapping surface fracture system. Different approaches have been used in the mapping of surface geological features, including fieldwork, aerial photography, airborne radar imaging systems, and satellite imagery. All of them are important as they provide information in different scales and of different degrees of accuracy. The integration of the information obtained from all these techniques is necessary for the most accurate and complete surface fracture mapping.

2.2.1 Fieldwork

Fieldwork involves direct measurements of geologic and topologic features on the ground. It provides the most accurate and reliable information about the structural features of the earth's surface, particularly the position, orientation, length, spacing, and density of surface fractures. The data obtained from fieldwork are also used to calibrate aerial-photo, airborne-radar, and satellite-imagery interpretations. It plays a vital role in any oil and gas exploration, and it was the only way possible for surface surveys before remote sensing technology was were available.

However, fieldwork is very tedious, slow, and expensive. In some cases, it is impossible to perform field measurements because an area is inaccessible. Further, extremely large-scale geologic features may not be correctly mapped from fieldwork.

2.2.2 Aerial Photography

The use of aerial photographs and associated interpretation methods can greatly reduce the time and expenses in mapping surface-fracture trace patterns. Using scales of 1:15,000 to 1:58,000, an aerial photo can cover an area of a few square miles.¹¹ Since what is captured in an aerial photo are usually secondary features such as vegetation alignments and soil tonals, special skills are required to interpret aerial photos so that the real surface fracture patterns and other geologic structures can be mapped. Using magnified stereoscopes, it is possible to delineate the true

position, orientation, spacing, length, and density of surface fractures.¹¹ Coupled with field work, aerial photography has been successfully used in mapping surface fracture patterns in field-wide scales for the purposes of exploration and production monitoring and management.^{1,11-13,17,19,21,28}

2.2.3 Airborne Radar Imaging Systems

As an alternative to aerial photography, side-looking airborne radar (SLAR) presents another approach for surface mapping.²² SLAR uses pulses of microwave energy generated and received from the sides of an aircraft to map geological features on the earth's surface. Unlike aerial photography, changes in aircraft altitude do not alter mapping scales because radar is a time-distance function of electronically recorded pulsed energy. Further, SLAR can operate during day or night and through cloud cover. SLAR may detect fractures where other methods such as conventional aerial photography or Landsat imagery are not always successful.

In addition, the airborne imaging spectrometer (AIS) and the thermal infrared multispectral scanner (TIMS), flown on NASA C-130 aircraft, can acquire digital spectral data of the earth's surface. Their spatial resolutions are 9 x 9 m and 25 x 25 m, respectively.²⁶ These techniques provide additional alternatives to conventional aerial photography.

2.2.4 Landsat Imagery

Landsat imagery presents excellent information for mapping large-scale surface geological features. In a basin-wide search for oil and gas accumulations, the use of Landsat imagery may detect previously unknown geological features which may be significant with respect to the location of hydrocarbons. Very large linear features may not be recognizable on aerial photographs. It was reported that the use of satellite images helped geologists find the western outline of the Delaware basin in parts of Texas and New Mexico.²³ More strikingly, a study of the satellite images of 15 giant oil and gas fields around the world concluded that a huge amount of exploration expenditures could have been saved if satellite images were available and had been used during the exploration of these fields, and that the analysis of satellite images and other remote-sensing information should be a top priority in the search for the future giants.¹⁶ In addition to being used for mapping surface lineaments, tonal anomalies, and other geological structures, Landsat data have also been used in conjunction with geochemical analysis for detecting correlation among surface fractures, hydrocarbon microseepage, and existing production trends.³³⁻³⁵

A great advantage in photogeological interpretation from satellite imagery is the capability for truly synoptic examination of regional geologic features with dimensions of tens to hundreds of miles. Regions inaccessible to field or conventional aerial photograph observations may be photogeologically mapped using satellite imagery.

A single satellite Multispectral-Scanner (MSS) image with a resolution of 79×79 m provides a picture of the earth's surface approximately 110 miles on a side, an area of coverage equivalent to about 500 conventional aerial photographs.^{23,32} Another Landsat imaging system, the Thematic Mapper (TM), has dramatic improvements over the MSS system including increased spatial resolution of 30×30 m, improved spectral separation, and expanded spectral range^{26,32,36}

Recently, a French satellite imaging system called SPOT has been used for geologic structure mapping.^{24,25,32} SPOT data complement data provided by Landsat satellites. Spatial resolutions (10×10 m and 20×20 m) of the two sensors of this imaging system represent a substantial improvement over SPOT's predecessors, the Landsat satellites.

No remote sensing techniques (aerial photography, Landsat imagery, etc.) will provide reliable mapping of surface fractures without substantial ground control. In other words, fieldwork is fundamental in surface mapping. The combination of fieldwork, aerial photography (or airborne radar imaging systems), and satellite imagery may provide the best chance for a complete and accurate surface fracture mapping.

2.3 Interpretation of Surface Fracture Patterns

The ultimate objective of surface fracture mapping and pattern analysis is to locate shallow to deep-seated structural and/or stratigraphic anomalies which are potential hydrocarbon entrapments. It is generally agreed that regional fracture systems, which originated in basement rocks and propagated upward to the surface, are regular and systematic. It is tectonic fractures, which can originate in geological structures in any zone below the surface down to the basement, that cause or produce irregularities in surface fracture patterns. Therefore, the key element in surface-fracture pattern analysis is to identify the surface-fracture pattern anomalies and to establish the characteristic correlation between these anomalies and the subsurface geologic structures. Two approaches have been used in the interpretation of surface fracture patterns for subsurface geological traps: geological interpretation, and mathematical and statistical analysis.

2.3.1 Geological Interpretation

Types of geological features in the subsurface that may produce fracture and/or lineament patterns (including curvilinear patterns) at the surface include but are not necessarily restricted to:¹⁵

- Differential compaction of sediments related to facies changes
- Differential compaction of sediments overlying the paleogeomorphic expression of subsurface structures
- Drape of overlying sediments resulting from periodic intermittent growth of structures in the subsurface that does not directly reach the surface

- Basement tectonic and structural activity

It is believed that all these subsurface geological features first produce fractures in their respective zones. The resultant subsurface-fracture patterns are then propagated upward to the surface. The mechanism of the direct upward propagation of the basement fracture patterns is believed to be responsible for most of the lineaments and some of the fractures at the surface. The success of using surface-fracture pattern analysis relies on the identification of the surface signatures of the corresponding subsurface geological features. In the following discussions, the significance is emphasized of three specific surface and subsurface features: surface circular anomalies, surface nu patterns, and subsurface folds.

Circular anomalies are one of the most significant features which can be observed from aerial photos and satellite images. In sedimentary terrain, there are several possibilities for the origin of those circular anomalies, some of which are of interest to oil and gas exploration.¹⁵

- Folding or doming related to tectonic movements, diapiric movement of salt or other evaporite deposits, or basinward movement of more rigid rocks over or between less viscous rock units
- Differential compaction of sediments over less compressible sedimentary bodies such as reefs or sand lenses
- Differential compaction of sediments over buried structural features such as fault scarps, domes, or folds
- Collapse or restructuring of rock bodies at or near the surface or at considerable depth as a consequence of
 - Solution of evaporite deposits or limestone
 - Conversion of limestone to dolomite or gypsum to anhydrite
 - Cauldron collapse

Since hydrocarbons are known to be associated with many of these subsurface structures, circular features deserve considerable attention in exploration although several surface or near-surface phenomena unrelated to hydrocarbon accumulation may also produce circular features on aerial photos and satellite images.

A nu pattern consists of an arcuate lineament intersecting a straight lineament at an acute angle to form a pattern that resembles a bird's beak or the lower case Greek letter v.¹⁸ Structural analysis suggests that this v pattern is formed by Riedel faults (R-faults) and conjugate Riedel faults (R'-faults) where they curve sharply at bends in wrench faults to form P-faults and P'-faults.¹⁸ Since folding is strongly associated with wrench faulting, surface nu patterns may bear significance for hydrocarbon traps in the subsurface.

As a general rule, the arcuate portion of a nu pattern tends to be structurally high, whereas the straight, or master fault portion, is structurally lower. The trend of an anticline is approximately

at right angles to the baseline (i.e., the master fault) of the largest nu pattern containing the anticline. Therefore, careful mapping of v patterns can be used to help reveal locations of potential hydrocarbon entrapments.¹⁸

Since subsurface folds are the most common structures for hydrocarbon accumulations, their surface expressions on aerial photographs and satellite images are extremely important for exploration. Ideally, subsurface folds are manifested at the surface as circular or elliptical anomalies with appropriately dipping strata. However, most of them along major trends may be defined by fracture or lineament intersections rather than apparent closures or circular features.¹⁵

Using the principles of rock mechanics and structural geology as well as outcrop observations, it was found that folds are predominantly associated with two types of fracture systems,² each of which consists of three subsets: one extension and two conjugate shear. The orientation of the extension fracture set of the first type of fracture is parallel to the strike of the folds, whereas that of the second type of fracture is perpendicular to the strike. Thus, the surface fracture expressions of a subsurface fold can be diverse because different combinations of the fractures associated with a fold may propagate to the surface. Common surface-fracture and lineament patterns indicative of subsurface folds include the followings characteristics:¹⁵

- The crest of an anticline or trough of a syncline is commonly marked by well-developed extension fractures orientated subparallel or subperpendicular to the fold axis (strike).
- Conjugate shear fractures often develop along the trend obliquely to the fold axis. Furthermore, fracture orientation and frequency are also sensitive to the local changes in the trend of the fold axis.
- Areas containing multiple fracture directions, even if they are not associated with any apparent surface closure, may overlie subsurface folds.
- Circular features transected by or tangent to subparallel lineaments or fracture traces are prime indicators of subsurface folds.

Transecting lineaments or fractures may represent extension fractures developed along the crest of a fold. In the case of drape folds, transecting lineaments may represent subsurface faults over which draping has occurred. Lineaments tangent to circular features may represent fractures generated by differential compaction of sediments over the flanks of a subsurface fold or, in the case of folds developed adjacent to through-going growth fault zones, the lineament may represent the growth fault itself.

- A distinct pattern of converging and mutually intersecting fractures may be associated with folds that develop in response to horizontal movement or as detachment folds. These include extension fractures that parallel the crest of a fold, and fractures generated by shear stress that trend obliquely to the axis of a fold.

Using aerial photographs, satellite images, and the geological interpretation methodology discussed, a detailed study was performed to find new exploration leads in Osage County, Oklahoma.¹⁵ The aerial photographs and satellite images of the county were acquired; mapped for surface lineaments, fracture traces, and circular and arcuate features; and then interpreted to identify 55 potential hydrocarbon traps. No information has been found as to the accuracy of these interpretations. A comparison study indicates that most giant oil and gas fields in the world are clearly expressed as circular anomalies on satellite images.¹⁶ Comparing existing oil and gas fields to their surface lineament patterns also suggests that clusters of overlapping nu patterns are generally associated with subsurface structural highs.¹⁸

The geological interpretation techniques are generally more qualitative than quantitative. Except for circular anomalies, which may be very strong indications of subsurface closures, geological interpretations of surface fracture patterns tend to be subjective. An alternative approach is to use mathematical and statistical techniques to capture the irregularity of surface fracture patterns.

2.3.2 Mathematical and Statistical Analysis

The surface fracture pattern anomalies, presumably resulting from the occurrence of subsurface geological structures, are indicated by irregularities in fracture frequency, density, orientation, length, and statistical distributions. The goal of mathematical and statistical analysis is to quantify the surface-fracture pattern anomalies through mathematical and statistical analyses of these fracture characteristics.

Fracture frequency, defined as the number of fractures per unit area, is one of the most apparent indicators of structural complexity. After partitioning a study area into small subblocks, the fracture frequency in each subblock can be estimated. Deviations from the "frequency norm" can be quantified through trend surface analysis.¹⁷ Comparisons between the surface frequency deviation distribution and subsurface structures show that the anomalies in fracture frequency are associated with structural closures. Basement uplift structures (i.e., active structures) are accentuated by positive fracture frequencies along their flanks, whereas "passive" structures, such as reefs, may be associated with negative fracture frequencies.¹⁷

Another approach for analyzing fracture frequency data is one in which the frequency deviation for each subblock is obtained and empirically converted into "structural intensity" values.^{1,18} The contour map of the structural intensity values can then be constructed and used to identify subsurface folds, reefs, fault traps, domes, and other structures. This is consistent with the outcrop observation that the intensity of deformation (i.e., fracturing) is directly proportional to the amount of structural relief.⁴

However, the trend surface analysis shows that the variation of fracture frequency is also strongly associated with surface rock lithology. Therefore, caution must be used in the interpretations of fracture frequency data.¹⁷

Fracture lengths are lognormally distributed. Deviations from lognormality tend to be associated with structural complications in the subsurface.¹⁷ The degree or severity of the deviations is indicated by the existence of correlation among the fracture-length statistical parameters, such as log-mean fracture length, standard deviation, skewness, and kurtosis. A numerical value is assigned if the correlation between any two parameters is significant through hypothesis testing. An index number is created by summing up all the numerical values corresponding to the significance testing results among all the statistical parameters. High-ranking index numbers indicate strong deviations from lognormality. As a result, locations for subsurface structures can be inferred.

Log-mean fracture length values can also be analyzed using trend surface analysis including residual analysis. The variations in log-mean fracture lengths may be indications of structural complications, although lithology also has a strong control. Fractures may be shorter over active structures. However, this effect may not occur over passive structures, such as those formed by a draping of sediments over bedrock highs.¹⁷

Fracture density refers to the total length of fractures per unit area. An alternative definition for fracture density is the total fracture intersections per unit area. The positions of known oil fields are associated with zones of relatively high fracture density.²⁹ The contour maps of fracture density values may also be used to empirically discriminate faults from fractures.¹⁹ Faults tend to be parallel to the contour curves of fracture density.

Fracture orientation is an effective parameter for fracture classifications. When coupled with fracture density data, fracture orientation is also used for plotting fracture rose diagrams, which can be analyzed to detect subsurface structures.

Rose diagrams of small subsets of an area can be compared against the grand rose diagram for the whole territory. A variation of the chi-square criterion can then be used to compare the subset against the composite rose diagram. Those which vary significantly from the composite diagram are zones of structural complications. A subset rose diagram can also be compared with all of its adjacent neighbors. Significant variations between neighboring diagrams would then indicate structural complexities.¹⁷

Rose diagrams can also be analyzed using a multivariate classification scheme. Active structures may be recognizable because their fracture patterns may differ from their immediate neighbors and may be isolated by classifications at higher group levels. However, passive structures may not be isolated by this technique.¹⁷

Once the location of a subsurface fold is identified, the local rose diagram may be used quantitatively to estimate the strike and the relative geometry of the structure using the parallelogram rule.²¹

Although mathematical and statistical analysis of fracture patterns is more objective than geological interpretations, the results of mathematical and statistical analyses are also affected by

factors other than subsurface structures, such as surface lithology. The integration of mathematical, statistical, and geological interpretations will provide more reliable results.

3.0 A CASE STUDY IN OSAGE COUNTY, OKLAHOMA

Located in the northeastern part of Oklahoma, Osage County has had prolific oil and gas production since 1897.³⁷ The tremendous amount of information documented over nearly a century from the county provides excellent opportunities for conducting case studies. The objective of this case study was to verify the validity of the hypotheses and theories presented in the previous literature review sections and to develop new techniques of using surface fracture information for inferring subsurface hydrocarbon traps.

3.1 Background Information

Geologically Osage County is located on the western flank of the Des Moinesian Cherokee basin, on the southwestern flank of the Chautauqua arch, and east of the southern extension of the Nemaha ridge (Figure 3-1). To the south lie the Arkansas Valley basin and en echelon fault zones, as well as the Quachita and Arbuckle mountain ranges. To the northeast is the Ozark dome.¹¹

The exposed rocks in Osage County are predominantly Middle and Upper Pennsylvanian. Slightly dipped toward the west, the surface rocks have been deformed. The eastern half of the

Figure 3-1 Study Area and Regional Geology¹¹

county contains many domes, anticlines, and structural basins; the western half contains very few structures.² The domes, anticlines, and structural basins are small and range in size from less than 1 to 3 mi². Although individual folds appear not to be systematically arranged, many of them lie in two northeastern-trending belts, as depicted in Figure 3-2.³⁷

The western belt contains many sharply folded domes and anticlines. The eastern belt occupies the easternmost part of the county. The strip of country between these two belts contains relatively few prominent domes or anticlines. The strikes of many of the domes and anticlines in the western belt and a few in the eastern belt are oriented in a northeastern direction. Also many of the most prominent domes and anticlines in the county lie in somewhat poorly defined three northwest-trending belts as displayed in Figure 3-2.³⁷

The subsurface rocks, as indicated in the stratigraphic column shown in Figure 3-3, are dominated by Pennsylvanian rocks deposited unconformably above a deformed sub-Pennsylvanian section. The entire Paleozoic section, with two major unconformities, lies on top of a severely eroded basement.³⁷

In the Arbuckle, Mississippi, Oswego and Big Lime, the oil and gas pools are primarily structural. However, in the Bartlesville, Burbank, Wayside, and Layton sandstones, the oil and gas pools occur in lenticular reservoir bodies and are therefore stratigraphic in nature.³⁷ The total area in Osage County producing oil and gas from the Bartlesville and Burbank sandstones is greater than the total area producing from all other zones.³⁷

Figure 3-2 Trends of Surface Anticlines and Domes in Osage County, Oklahoma³⁷

Figure 3-3 Stratigraphic Column Showing Positions of Strata Producing Hydrocarbons within Northeast Oklahoma³⁷

Figure 3-4 Basement Structures in Osage County, Oklahoma³⁸

The basement structure in Osage County is not well defined due to sparse deep wells penetrating the basement rocks. One interpretation of the basement structure is shown in Figure 3-4, in which two major basement deformation structures are identified: the Labette fault and the Osage island. The fault strikes approximately northeast across west-central Osage County. The Osage island refers to a basement dome in the southeast of the county.^{15,38}

Another interpretation of the basement structure is shown in Figure 3-5.^{15,38} Five major faults and numerous basement highs are indicated. The northeast-trending fault in the west-central part of the county and the west-east-trending fault in the southern part of the county are believed to be late Pennsylvanian in age. The other four basement faults are oriented in a northwest-southeast direction. The basement highs include the Osage island in the southeast and other highs in the west-central and north-central parts of the county.³⁹

3.2 Digitization of Surface and Subsurface Features

The purpose of digitizing surface and subsurface features is to provide digital data for quantitative analysis and graphical presentation. The surface lineaments, fracture traces, and circular and arcuate anomalies in Osage County were mapped from satellite images and aerial photographs.¹⁵ The surface anticlines and domes in the county also were mapped from field studies.⁴² In total, 56 lineaments (Figure 3-6), 3,368 fracture traces (Figure 3-7), 156 circular features (Figure 3-8), 235 arcuate features (Figure 3-9), and 207 crests of anticlines and domes (Figure 3-10) were digitized.

Figure 3-5 Basement Structures in Osage County, Oklahoma³⁹

Figure 3-6 The 56 Surface Lineaments in Osage County, Oklahoma

Figure 3-7 The 3,368 Surface Fracture Traces in Osage County, Oklahoma

Figure 3-8 The 156 Surface Circular Features in Osage County, Oklahoma

Figure 3-9 The 235 Surface Arcuate Features in Osage County, Oklahoma

Figure 3-10 Crests of 207 Surface Anticlines and Domes in 16 Townships in Osage County, Oklahoma

Figure 3-11 The 499 Subsurface Structures from the Mississippian Chat Formation in Osage County, Oklahoma

In addition, 499 subsurface structures (Figure 3-11) and 177 subsurface structurally low closures from the Mississippian Chat Formation (Figure 3-12) were digitized.⁴⁰ The surface and subsurface features were compared to investigate any correlation between them and to verify the significance of the surface features for implying subsurface oil and gas traps.

3.3 Correlation in Orientation Among Surface Lineaments, Fracture Traces,

Anticlines and Domes, and Subsurface Structures

The validity of using surface features to locate subsurface oil and gas traps rests on the hypothesis that surface features are indicative of subsurface structures. Data from Osage County were used to verify that at least a correlation in orientation exists between surface and subsurface features.

Figure 3-13 shows the rose diagram of the 56 major lineaments in Osage County. One can easily see that these lineaments can be subgrouped into two sets: one with an average orientation of N52°E, the other N39°W. The two sets are practically orthogonal. A rose diagram of the 3,368 surface fracture traces is given in Figure 3-14. The surface fracture traces also can be subgrouped into two sets: one with an average orientation of N46°E, the other N39°W. A close agreement in orientation between the surface lineaments and fracture traces is observed.

Figure 3-12 The 177 Subsurface Structural Lows from the Mississippian Chat Formation in Osage County, Oklahoma

Figure 3-13 Rose Diagram of the 56 Major Lineaments in Osage County, Oklahoma

Figure 3-14 Rose Diagram of the 3,368 Surface Fracture Traces in Osage County, Oklahoma

A rose diagram of the 207 crests of surface anticlines and domes from 16 of the 71 townships in Osage County, is shown in Figure 3-15. Although the pattern is somewhat diffuse, this rose diagram indicates that the surface anticlines and domes are primarily oriented in northeast-southwest or northwest-southeast direction.

Represented by rectangles during the digitization process, the 499 subsurface structures from the Mississippian Chat Formation were analyzed by constructing the rose diagram of their strike directions (Figure 3-16). The subsurface structures can be similarly divided into two sets: one with an average direction of N47°E, the other N34°W. A comparison between Figures 13 and 16 indicates that surface lineaments and subsurface structures are very consistent in orientation. When Figure 3-14 is compared with Figure 3-16, an exceptional agreement in both orientation and general rose diagram shape is observed between the surface fracture traces and subsurface structures. A correlation between the surface anticlines and domes, and subsurface structures also is observed when Figures 3-15 and 3-16 are compared. Therefore, it can be concluded that surface lineaments, fracture traces, anticlines, and domes are strongly correlated in orientation with the subsurface structures in Osage County, Oklahoma.

Although the correlation in orientation between surface lineaments, fracture traces, anticlines, and domes, and subsurface structures verifies the feasibility of using surface features for delineating subsurface structures, it does not, however, indicate exact locations for potential oil and gas entrapments. The correlation in position must be established to achieve this goal.

Figure 3-15 Rose Diagram of the 207 Surface Anticlines and Domes in Osage County, Oklahoma

Figure 3-16 Rose Diagram of the 499 Subsurface Structures in Osage County, Oklahoma

3.4 Significance of Surface Lineaments

The 56 surface lineaments in Osage County, discussed earlier, consist of two approximately orthogonal sets: one with an average orientation of N52°E, the other N39°W. Additional interesting characteristics are revealed by a closer examination of the surface lineament system shown in Figure 3-6.

First of all, Osage County is bounded on its west and southwest by the Arkansas River. The course of the river exhibits a remarkable relationship with the surface lineaments. The northwest-trending lineaments are approximately parallel to the sections of the Arkansas River along the southwestern boundary of Osage County. The northeast-trending lineaments are generally parallel to the sections of the convex parts of the Arkansas River along the western boundary of the county. Since surface drainage systems, such as rivers, washes, and creeks, reflect subsurface weakness zones or fault systems in most cases, it is reasonable to believe that at least some of the 56 lineaments in Osage County, if not all, are the expressions of faults or fractures.⁴¹

Further, the northeast-trending lineaments are generally longer and more continuous, whereas the northwest-trending lineaments are shorter, more disconnected, and truncated by the northeast-trending ones. Therefore, the northwest-trending lineaments probably reflect older subsurface faults which later were truncated by younger northeast-trending faults expressed at surface by the northeast-trending lineaments. This interpretation is consistent with the basement structures interpreted from a magnetic analysis (Figure 3-5). The four northwest-trending basement faults are apparently parallel to the northwest-trending surface lineaments. The one northeast-trending fault of Late Pennsylvanian age is parallel to the northeast-trending surface lineaments. This further strengthens the validity of the assumption that the surface lineaments in Osage County are the reflections of subsurface fault systems.

Combining these observations and analyses, the surface lineaments in Osage County are very likely regional fractures as defined in structural geology: The northeast-trending lineaments are the primary set; the northwest-trending ones are the secondary set. Since regional fractures result from large-scale tectonic activities, the lineaments generally represent fault systems which originate from basement or other deep subsurface rocks, and later propagated upward to the surface.

Once the identity of the surface lineaments in Osage County is solved, the next question is how to use the surface lineaments to infer subsurface features.

3.5 Correlation in Position Between Surface Lineaments and Subsurface Structures

It is generally believed that basement faults tend to propagate upward to every younger formation up to the surface. Other subsurface features are somewhat controlled by the basement

fault system and basement topography. Therefore, subsurface oil and gas traps, whether structural or stratigraphic, are more likely to develop along subsurface fault zones. Since the surface lineaments in Osage County reflect the corresponding subsurface fault system, the subsurface oil and gas traps in the county should be aligned with the surface lineaments. To verify this, the surface lineaments in Osage County were compared to the subsurface structural and stratigraphic traps.

Figure 3-17 shows the overlap of the surface lineaments (Figure 3-6) and the subsurface structures (Figure 3-11). The correlation in position between the lineaments and the structures is clear. Especially in the south-central, east-central, and southeastern parts of the county, the subsurface structures are closely associated with the surface lineaments. However, this relationship is less prominent in the western and northwestern parts of the county. Nevertheless, Figure 3-17 provides irrefutable evidence to support the previously mentioned hypothesis. Therefore, surface lineaments can be used to delineate general locations for subsurface structures.

To investigate the association in position between surface lineaments and subsurface stratigraphic traps, an overlap of the 56 surface lineaments and the subsurface traps from the Bartlesville and Burbank sandstones was constructed (Figure 3-18). Oil and gas pools in the Bartlesville and Burbank sandstones were used because most of the traps from these two sandstones are lenticular sand bodies and therefore stratigraphic. One can see that pools in the

Figure 3-17 Overlap of Surface Lineaments (Lines) and Subsurface Structures (Rectangles) in Osage County, Oklahoma

Figure 3-18 Overlap of Surface Lineaments (Lines) and Subsurface Stratigraphic Traps (Shaded Areas) in Osage County, Oklahoma

Burbank Sandstone are approximately aligned with the northwest-trending surface lineaments in the western half of the county. The major part of Burbank field appears to lie between two northwest-trending surface lineaments. It may have been resulted from a graben in the basement. Oil and gas pools in the Bartlesville Sandstone appear to be associated with both northwest- and northeast-trending surface lineaments in the eastern half of the county. However, the correlation in position between the surface lineaments and subsurface stratigraphic traps appears to be less strong than that between the surface lineaments and subsurface structures.

Further examination of Figures 17 indicates a tendency of subsurface structures on the southeastern side of the northeast-trending surface lineaments. This tendency, however, does not seem to exist with the northwest-trending surface lineaments. This phenomenon can be explained by the fact that most faults are not perfectly vertical discontinuous planes. Therefore, a shift can occur between surface and subsurface features. This characteristic is also observed when surface folds are compared with the corresponding subsurface folds in the Oswego Limestone formation in Osage County.³⁷ The crests of surface and subsurface folds appears to be shifted about 1,000 ft. Of 101 surface folds in eastern Osage County for which considerable structural control is available, the crests of 62 folds in the Oswego Limestone lie northwest, west, or southwest of the same folds in the exposed rocks. In 20, the subsurface crests lie directly beneath the surface crests. And in 14, the subsurface crests lie northeast, east, or southeast of the surface crests.³⁷

In summary, the surface lineaments in Osage County are strongly correlated in position with the subsurface structures from the Mississippian Chat Formation. A less strong correlation exists with the positions of stratigraphic pools in the Bartlesville and Burbank sandstones. There is a shift between surface and subsurface structures. For exploration purposes, therefore, surface lineaments provide a general guide for positioning exploratory drilling and/or for planning seismic and geochemical surveys. A geological analysis is required to identify the direction and distance of the shift between surface and subsurface features so that the locations for exploratory drilling and/or seismic and geochemical surveys may be further confined.

3.6 Significance of Surface Fracture Traces

The previous discussion has shown that major surface lineaments provide general locations for potential subsurface oil and gas traps. However, additional criteria are required in order to further pinpoint locations so that the risk associated with exploratory drilling can be reduced and the efficiency of finding oil and gas reserves improved.

As shown in Figure 3-7, the 3,368 surface fracture traces in Osage County are simply surface linear features on a smaller scale than those lineaments shown in Figure 3-6. The rose diagram of these surface fractures traces (Figure 3-14) clearly indicates they can be divided into two orthogonal sets oriented northeast and northwest. Additional characteristics of the surface fracture traces can be obtained through a statistical analysis.

Figure 3-19 shows the histogram of the surface-fracture trace orientations (0° is east, 90° is north). Ninety degrees appears to be an appropriate location to partition the surface fracture traces into two sets. After a statistical analysis is applied, statistical parameters for each set are obtained. The northeast-trending fracture set ($0-90^\circ$) has a mean orientation of 44° (N 46° E), and a standard deviation of 20° . The northwest-trending fracture set ($90-180^\circ$) has a mean orientation of 129° (N 39° W) and a standard deviation of 19° . Normal, lognormal, and triangular distributions provide close fits to the orientations of the surface fracture traces in each set.

Figure 3-20 shows those northeast-trending surface-fracture traces whose orientations fall within one standard deviation from their mean orientation (N 46° E). Similarly, those northwest-trending surface-fracture traces whose orientations fall within one standard deviation of their mean orientation (N 39° W) are shown in Figure 3-21. The overlap of Figures 3-20 and 3-21 is shown in Figure 3-22. The parallelism within each set, the orthogonality between the two sets, and the consistency with the major lineaments (as seen in Figure 3-22), indicate that these surface fracture traces, like the major surface lineaments (Figure 3-5), can be regional fractures. They may also be tectonic fractures associated with regional fractures (major lineaments).

Those surface fracture traces which do not fall into these two sets (Figures 3-20 and 3-21) are shown in 3-23. These residual surface-fracture traces likely may be tectonic fractures associated with local structures. Therefore, the surface fracture traces are a combination of regional and tectonic fractures.

Figure 3-19 Histogram of the Surface-Fracture Trace Orientations

Figure 3-20 Northeast-Trending Surface-Fracture Traces Within One Standard Deviation from Mean Orientation

Figure 3-21 Northwest-Trending Surface Fracture Traces Within One Standard Deviation from Mean Orientation

Figure 3-22 Overlap of Northeast- and Northwest-Trending Fracture Traces

Figure 3-23 Residual Surface-Fracture Traces in Osage County, Oklahoma

3.7 Correlation Between Surface Fracture Density and Subsurface Structures

Fracture density is generally defined as total fracture length per unit area. In this study, fracture density is more specifically defined as the total fracture length in feet per 100 x 100 ft area. The surface fracture density distribution in Osage County was calculated section by section for 2,237 sections within the county. Figure 3-24 shows the surface fracture density distribution in the sections of township R10E T25N. Ranging from 0 to 13.7 (Figure 3-25), the surface fracture density in Osage County has a global mean of 2.79 and a standard deviation of 2.16. A statistical analysis shows that a Weibull distribution provides the best fit to the histogram in Figure 3-25.

A global residual surface-fracture density distribution is created by subtracting a base density value from the density distribution over the county. Any section with a positive residual surface-fracture density is considered an anomalous section. When the global mean is used as the base value, 988 anomalous sections are identified. When 3.87, 4.95, and 6.03 are used as the base values, the number of anomalous sections becomes 625, 350 and 194, respectively. These anomalous sections are graphically shown in Figures 3-26-3-29. It is easy to see from these figures that there are more anomalous sections in the western half than in the eastern half of the county. However, as observed by many authors, there are actually more surface and subsurface

Figure 3-24 Surface-Fracture Density Distribution in the Sections of Township R10E T25N

Figure 3-25 Histogram of Surface-Fracture Density Distribution

Figure 3-26 The 988 Anomalous Sections Indicated by a Global Residual Surface-Fracture Density Distribution in Osage County (base value=2.79)

Figure 3-27 The 625 Anomalous Sections Indicated by a Global Residual Surface-Fracture Density Distribution in Osage County (base value=3.37)

Figure 3-28 The 350 Anomalous Sections Indicated by a Global Residual Surface-Fracture Density Distribution in Osage County (base value=4.95)

Figure 3-29 The 194 Anomalous Sections Indicated by a Global Residual Surface-Fracture Density Distribution in Osage County (base value=6.03)

half of the county are primarily sandstones whereas those in the western half are limestones. In order to reduce the effect of surface lithology in the analysis, a new procedure was developed which analyzes surface-fracture density distribution based on local mean values. A local mean fracture-density value was first calculated for each of the 71 townships in Osage County. A local residual surface-fracture density distribution then was created by subtracting the local means from the corresponding fracture density values. If any section with a positive local residual surface-fracture density value is considered an anomalous section, 998 such anomalous sections are identified in the county. They are graphically displayed in Figure 3-30.

One can see from Figure 3-26 that the anomalous sections defined by a global residual surface-fracture density distribution with the global mean as the base value exhibit two linear trends oriented in northeast-southwest and northwest-southeast directions, respectively. When the base value is increased to 3.87, 4.95, and 6.03, the corresponding distributions of the anomalous sections (Figures 3-27 thru 3-29) display similar linear trends, although the number of anomalous sections is progressively reduced as the base value is increased.

The two linear trends are also displayed in Figure 3-30, in which anomalous sections are defined by the local residual surface-fracture density distribution. It is not surprising to find that the linear characteristics of the distributions of anomalous sections defined by the residual surface-fracture density appear consistent with those of the subsurface structures (Figure 3-11) in Osage County. This association provides evidence for the possibility of using residual surface-fracture density values as an indicator for locating subsurface structures.

Figure 3-30 The 998 Anomalous Sections Indicated by the Local Residual Surface-Fracture Density Distribution in Osage County

Figure 3-31 Overlap of Subsurface Structures (Rectangles) and Anomalous Sections (Shaded Areas) Indicated by the Global Residual Surface-Fracture Density Distribution with the Global Mean as the Base Value

When the 499 subsurface structures of the Mississippian Chat Formation are compared with the 988 anomalous sections indicated by the global residual surface-fracture density distribution with the global mean as the base value (Figure 3-31), 278 (55.71%) of the 499 subsurface structures are associated with 396 (40%) of the 988 anomalous sections.

However, when the 499 subsurface structures are compared with the 998 anomalous sections indicated by the local residual surface-fracture density distribution (Figure 3-32), 317 (63.53%) of the 499 subsurface structures are found to be associated with 415 (41.58%) of the 998 anomalous sections. Clearly, the local residual surface-fracture density distribution is a more effective indicator of subsurface structures than the global residual surface-fracture density distribution. The use of local fracture density means in generating the local residual surface-fracture density distribution reduces the effect of surface lithology in the analysis of surface fractures.

Those anomalous sections indicated by the local residual surface-fracture density distribution and not associated with the 499 known subsurface structures are potential locations for exploring for additional structural traps in Osage County. Caution, however, must be taken when local or global residual surface-fracture density distributions are used for exploration because an area of a high residual surface-fracture density may also be associated with a subsurface structural low. This characteristic of the residual surface-fracture density is demonstrated in Figure 3-33, where 177 subsurface structural lows overlap with the 998 anomalous sections indicated by the local residual surface-fracture density distribution in Osage

Figure 3-32 Overlap of Subsurface Structures (Rectangles) and Anomalous Sections (Shaded Areas) Indicated by the Local Residual Surface-Fracture Density Distribution

Figure 3-33 Overlap of Subsurface Structural Lows (Rectangles) and Anomalous Sections (Shaded Areas) Indicated by the Local Residual Surface-Fracture Density Distribution

County. It was found that 119 (11.92%) of the 998 anomalous sections appear to be associated with 94 (53.11%) of the 177 subsurface structural lows.

3.8 Correlation Between Surface Fracture Frequency and Subsurface Structures

Surface fracture frequency is generally defined as the number of fractures per unit area. In this study, it is more specifically defined as the number of fractures per section. A single long fracture trace crossing several sections or even several townships will be truncated by section boundaries and will be counted multiple times. A frequency value was first calculated in this way for each section in Osage County. Figure 3-34 shows the surface-fracture frequency distribution in the sections of township R10E T25N. A mean value was then obtained for each township within the county. A local residual surface-fracture frequency distribution was generated by subtracting the local means from the fracture frequency values throughout the county. Any section with a positive residual surface-fracture frequency value is an anomalous section. In total, 983 such anomalous sections were identified in Osage County (Figure 3-35).

Figure 3-34 Surface-Fracture Frequency Distribution in the Sections of Township R10E T25N

Figure 3-35 983 Anomalous Sections Indicated by the Local Residual Surface-Fracture Frequency Distribution in Osage County, Oklahoma

The significance of the surface fracture frequency as an indicator for inferring subsurface structures was assessed by constructing an overlap of the 499 subsurface structures with the 983 anomalous sections indicated by the local residual surface-fracture frequency distribution. The result is shown in Figure 3-36. Four hundred sixteen (42.32%) of the 983 anomalous sections are associated with 314 (62.93%) of the 499 subsurface structures. This correlation in position between the surface fracture frequency and the subsurface structures is very similar to that between the surface fracture density and the subsurface structures (Figure 3-32).

In addition, an overlap constructed of the 177 subsurface structural lows with the 983 anomalous sections indicated by the local residual surface-fracture frequency distribution is shown in Figure 3-37. One hundred twenty-four (12.61%) of the 983 anomalous sections appear to be associated with 97 (54.80%) of the 177 subsurface structural lows.

Therefore, of the 983 anomalous sections, those which are not associated with the 499 known subsurface structures and the 177 subsurface structural lows may be potential locations for additional subsurface structures. Some of those potential sections, however, may overlie subsurface structural lows.

Figure 3-36 Overlap of Subsurface Structures (Rectangles) and Anomalous Sections (Shaded Areas) Indicated by the Local Residual Surface-Fracture Frequency Distribution

Figure 3-37 Overlap of Subsurface Structural Lows (Rectangles) and Anomalous Sections (Shaded Areas) Indicated by the Local Residual Surface-Fracture Frequency Distribution

3.9 Correlation Between Surface-Fracture Orientation Complications and Subsurface Structures

Surface fracture orientation, as discussed in the literature review sections, provides important information for surface and subsurface geological analysis. Areas with converging fracture traces (or with a fracture system of multiple orientations) are likely to overlie subsurface structures. The objective of this section is to identify the anomalous areas indicated by converging or multiply oriented surface fracture traces, and to investigate the correlation between these anomalous areas and the subsurface structures in Osage County, Oklahoma.

Orientation data can be graphically displayed using rose diagrams. The grand rose diagram for the 3,368 surface fracture traces in Osage County is shown in Figure 3-14. To identify anomalous sections, rose diagrams of subareas must be constructed.

Figure 3-38 shows the rose diagram of the surface fracture traces in Osage County township by township. One can see that the rose diagrams from the 71 townships are not uniform. Those with multiple (e.g., more than 2) orientations may indicate subsurface structural complications. Although these township rose diagrams may offer valuable information for reservoir production operations and management, rose diagrams of a larger scale (i.e., smaller areas) are needed to investigate the correlation between the surface-fracture orientation complexities and subsurface structures because the sizes of the subsurface structures in Osage County (Figure 3-11) are generally much smaller than the size of a township. Therefore, in this study, a rose diagram for

Figure 3-38 Rose Diagrams of Surface Fracture Traces for 71 Townships in Osage County, Oklahoma

Figure 3-39 Rose Diagrams for the Sections for Township R10E T25N in Osage County, Oklahoma

each of the 2237 sections in Osage County was generated. The rose diagrams for each of the 36 sections in township R10E T25N are shown in Figure 3-39.

As shown in Figure 3-19, the surface fracture orientations range from 0° (east) to 180° (west). Each rose diagram consists of 18 classes, each of which represents 10°. Any section with a fracture rose diagram of more than a given number of classes covered is an anomalous section. In this study, it is arbitrarily assumed that a section with a rose diagram covering more than five classes is anomalous. Eight such anomalous sections were identified in township R10E T25N. In total, 378 anomalous sections indicated by irregular rose diagrams were identified in Osage County (Figure 3-40).

Figure 3-41 is the overlap constructed of the 378 anomalous sections and the 499 subsurface structures in Osage County. One hundred forty-nine (39.42%) of the 378 anomalous sections are associated with 128 (25.65%) of the 499 subsurface structures in the county. Similarly, Figure 3-42 is the overlap constructed of the 378 anomalous sections and the 177 subsurface structural lows. It appears that 44 (11.64%) of the 378 anomalous sections are associated with 41 (23.16%) of the 177 mapped subsurface structural lows. The other 185 anomalous sections, which are not associated with any of the 499 known subsurface structures and any of the 177 subsurface structural lows, are potential locations for finding additional subsurface structures.

Figure 3-40 The 378 Anomalous Sections Indicated by Irregular Rose Diagrams in Osage County, Oklahoma

Figure 3-41 Overlap of Subsurface Structures (Rectangles) and Anomalous Sections (Shaded Areas) Indicated by Irregular Rose Diagrams in Osage County, Oklahoma

Figure 3-42 Overlap of Subsurface Structural Lows (Rectangles) and Anomalous Sections (Shaded Areas) Indicated by Irregular Rose Diagrams in Osage County, Oklahoma

3.10 Significance of Circular and Arcuate Features, and Their Association with Subsurface Structural Features

Circular and arcuate features are expressions of geological structures, such as domes, anticlines, depressions, and volcanoes. Some of these may only be identified from vegetation and/or tonal anomalies. As discussed in the literature review sections, these circular and arcuate features may represent the surface manifestations of subsurface traps.

As shown in Figures 3-8 and 3-9, 156 surface circles and 235 surface arcuate features were identified in Osage County. An analysis indicates that 436 sections in the county are associated with these surface circular and arcuate features. These 436 sections can be considered as anomalous sections indicated by the surface circular and arcuate anomalies in Osage County.

Figure 3-43 shows that 176 (40.37%) of the 436 anomalous sections are associated with 134 (26.85%) of the 499 subsurface structures. Similarly, if an overlap is also constructed of the 177 subsurface structural lows and the surface circular and arcuate features, 59 (13.53%) of the 436 anomalous sections are associated with 49 (27.68%) of the 177 subsurface structural lows (Figure 3-44).

Figure 3-43 Overlap of Subsurface Structure (Rectangles) and Anomalous Sections Indicated by Surface Circular and Arcuate Features in Osage County, Oklahoma

Figure 3-44 Overlap of Subsurface Structural Lows (Rectangles) and Anomalous Sections Indicated by Surface Circular and Arcuate Features in Osage County, Oklahoma

Surface circular and arcuate features correlate with both subsurface structural highs and lows. Therefore, when surface circular and arcuate features are used as an indicator for locating subsurface traps, the uncertainty must be considered and quantified since these circular and arcuate features may also overlie subsurface structural lows.

Of the 436 anomalous sections, those which are not associated with any of the 499 known surface structures or any of the 177 subsurface structurally low closures are potential locations for finding additional traps in Osage County, Oklahoma. The statistics presented in this section can be used to quantitatively assess the uncertainty involved.

3.11 Evaluation and Discussion

The effectiveness of each individual surface-fracture characteristic as an indicator of subsurface structures was evaluated separately in the previous sections. This section presents a comparison and summary to rank all potential indicators analyzed in this study.

Table 3-1 is a summary of the comparison of the 499 known subsurface structures from the Mississippian Chat Formation and the various anomalous sections indicated by surface-fracture density, frequency, orientation, and by surface circular and arcuate features. The fifth column shows the values of correlation factor, which is defined as the difference in the percentage values given in columns 2 and 3, and then divided by the percentage value in column 2. The numbers in the sixth column are ranks of correlation based on the values in column 5. The numbers in the seventh column show the ranks of effectiveness of the potential indicators for inferring subsurface structures. The ranks in this column are based on the corresponding percentage values given in column 4.

The correlation between the potential indicators and the subsurface structures is clearly indicated by the larger percentage values in column 3 as compared to those in column 2 since a total randomness (i.e., no correlation) would imply equivalent values in columns 2 and 3. The relative significance of this correlation is quantitatively characterized by the correlation factor values given in column 5 and ranked in column 6. Surface fracture orientation (or rose diagrams) appears to be the strongest indicator of subsurface structures, followed by local surface-fracture frequency and density distributions. Surface circular and arcuate features appear to be the least effective indicator of subsurface structures.

The effectiveness of the potential indicators is indicated by the percentage values shown in column 4 and ranked in column 7. All four indicators have a similar success rate of about 40% in indicating subsurface structures in Osage County.

Similarly, the correlation between potential indicators and the 177 mapped surface structural lows is summarized in Table 3-2. It appears that surface circular and arcuate features are more strongly correlated with subsurface structural lows than the other three indicators. Furthermore, they are more correlated with subsurface structural lows than structural highs. Although we

may not be particularly interested in searching for subsurface structural lows, the information provided in Table 2 may be useful in assessing the uncertainty in using surface fracture analysis for delineating subsurface structures.

3.12 Summary of the Case Study in Osage County

In this case study, an excellent database was established for surface fracture analysis for hydrocarbon exploration. It includes digital versions of surface lineaments, fracture traces, and circular and arcuate features obtained from remote sensing, as well as digital versions of subsurface structural highs and lows, and surface anticlines and domes obtained from geological mapping. A comprehensive set of computer programs were developed as tools for surface fracture analysis. The significance of surface lineaments, fracture traces, and circular and arcuate features was evaluated as potential indicators of subsurface structures. The correlation in both orientation and position between the surface and subsurface features was quantified. Potential indicators for delineating subsurface structures were evaluated.

In the following section, a comprehensive methodology is proposed for using remote sensing data and surface fracture analysis for hydrocarbon exploration.

Table 3-1 Comparison Between Surface Features and Subsurface Structures

Potential Indicator	Number(Percentage) of Anomalous Sections Identified in Osage County	Number(Percentage) of 499 Subsurface Structures Associated with Anomalous Sections	Number(Percentage) of Anomalous Sections Associated with 499 Subsurface Structures	Correlation Factor	Rank of Correlation	Rank of Effectiveness
Local Residual Surface-Fracture Density Distribution	998 (44.61%)	317 (63.53%)	415 (41.58%)	0.4241	3	2
Local Residual Surface-Fracture Frequency Distribution	983 (43.94%)	314 (62.93%)	416 (42.32%)	0.4322	2	1
Surface Fracture Orientation (Rose Diagrams)	378 (16.90%)	128 (25.65%)	149 (39.42%)	0.5178	1	4
Surface Circular and Arcuate Features	436 (19.49%)	134 (26.85%)	176 (40.37%)	0.3776	4	3

Table 3-2 Comparison Between Surface Features and Subsurface Structural Lows

Potential Indicator	Number (Percentage) of Anomalous Sections Identified in Osage County	Number (Percentage) of 177 Subsurface Structural Lows Associated with Anomalous Sections	Number (Percentage) of Anomalous Sections Associated with 177 Subsurface Structural Lows	Correlation Factor	Rank of Correlation	Rank of Effectiveness
Local Residual	998	94	119	0.1905	4	3
Surface-Fracture Density Distribution	(44.61%)	(53.11%)	(11.92%)			
Local Residual	983	97	124	0.2472	3	2
Surface-Fracture Frequency Distribution	(43.94%)	(54.80%)	(12.61%)			
Surface Fracture Orientation (Rose Diagrams)	378 (16.90%)	41 (23.16%)	44 (11.64%)	0.3704	2	4
Surface Circular and Arcuate Features	436 (19.49%)	49 (27.68%)	59 (13.53%)	0.4202	1	1

4.0 A SYSTEMATIC METHODOLOGY FOR USING SURFACE FRACTURE MAPPING AND PATTERN ANALYSIS FOR HYDROCARBON

EXPLORATION

Generally, there are four basic steps in hydrocarbon exploration: (1) regional geologic reconnaissance and cursory appraisal of geomorphic features, (2) detailed geologic surface and subsurface mapping, (3) ground geophysical exploration supplemented, if warranted, with aerial geophysical surveys, and (4) actual drilling operations.²³ Because each succeeding step is more expensive than the preceding one, for economic reasons every available means should be employed to reduce the total exploration expenses without sacrificing efficiency or the accumulation of necessary geological data.

As part of steps (1) and (2), the success of surface fracture mapping and pattern analysis to infer subsurface structures may result in significant cost reductions in oil and gas exploration. Therefore, the following integrated procedure should be used to conduct surface fracture mapping and to perform fracture pattern analysis and interpretations for oil and gas exploration:

4.1 Acquisition and/or Generation of Satellite Images and Aerial Photographs

4.1.1 Acquisition and/or Generation of Landsat Images

Option 1. Black and White Landsat Images

Black and white satellite images for every part of the lower 48 states of the United States can be purchased from the U.S. Geological Survey (USGS). The images have a nominal size of 7.3 inches, and cover an area of 110 x 110 mi. Both film negatives and positives are available. This option is inexpensive and suitable for initial reconnaissance.

Option 2. Landsat Computer-Compatible Tapes (CCT)

Computer-compatible tapes containing satellite data for any part of the United States can be purchased from the USGS. After mathematical manipulations for color-contrast enhancements, the satellite data are processed to produce false-color composites (color satellite photos). This option requires special equipment and software for data processing and analysis. However, it provides better color satellite images for surface lineament and/or fracture mapping. It may also be directly used for petroleum exploration.³³

Option 3. SPOT Images

Compared to Landsat images, SPOT images have improved spatial resolutions. Further, SPOT imaging data can be purchased in floppy disk format and can be processed to produce stereo images. As a result, desktop computers can be used for processing the imaging data and better photogeological interpretation can be obtained using stereo images.^{30,32} Specially designed software is still required.

4.1.2 Acquisition of Aerial Photographs

Option 1. Black and White and Color Infrared from NHAP

Black and white and color infrared aerial photographs for any part of the lower 48 states, acquired by the National High Altitude Photography Program (NHAP), can be obtained from the USGS. With a scale of 1:80,000, a NHAP black and white aerial photograph has a ground coverage of 11 x 11 mi. A NHAP color infrared photograph has a scale of 1:58,000 and a ground coverage of 8 x 8 mi.

Option 2. Black and White and Color Infrared from NAPP

The National Aerial Photography Program (NAPP) provides both black and white and color infrared aerial photos with better spatial resolutions. With a scale of 1:40,000, a NAPP aerial photograph (black and white or color infrared) has a ground coverage of 5 x 5 mi. However, NAPP does not provide complete coverage of the lower 48 states. For example, the Black Mesa basin in northeast Arizona has not been completely covered by NAPP.

4.2 Interpretation of Satellite Images and Aerial Photographs for Surface Lineaments, Fracture Traces, and Circular and Arcuate Anomalies

4.2.1 Initial Mapping

Satellite images are first interpreted to identify major lineaments and circular and arcuate anomalies. Priority regions are then identified. After that, aerial photographs are interpreted for detailed mapping of surface fractures and circular and arcuate anomalies in one of those priority regions. Color Landsat images and/or aerial photos are generally required for effective interpretation of circular and arcuate features indicated by subtle tonal anomalies.

4.2.2 Fieldwork to Calibrate the Initial Mapping

The purpose of a field study is to determine the accuracy of satellite image and aerial photograph interpretations, as well as to obtain basic information of surface geological structures.

4.2.3 Final Interpretation of Satellite Images and Aerial Photographs to Map Surface Lineaments, Fracture Traces, and Circular and Arcuate Anomalies

Satellite images and aerial photographs are interpreted for detailed surface features in all the priority regions identified. The surface lineaments, fracture traces, and circular and arcuate anomalies in the areas adjacent to the priority regions may also be mapped to provide more complete pictures.

4.3 Surface Fracture Analysis for Delineating Subsurface Traps

4.3.1 Geological Analysis of Surface Major Lineaments

The purpose of a geological analysis of surface major lineaments is to identify the origin of the lineaments and to recognize the regional structural style (i.e., basement involved or detached). If they are found to truly reflect subsurface weakness zones or fault systems, the surface lineaments may have been the surface manifestation of the subsurface controlling mechanism for the formation of other geological features. In particular, subsurface traps are more likely to develop along surface major lineaments.

4.3.2 Geological and Statistical Analysis of Surface Fracture Traces

The goal of this geological analysis is to identify the origin of the surface fracture traces (regional or tectonic) and to aid in the interpretation of regional structural style. The analysis includes the construction of a rose diagram and a histogram of surface fracture orientation, and the screening of surface fracture traces based on orientation.

4.3.3 Mathematical Analysis of Surface Fracture Orientation

An appropriate scale (for example, section by section) is first selected. Surface lineaments and fractures traces are then truncated by section boundaries. Both a grand rose diagram and rose diagrams for all individual sections are constructed. A numerical value is generated for each section to quantify the irregularity of the corresponding rose diagram as compared to the grand rose diagram. After a cutoff value is selected, any section with a higher numerical value (i.e., a irregular rose diagram) is considered anomalous. All anomalous sections thus defined are identified as potential locations for subsurface structures.

4.3.4 Mathematical Analysis of Surface Fracture Frequency

Similar to the analysis of fracture orientation, the analysis of surface fracture frequency requires the selection of an appropriate scale, preferably the same as that for fracture orientation analysis (for example, section by section). A frequency number is first calculated for each subarea. Local averages are then calculated for larger subareas (for example, township by township). A local residual surface-fracture frequency distribution is created by subtracting the local means from the corresponding frequency distribution over the study region. All sections with positive local residual surface-fracture frequency values are identified as anomalous locations for potential subsurface structures.

4.3.5 Mathematical Analysis of Surface Fracture Density

Equivalent to the analysis of surface fracture frequency, the analysis of surface fracture density includes the calculation of total fracture length per unit area for each subarea (e.g., a section), the local averages in larger subareas (e.g., townships), and subsequently a local residual surface-fracture density distribution over the study area. Those subareas (sections) with positive local residual surface-fracture density values are identified as anomalous locations for potential subsurface structures.

4.3.6 Geological Interpretation of Surface Circular and Arcuate Features

Areas with surface circular and arcuate features are identified as anomalous locations. Understanding the surface and subsurface geology is essential to the interpretation of these surface features. Since surface circular and arcuate features are equally likely to overlie subsurface structural highs and lows, caution must be taken when they are applied analyses for exploration. Nevertheless, surface circular and arcuate features provide an additional criterion to increase the efficiency of delineating subsurface structures.

4.3.7 Identification and Ranking of Priority Locations

Five criteria have been established to define anomalous locations for potential subsurface structures. They are (1) surface major lineaments, (2) surface fracture orientation, (3) surface fracture frequency, (4) surface fracture density, and (5) surface circular and arcuate features. Any area indicated by any of these five criteria as anomalous is a priority location. An area indicated by all five criteria as anomalous is ranked as the most important priority location. All priority locations are ranked according to the number of criteria by which these priority locations are indicated.

4.4 Integration of Surface Fracture Analysis with Geochemical and Geophysical Analyses for Delineating Exploration Leads

The priority locations identified using surface fracture analysis provide important information for planning geochemical and/or geophysical surveys. Great care must be used if they are directly used as sites for exploratory drilling since the chance for these priority locations to overlie subsurface structures is far from 100% (it is about 40% in Osage County). However, the efficiency or reliability can be drastically improved when the priority locations defined by surface fracture analysis are integrated with the results from geochemical and geophysical surveys. The final results (prime potential locations) can be used as exploration leads for exploratory drilling.

The methodology presented in this section was based on the information obtained from a literature review and the case study conducted in Osage County, Oklahoma. In the next section, attempts are made to apply this methodology for oil and gas exploration in northeastern Arizona.

5.0 USE OF REMOTE SENSING DATA AND SURFACE FRACTURE ANALYSIS FOR OIL AND GAS EXPLORATION IN NORTHEASTERN ARIZONA

5.1 Introduction

The use of remote sensing data and surface fracture analysis as a tool for hydrocarbon exploration requires (1) an understanding of regional structural styles and basement structures, (2) a reliable mapping of surface lineaments, fracture traces, and circular and arcuate anomalies, and (3) geological and statistical analysis of the mapped surface features. The objective is to identify potential locations of subsurface hydrocarbon traps.

In this section, the methodology presented in the previous section is used to delineate priority locations for potential subsurface hydrocarbon traps in northeastern Arizona.

5.2 Study Areas

The investigation of surface lineaments mapped from monoclinial analysis and Landsat Imagery interpretation covers all of northeastern Arizona (Figure 5-1), ranging from the Mogollon Rim in the south to the Arizona-Utah border in the north, from the Kaibab Uplift in the west to the Arizona-New Mexico border in the east. This area comprises approximately 32,000 mi². Well-known physiographic and topographic features in this study area include the restricted Black Mesa basin, Defiance Uplift, Tyende Saddle, Piute Folds, Kaibito Saddle, Preston Bench, Cameron Bench, Echo Cliffs Uplift, Kaibab Uplift, and Little Colorado River.

The photogeological analysis was done on two separate areas (Figure 5-1). The smaller, westernmost area, commonly called the Cameron area, comprises roughly 775 mi² in Coconino County. The larger area includes the northern two-thirds of the restricted Black Mesa basin, the northern extension of the Black Mesa basin (Kaibito Saddle), and the Beautiful Valley in the east. This area comprises approximately 4950 mi² in parts of northern Apache and Navajo counties. It includes parts of Navajo and Hopi Indian reservations.

5.3 Structural Styles and Basement Structures in Northeastern Arizona

An understanding of regional structural styles and basement structures is fundamentally important to any exploration effort because different types of oil and gas trapping mechanism are associated with different structural styles.⁴⁴ Structural styles are classified as detached or basement involved. Basement-involved structural styles are further categorized as arches and

Figure 5-1 Aerial-Photo (Light Shading) and Landsat-Image (Dark Shading) Coverage Areas in Arizona

domes, compressional blocks, extensional blocks, and wrench faults. Salt domes, detached normal faults, and thrust-fold belts are types of detached structural styles.

Northeastern Arizona, located in the southwestern part of the Colorado Plateau, has been the focus of numerous geological investigations for hydrocarbon and other mineral potentials.⁴⁵⁻⁵⁰ The structural style of this region appears to be that of a basement-involved extensional fault block.⁵¹ Characterized by extensive extensional faulting, the Precambrian basement rocks in northeastern Arizona were exposed in the Grand Canyon area, Mogollon Rim, Four Corners area, and Defiance Uplift.^{49,51,52} Both northeast- and northwest-trending block faulting exists, with the northeast-southwest as the predominant orientation of the basement structural grains.⁴⁸

The basement-faulting period was followed by deposition, emergence, erosion, regional tilting, and basin formation during the Paleozoic and Mesozoic.⁴⁸ The basic structural grain of the formations formed during this relatively stable period is in a northwest-southeast direction, with a few exceptions oriented northeast-southwest.^{53,54} After that, the Laramide orogeny occurred across the region between the Cretaceous and Eocene causing massive folding, monoclinical flexuring, uplifting, and formation of the Black Mesa basin under compressive stress conditions.^{48,55} Laramide deformation reflects a north or northeast orientation, which may represent a reactivation of major Precambrian zones of weakness.^{49,55} The region is believed to have been subjected to tensional stress conditions from the Miocene up to recent time.⁵⁵

The Precambrian basement structures of northeastern Arizona have been investigated through outcrop observations, surface lineament analyses, gravity and aeromagnetic surveys, and surface monoclinial analyses.^{50,52-56} Figure 5-2 shows one interpretation of the basement faulting systems in northeastern Arizona, which was obtained through an integration of Landsat, gravity, thermal gradient, and aeromagnetic data.⁵⁰ The Precambrian basement rocks appear to be divided into regular, fault-bounded blocks, which trend predominantly northeast-southwest. The average width of these blocks is approximately 25 mi, and they tend to be truncated or terminated by north-south and northwest-southeast trending faults.^{50,53} In addition, there are three basement arching systems corresponding to three volcanic areas: San Francisco Mountains, Hopi Buttes, and White Mountains.⁵⁰

Many investigators have described basement control of Phanerozoic deformation in northeastern Arizona. In the Grand Canyon region, many basement faults have been reactivated many times, and propagated upward to the surface.^{55,56,58} Many of the major monoclines (e.g., Comb, Echo Cliffs, and Cow Spring monoclines) indeed are associated with faulting in the Precambrian basement.^{50,53} The monoclines in the region developed as a response to differential movements of basement blocks along high-angle faults.⁵³ In the eastern Grand Canyon region, all of the monoclines exposed to the crystalline basement are underlain by Precambrian normal faults.⁵⁷

Further evidence supporting the basement control of Phanerozoic structures in northeastern Arizona includes the alignment of many eruptive centers along major fault systems (i.e., Bright

Figure 5-2 Basement Fault Systems Interpreted from an Integration of Landsat and Geophysical Data in Northeastern Arizona⁵²

Angel and Mesa Butte fault systems) to the west of the study area⁵⁶ and of earthquake epicenters along major monoclines (e.g., Cow Spring monocline).⁵⁰

The extensively faulted basement, its control of Phanerozoic deformation, and the propagation of the basement fault systems to the surface indicate the applicability of lineament and fracture analysis to hydrocarbon exploration in northeastern Arizona.

5.4 Surface Lineament Analysis in Northeastern Arizona

This section reviews three previous studies on surface-lineament mapping from monoclinial analysis and from Landsat images. The consistencies and/or discrepancies among them are assessed, as is the significance of surface lineaments and surface fracture zones in hydrocarbon exploration in northeastern Arizona. Preliminary priority locations for potential oil and gas entrapment in northeastern Arizona are identified.

5.4.1 Monoclinial Analysis

Based on the hypothesis that monoclines within the Colorado Plateau developed as a response to differential movements of basement blocks along high-angle faults, one study showed that the surface monoclinial traces can be used as a guide to identify major fracture zones which are believed to divide the Colorado Plateau into blocks.⁵³ Surface fracture zones thus defined in the plateau are shown in Figure 5-3. A rose diagram of those fracture zones is given in Figure 5-4. One can see from Figures 5-3 and 5-4 that there are four preferred directions for the inferred fracture zones in the Colorado Plateau: N20°W, N55°W, N20°E, and N55°E. They are interpreted as the reflection of the Precambrian basement weakness zones in the Colorado Plateau.

The inferred surface fracture zones for a portion of the Colorado Plateau tectonic province of Arizona are shown in Figure 5-5, which was obtained by integrating monoclinial and aeromagnetic analysis.⁴³ The rose diagram of the inferred fracture zones in northeastern Arizona (Figure 5-6) indicates the consistency in trend between those within Arizona and those in the whole Colorado Plateau. The significance of the structural model derived from this study is discussed later.

5.4.2 Landsat Imagery Analysis

In addition to monoclinial analysis, Landsat images have also been used for mapping surface lineaments and other geological features in northeastern Arizona. A study showed that an integration of Landsat, gravity, and aeromagnetic data may result in a more realistic structural model of northeastern Arizona because these three types of data provide information for different parts of the earth crust: Landsat images to map surface lineaments, aeromagnetic data to detect basement structures, and gravity data to discern anomalies within sedimentary strata.⁵⁰ The surface lineaments interpreted from Landsat images in the study is shown in Figure 5-7; the

Figure 5-3 Inferred Fracture Zones from Monoclinical Traces in the Colorado Plateau ⁵³

Figure 5-4 Rose Diagram of the Inferred Fracture Zones in the Colorado Plateau

Figure 5-5 Inferred Fracture Zones from a Monoclinal Analysis in Northeastern Arizona⁵³

Figure 5-6 Rose Diagram of the Inferred Fracture Zones in Northeastern Arizona

Figure 5-7 Surface Lineaments Interpreted from Landsat Images in Northeastern Arizona⁵⁰

corresponding rose diagram is in Figure 5-8. The final Precambrian basement fault systems interpreted from this study and its corresponding rose diagram are shown in Figures 5-2 and 5-9, respectively. Figure 5-8 indicates that the surface lineaments mapped in the study consist of two major sets oriented northwest-southeast and northeast-southwest, and two minor sets orientated north-south and west-northwest-east-southeast. The basement faults in Figure 5-2, however, consist of only two sets oriented northwest-southeast and northeast-southwest, as indicated in Figure 5-9.

Mapping surface lineaments in Arizona using Landsat data was also reported in another study, in which Quaternary fractures were emphasized during image interpretation.⁵⁹ Surface lineaments for the whole state of Arizona were mapped. Figure 5-10 shows those in northeastern Arizona; Figure 5-11 shows the corresponding rose diagram. It can be clearly seen that the surface lineaments in northeastern Arizona mapped from this study consist of three sets oriented northwest-southeast, northeast-southwest, and north-south. No attempt was made to interpret the basement structures based on these surface lineaments since the emphasis of the study was on Quaternary fractures.

5.4.3 Comparisons and Discussions

A comparison of Figures 5-8 and 5-11 indicates that the surface lineaments mapped from the two Landsat image interpretations are very consistent in trend. Both figures portray almost

Figure 5-8 Rose Diagram of the Surface Lineaments (in Figure 51) Interpreted from Landsat Images in Northeastern Arizona

Figure 5-9 Rose Diagram of the Basement Faults in Northeastern Arizona

Figure 5-10 Surface Lineaments with Emphasis on Quaternary Fractures Interpreted From Landsat Images⁵⁹

Figure 5-11 Rose Diagram of the Surface Lineaments Interpreted from Landsat Images with Emphasis on Quaternary Fractures

identical structural grains (i.e., northeast-southwest, north-south, northwest-southeast) although the density of lineaments mapped from these two studies is quite different, as can be seen by comparing Figures 5-7 and 5-10. This discrepancy in density can be explained by the fact that the objective of the first lineament study (Figure 5-7) was to detect basement weakness zones or fault systems, whereas that of the second lineament study (Figure 5-10) was to map Quaternary fractures. Both lineament studies appear to support the interpretation of the basement fault systems given in Figure 5-2.

A comparison of Figures 5-6 and 5-8 shows that both the surface fracture zones identified from the monoclinial analysis and the surface lineaments mapped from a Landsat image interpretation consist of four sets with northeast-southwest and northwest-southeast as the two primary orientations. The two minor sets from these two studies, however, differ slightly in orientation.

In summary, both monoclinial and lineament analyses, as well as gravity and aeromagnetic data, indicates the validity of the basement fault systems given in Figures 5-2, with northeast-southwest and northwest-southeast as the two basic basement structural grains. Additional minor basement fault systems may also exist, but they are probably less significant. Therefore, a combination of the basement fault systems interpreted from Landsat and geophysical data (Figure 5-2) and the surface fracture zones interpreted from monoclinial analysis (Figure 5-5) may provide a realistic and more detailed representation of the internal structures of the earth crust rocks in northeastern Arizona. The overlap of the basement fault systems and the surface fracture zones is shown in Figure 5-12.

Figure 5-12 **Overlap of the Surface Fracture Zones (Dark Lines) Interpreted from Monoclinial Analysis and the Basement Fault Systems (Light Lines) Interpreted from An Integration of Landsat and Geophysical Data in Northeastern Arizona**

5.4.4 Significance of Surface Fracture Zones and Basement Fault Systems for Oil and Gas Exploration in Northeastern Arizona

Figure 5-13 shows the relationship of the surface major fracture zones inferred from a monoclinial analysis to the distribution of the oil and gas pools and salt anticlines in the Colorado Plateau.⁵³ Oil and gas pools are shown in black. Patterned areas are salt anticlines. Circled numbers represent the following oil and gas pools:⁵³

- 1) McElmo Dome
- 2) Tohonadla
- 3) Gothic Mesa
- 4) Aneth
- 5) Andy's Mesa
- 6) SE Lisbon
- 7) Big Flat
- 8) Big Indian
- 9) Lisbon
- 10) Tocito Dome
- 11) Table Mesa
- 12) Rattlesnake
- 13) Hogback
- 14) Horseshoe Canyon
- 15) Many Rocks
- 16) Bisti
- 17) Escrito
- 18) Dineh-bi-Keyah
- 19) Bita Peak, Teec Nos Pos, Twin Falls Creek
- 20) East Boundary Butte, North Toh-Atin
- 21) Dry Mesa, Black Rock

Figure 5-13 shows that (1) all the salt anticlines and many of the oil and gas pools are oriented in northwest-southeast, parallel to one of the surface fracture-zone systems, (2) some of the salt anticlines and many of the oil and gas pools lie along or at the intersections of the surface fracture zones, and (3) virtually all of the oil and gas pools in Arizona are positioned on the traces of the surface fracture zones. These observations tend to confirm the hypothesis that

Figure 5-13 Relationship of the Inferred Fracture Zones to the Distribution of Oil and Gas Pools and Salt Anticlines in the Colorado Plateau

surface fracture zones and/or basement fault systems, as loci of major fracturing, folding, and rapid facies changes, exert some control on the entrapment of oil and gas.

On the premise that this hypothesis is true in the San Juan and Paradox basins (including the extreme northeastern corner of Arizona), it is not unreasonable to postulate that oil and gas pools in the rest of northeastern Arizona, if they exist, are likely to be located along the surface fracture zones and/or the basement fault traces. In other words, there is a better chance of striking subsurface structures (i.e., traps) along these surface fracture zones and/or basement fault traces than elsewhere. Therefore, the surface fracture zones and subsurface basement fault systems, as shown in Figure 5-12, can be used as a guide for oil and gas exploration in the region.

5.4.5 Priority Locations for Potential Oil and Gas Traps in Northeastern Arizona Based on Surface Lineament Analysis

Hydrocarbon production in Arizona is currently confined to the Arizona part of the Four Corners area (i.e., extreme northeastern Arizona). As an element of a basin analysis project, the objective of this study is to provide priority locations for potential exploratory drilling and/or further geophysical and geochemical investigations beyond the Four Corners area into the general Black Mesa basin region.

The relationship of the surface fracture zones to the oil and gas pools in the San Juan and Paradox basins (Figure 5-13) suggests that the fracture zones in northeastern Arizona shown in

Figure 5-5 could be used to identify additional oil and gas traps. On the other hand, the basement fault systems, shown in Figure 5-2 and obtained from an integration of Landsat and geophysical data, may provide a more detailed description of Phanerozoic structures in the region. Figure 5-12 shows that only a few surface fracture zones coincide in position with basement faults, although they are generally consistent in orientation. To investigate their relative effectiveness, the surface fracture zones and the basement fault systems were compared with some of the well locations with oil shows identified in northeastern Arizona.

Figure 5-14 shows a distribution of oil shows in northeastern Arizona. Many of the oil shows within the Four Corners area are actual producing wells, whereas no commercial production has been reported in the rest of the region. Although not prominent, those oil shows in the south part of the study area seem to follow a weak trend oriented northwest-southeast; those in the north central part of the study area appear to follow a trend oriented northeast-southwest. These two trends are parallel to the principal orientations of the surface fracture zones and the basement fault systems. However, more data are needed to confirm this observation.

Figure 5-15 shows the relationship of the oil shows to the surface fracture zones inferred from a monoclinical analysis. Of 88 oil shows in the region, 20 of them appear to lie along those fracture zones. Similarly, the relationship of the oil shows to the basement fault traces interpreted from an integration of Landsat and geophysical data is depicted in Figure 5-16. It appears that 31 of the 88 oil shows are positioned along the basement fault traces. The basement fault systems have a better correlation with the oil shows than the surface fracture zones, although the total

Figure 5-14 Locations of Oil Shows in Northeastern Arizona

Figure 5-15 Relationship of Oil Shows (Squares) to Surface Fracture Zones in Northeastern Arizona

Figure 5-16 Relationship of Oil Shows (Squares) to Basement Fault Systems in Northeastern Arizona

Figure 5-17 Well Locations with Oil Shows (Squares) on the Overlap Map of Basement Fault Systems (Light Lines) and Surface Fracture Zones (Dark Lines) in Northeastern Arizona

length of the basement fault traces is larger than that of the surface fracture zones. This study suggests, therefore, that a combination of the surface fracture zones and the basement fault systems (Figures 5-12 or 5-17) be used to infer subsurface oil and gas traps. That is, as the first step in hydrocarbon exploration in northeastern Arizona, exploratory drilling should be located and/or geophysical and geochemical surveys conducted along (or across) these surface fracture zones and basement fault systems.

To further pinpoint the priority locations of potential subsurface oil and gas traps, small-scale surface fracture traces and surface drainage patterns discernible from aerial photographs should be analyzed. The analysis of the small-scale surface fracture traces in northeastern Arizona is discussed in the following section.

5.5 Analysis of Surface Fracture Traces in Northeastern Arizona

The analysis of surface-fracture traces involved photogeological interpretation of surface fracture traces and circular and arcuate anomalies from aerial photographs, and geological and mathematical analysis of these surface features. The objectives were to provide additional information for constructing a more realistic structural model and to identify more detailed anomalous locations of potential subsurface oil and gas traps in northeastern Arizona.

5.5.1 Photogeological Study

The photogeological study included two separate areas: the Cameron area and the Black Mesa basin area (Figure 5-1). Aerial photographs used in this study were purchased from the U.S. Geological Survey (USGS). They are high-altitude, false-color infrared photographs taken from aircraft flown during 1980 -1985 as part of the National High Altitude Photography program (NHAP). Forty such 9 x 9 in aerial photographs were acquired to cover the Cameron area. Another 154 were acquired to cover the Black Mesa basin area. The scale of these photographs is supposed to be 1:58,000. However, the actual scale ranges from about 1:62,000 to slightly less than 1:60,000. This scale discrepancy created minor problems for photogeological interpretation and map compilation. Some difficulty was experienced during stereoscopic viewing because overlapping aerial photographs in some flight lines were exposed on different dates and at slightly different scales. Overall, however, the NHAP color-infrared photographs were very well suited to mapping fracture traces in this desert environment. The special properties of the false-color infrared photography enhanced expression of vegetation-highlighted fracture traces, and the fine-grained quality of the color photographs emphasized even the smallest details, especially given the small scale of the photographs.

Fractures, faults, linears, curvilinear lines, drainage, and culture were annotated stereoscopically on clearfilm overlays of the aerial photographs using a pocket and/or a mirror-type reflecting stereoscope. The 3x magnification of the instruments allowed very accurate and detailed delineation of even the faintest fracture traces. Detailed drainage patterns were also mapped.

The photograph data were compiled to base maps by first determining average photo scale along flight lines for each base map area. Then, Xerox enlargements of the 1:100,000 scale USGS topographic base maps were made at the average photo scales, facilitating and simplifying the transfer of photo data by tracing annotations from the photo overlays directly onto the enlarged 1° x 30' quadrangles.

The recognition of surface fracture traces on aerial photographs was based on the following criteria:

- Visual identification of actual crevices in the rock outcrops
- Alignments of vegetation growing in erosion-widened fractures
- Straight-line drainage segments initially formed and controlled by fractures in the bedrock surface
- Straight-line tonal or color changes in surface soils and rocks
- Locations of dikes of igneous rock injected into the weak zones in the host rock caused by fractures and faults
- Straight cliff edges

The surface fracture traces in northeastern Arizona were created by many different mechanisms and at various times. Some deep-seated stress system is believed to be responsible for the final

gross fracture patterns. It is those surface fractures which originated from deep formations that may bear significance for inferring subsurface oil and gas traps.

5.5.2 Digitization of Surface-Fracture Traces

The surface fracture traces mapped from the photogeological interpretation in the Black Mesa basin and Cameron areas were subsequently digitized for further geological and mathematical analyses. A computer program was developed for the specific purpose of digitizing surface fracture traces and other linear features. Written in QBasic, the program automatically stores the coordinates of the two end points for an individual fracture trace from a digitizing board as soon as a stylus is pressed. In total, 37,914 surface fracture traces were digitized in the Black Mesa basin area, and 6,104 in the Cameron area.

Figure 5-18 shows the 37,914 surface-fracture traces mapped in the Black Mesa basin area. Individual fracture traces can not be seen clearly due to the small scale (approximately 1:820,000). In general, fractures are better exposed in the northern and central parts of this study area. A few of northeast-trending blank strips, visible across the area, are apparently caused by alluvium coverage associated with washes and valleys (from west to east, they correspond to Klethla Valley and Long House Valley, Moenkopi Wash, Dinnebito Wash, Oraibi Wash, Wepo Wash, Polacca Wash, Chinle Wash, and Nazlini Wash). Additional areas of sparse surface

Figure 5-18 The 37,914 Surface-Fracture Traces in the Black Mesa Basin Area (Approximate Scale: 1:820,000)

Figure 5-19 The 6,104 Surface-Fracture Traces in the Cameron Area (Approximate Scale 1:290,000)

fracture traces in the west, southwest, southeast, and northeast of the study area are due to sand-dune coverage.

The 6,104 surface-fracture traces mapped in the Cameron area are shown in Figure 5-19. More surface fractures and faults were observed in the northwestern than in the southeastern half of the area. Blank patches in the southwest and south-central are due to coverage by lava flows. The scarcity of surface fractures in the east is largely due to sand coverage associated with the Painted Desert. A small blank area in the northwest reflects cultivation activities. Part of the blank areas in the east and northwest is also due to alluvium coverage associated with the Little Colorado River, which runs across the area from southeast to northwest. The extensiveness of lava flows, faulting, and fracturing reveals the active tectonic history of the area.

5.5.3 Orientation Analysis of Surface-Fracture Traces

A composite rose diagram for the total 44,018 surface-fracture traces mapped in the Black Mesa basin and Cameron areas is shown in Figure 5-20. The surface fracture traces consist of roughly four sets: northwest, north, northeast, and east-northeast. The north-trending set appears to be the most prominent. A comparison of Figure 5-20 to Figures 5-8 and 5-11 shows that the surface-fracture traces in the Black Mesa basin and Cameron areas and the surface lineaments in the whole northeastern Arizona are essentially consistent in orientation. Both surface fracture

Figure 5-20 Composite Rose Diagram of the 44,018 Surface-Fracture Traces Mapped in the Black Mesa Basain Area and Cameron Area

traces and surface lineaments have northwest, north, and northeast as the three fundamental structural grains.

However, the rose diagrams for the surface-fracture traces and surface lineaments are far from being identical. In Figure 5-8, there is a minor set of surface lineaments oriented west-northwest. There is also a minor set of surface fracture traces (Figure 5-20), but it trends east-northeast. This discrepancy is not significant because only small percentages of the total surface lineaments and surface-fracture traces fall into these two minor sets. A more prominent discrepancy occurs in the general shapes of these rose diagrams. Figures 5-8 and 5-11 show that the northwest- and northeast-trending sets are the two primary sets for the surface lineaments, with the north- and west-northwest-trending sets as the secondary sets. The surface-fracture traces (Figure 5-20), however, have the north-trending set as the primary and the northwest- and northeast-trending sets as the secondary. This difference may be explained by the fact that surface lineaments are more likely to reflect tectonic activities that originated from basement and/or other deep zones, whereas surface fracture traces are more likely to have resulted from more recent tectonic events. If this is true, the rose diagram of the surface lineaments (Figures 5-8 and 5-11) will depict the structural grains of the basement, whereas that of the surface-fracture traces (Figure 5-20) provides a composite profile of both basement and surface structural grains as some of those basement structures propagate to the surface. This explanation is consistent with the discussion of the basement structures in the previous sections.

Figure 5-21 Rose Diagram of the 37,914 Surface-Fracture Traces in the Black Mesa Basin Area

On the other hand, Figure 5-20 could also imply that there is a significant set of basement fault system oriented north-south in northeastern Arizona. This set apparently has not been identified in various gravity and aeromagnetic investigations. More data are required to confirm this postulation.

Figure 5-21 is the rose diagram of the 37,914 surface-fracture traces mapped in the Black Mesa basin area. It is almost identical to the composite rose diagram (Figure 5-20). Similarly, a rose diagram also was generated for the 6,104 surface-fracture traces mapped in the Cameron area (Figure 5-22). Different from the composite rose diagram (Figure 5-20), Figure 5-22 indicates that the surface-fracture traces in the Cameron area consist of only two sets oriented north-south and northeast-southeast. This orientation anomaly is caused by extensive wrench faulting in the Cameron area.

Figure 5-22 Rose Diagram of the 6,104 Surface-Fracture Traces in the Cameron Area

6.0 CONCLUSIONS AND RECOMMENDATIONS

A combination of Landsat data, aerial photos, and field study presents a cost-effective approach for mapping surface lineaments, fracture traces, and circular and arcuate anomalies. The correlation between surface fracture system and subsurface geological features, as observed by many investigators from both engineering and outcrop studies, provides a foundation for using surface fracture analysis for delineating subsurface oil and gas traps. An integration of geological and mathematical analysis is the key in developing a systematic methodology of using surface fracture information for hydrocarbon exploration.

The case study in Osage County, Oklahoma, provided irrefutable evidence to the applicability of surface fracture analysis for hydrocarbon exploration. A strong correlation in both orientation and position was observed between surface lineaments and subsurface structural traps. Although a similar relationship appears to exist between surface lineaments and subsurface stratigraphic traps, surface fracture analysis is more effective for detecting subsurface structural traps than stratigraphic traps. Surface lineaments can be used as a general guide in selecting the locations for further geochemical and/or geophysical surveys, as well as for exploratory drilling when other information is not available.

Surface fracture characteristics (namely orientation, frequency, and density) are associated with subsurface structural complications. They can be used as indicators for identifying the potential locations for subsurface structures. The success rate of using these indicators in delineating subsurface structures is approximately 40% in Osage County, Oklahoma.

Surface circular and arcuate anomalies are equally associated with both subsurface structural highs and lows. As a result, surface circular and arcuate features may not be as effective as the surface fracture characteristics (orientation, frequency, and density) in locating subsurface structural traps. However, these surface circular and arcuate features are more effective than surface fracture characteristics in searching for subsurface stratigraphic traps.

A systematic methodology can be employed for using remote-sensing information to map surface geological features, and for using surface fracture analysis as a cost-effective tool in hydrocarbon exploration. Five quantitative criteria are identified in using surface lineaments, surface fracture characteristics (orientation, frequency, and density), and surface circular and arcuate features for identifying potential locations of subsurface hydrocarbon traps. The methodology was used to delineate additional oil and gas traps in Osage County, Oklahoma.

The methodology was also applied to oil and gas exploration in northeastern Arizona. A geological analysis revealed that the structural style of northeastern Arizona is that of basement-involved extensional fault blocks, and the Precambrian basement rocks are divided into regular blocks bounded by northeast- and northwest-trending fault systems. in the photogeological

study conducted in the Black Mesa basin area and the Cameron area. over 44,000 surface fracture traces were mapped from color-infrared aerial photographs. An orientation analysis of the surface fracture traces and the surface lineaments indicates that the basic structural grains of northeastern Arizona consist of three major components trending northwest, north, and northeast. The analysis performed of the surface lineaments, surface fracture zones, and basement fault systems in northeastern Arizona indicates a subtle relationship between the oil shows and the surface fracture zones and basement fault systems in the region. This study suggests that a combination of the surface fracture zones and basement fault systems be used as a guide for oil and gas exploration in northeastern Arizona. Areas along any of the surface fracture zones and/or the basement fault traces are priority locations for potential subsurface hydrocarbon accumulations. Particularly, attention should be given to those areas of multiple intersections of the surface fracture zones and basement fault systems in the region.

The characteristics, such as frequency, density, and orientation, of the surface fracture traces in northeastern Arizona need to be analyzed. Locations of high residual frequency, high residual density, and anomalous rose diagrams should be identified as potential positions for subsurface oil and gas traps. In addition, a few circular anomalies mapped from aerial photographs in the Black Mesa basin area and the Cameron area need to be analyzed to investigate their significance for oil and gas exploration in the corresponding areas. Because surface drainage systems in the Black Mesa basin area and the Cameron area have been mapped from aerial photographs, a drainage pattern analysis is recommended to identify the locations of surface and subsurface structures.

The methodology and techniques presented in this study were developed in the geological environment of Osage County, Oklahoma. They are applicable to regions of similar structural styles (basement-involved styles and shallow reservoir potentials). Surface fracture mapping and pattern analysis are not the entire answer to the problems of hydrocarbon exploration, but they constitute an important element of information and techniques to be coupled with other technologies to increase exploration efficiency.

7.0 REFERENCES

- 1) Blanchet, P.H., 1957. Development of Fracture Analysis as Exploration Method, *AAPG Bulletin*. 41(8): 1748-59.
- 2) Stearns, D.W., and M. Friedman, 1972. Reservoirs in Fractured Rocks. *AAPG. Memoir* 16: 82-100.
- 3) Hodgson, R.A., 1961. Regional Study of Jointing in Comb Ridge-Navajo Mountain Area, Arizona and Utah. *AAPG Bulletin*. 45(1).
- 4) Hodgson, R.A., 1965. Genetic and Geometric Relations Between Structures in Basement and Overlying Sedimentary rocks, with Examples from Colorado Plateau and Wyoming. *AAPG Bulletin*. 49(7): 935-49.
- 5) Kelley, V.C., and N.J. Clinton, 1960. *Fracture Systems and Tectonic Elements of the Colorado Plateau*. University of New Mexico Publications in Geology, Number 6, University of New Mexico Press, Albuquerque.
- 6) Nickelsen, R.P., and V.D. Hough, 1967. Jointing in the Appalachian Plateau of Pennsylvania. *Geological Society of American Bulletin*, Vol. 78: 609-30.
- 7) Rumsey, I.A.P., 1971. Relationship of Fractures in Unconsolidated Superficial Deposits to Those in the Underlying Bedrock. *Modern Geology*. Vol. 3: 25-41.
- 8) Lorenz, J.C., L.W. Teufel, and N.R. Warpinski, 1991. Regional Fractures I: A Mechanism for the Formation of Regional Fractures at Depth in Flat-Lying Reservoirs. *AAPG Bulletin*. 75(11): 1714-37.
- 9) Lorenz, J.C., and S.J. Finley, 1991. Regional Fractures II: Fracturing of Mesaverde Reservoirs in the Piceance Basin, Colorado. *AAPG Bulletin*. 75(11): 1738-57.
- 10) Merin, I.S., and W.R. Moore, 1986. Application of Landsat Imagery to Oil Exploration in Niobrara Formation, Denver Basin, Wyoming. *AAPG Bulletin*. 70(4): 351-59.
- 11) Hagen, K.B., 1972. *Mapping of Surface Joints on Air Photos can Help Understand Waterflood Performance Problems at North Burbank Unit, Osage and Kay Counties, Oklahoma*. M.S. Thesis, The University of Tulsa, Tulsa, Oklahoma.
- 12) Alpay, O.A., 1969. Application of Aerial Photographic Interpretation to the Study of Reservoir Natural Fracture Systems. SPE 2567, presented at the 44th Annual Fall Meeting of the Society of Petroleum Engineers of AIME, Denver, Colorado, September 28-October 1.

REFERENCES

- 13) Overbey, W.K., Jr., and R.L. Rough, 1968, Surface Studies Predict Orientation of Induced Formation Fractures. *Producers Monthly*. 32(16).
- 14) Overbey, W.K., Jr., and R.L. Rough, 1971. *Prediction of Oil- and Gas-Bearing Rock Fractures From Surface Structural Features*. Report of Investigations 7500. Bureau of Mines, United States Department of the Interior.
- 15) 1984. *Assessment of the Oil and Gas Potential of Osage County, Oklahoma Based on Remote Sensing*. Osage Tribal Council, Pawhuska, Oklahoma.
- 16) Halbouty, M.T., 1980. Geologic Significance of Landsat Data for 15 Giant Oil and Gas Fields. *AAPG Bulletin*. 64(1): 8-36.
- 17) Podwysocki, M.H., 1974. *An Analysis of Fracture Trace Patterns in Areas of Flat-Lying Sedimentary Rocks for the Detection of Buried Geologic Structure*. Report X-923-74-200. Goddard Space Flight Center, Greenbelt, Maryland.
- 18) Peterson, R., 1979. Oil and Gas Exploration by Pattern Recognition of Lineament Assemblages Associated with Bends in Wrench Faults. Proceedings of the Thirteenth International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, April 23-27, Vol. 2: 993-1014.
- 19) Haman, P., 1964. *Geomechanics Applied to Fracture Analysis on Aerial Photographs*, West Canadian Research Publications of Geology and Related Sciences. Number 2, Calgary, Canada.
- 20) Collins, R.J., F.P. McCown, L.P. Stonis, G.J. Petzel, and J.R. Everett, 1974. *An Evaluation of the Suitability of ERTS Data for the Purposes of Petroleum Exploration*. Report E74-10704, CR-139433, Goddard Space Flight Center, Greenbelt, Maryland.
- 21) Huntington, J.F., 1969. Methods and Applications of Fracture Trace Analysis in the Quantification of Structural Geology. *Geological Magazine*. 106(5): 430-51.
- 22) Rumsey, I.A.P. and R.H. Gelnett, 1976. Airborne Radar Finds Deep Fracture Controlled Pools. *World Oil*. 182(1): 115.
- 23) Halbouty, M.T., 1976. Application of Landsat Imagery to Petroleum and Mineral Exploration. *AAPG Bulletin*. 60(5): 745-93.
- 24) Berger, Z., T.H. Lee Williams, and D.W. Anderson, 1992. Geologic Stereo Mapping of Geologic Structures with SPOT Satellite Data. *AAPG Bulletin*. 76(1): 101-20.
- 25) Wessel, G.R., 1993. Geologic Stereo Mapping of Geologic Structures with SPOT Satellite Data: Discussion. *AAPG Bulletin*. 77(4): 660-1.
- 26) Lang, H.R., S.L. Adams, J.E. Conel, B.A. McGuffie, E.D. Paylor, and R.E. Walker, 1987. Multi-spectral Remote Sensing as Stratigraphic and Structural Tool, Wind River Basin and Big Horn Basin Areas, Wyoming. *AAPG Bulletin*. 71(4): 389-402.

- 27) Sabins, F.F., Jr., 1987. *Remote Sensing: Principles and Interpretation*. Second Edition, W.H. Freeman and Company, New York, Chapter 8 (Resource Exploration).
- 28) Johnsgard, S.K., 1988. *The Fracture Pattern of North-Central Kansas and Its Relation to Hydrocarbon Soil Gas Anomalies over the Midcontinent Rift System*. M.S. Thesis, The University of Kansas, Kansas Geological Survey Open-File Report # 88-25.
- 29) Vixø, D.L., and J.G. Bryan, 1984. Reconnaissance Hydrocarbon Prospect Generation with Integrated Potential Field and Remotely Sensed Data, Southern Illinois Basin. Presented at the International Symposium on Remote Sensing of Environment, Third Thematic Conference, Remote Sensing for Exploration Geology, Colorado Spring, Colorado, April 16-19.
- 30) Welch, R., 1989. Desktop Mapping with Personal Computers. *Photogrammetric Engineering and Remote Sensing*, 55(11): 1651-62.
- 31) Quillin, M.E., 1983. *A Statistical Study of Fracture Orientation and Spacing on The East Kaibab Monocline, Arizona*. Master's Thesis, University of Oklahoma, Norman, Oklahoma.
- 32) Berger, Z., 1994. *Satellite Hydrocarbon Exploration, Interpretation and Integration Techniques*. Berlin Springer-Verlag.
- 33) Sundberg, K.R., 1990. Multispectral Imagery (LANDSAT) Hydrocarbon Alteration Signature: Definition of the Signature Based on Studies of Probable Hydrocarbon Microseepage in the United States Mid-Continent. *Association of Petroleum Geochemical Explorationists Bulletin* 6.
- 34) McCoy, R.M., K. Clem, and M.J. Havertz, 1986. Lineaments, Fractures, and Surface Geochemical Surveys Applied to Well Site Evaluation in the Altamont-Bluebell Field, Uinta Basin, Utah. *Association of Petroleum Geochemical Explorationists Bulletin*. 2(1).
- 35) Havertz, M.J., and R.M. McCoy, 1985. Combining Remote Sensing and Geochemistry to Estimate Oil Production in the Uinta Basin. *Association of Petroleum Geochemical Explorationists Bulletin*. 1(1).
- 36) Morgan, K., D. Koger, and D. Dees, 1986. Landsat Image Enhancement for Tonal Anomalies. *Association of Petroleum Geochemical Explorationists Bulletin*. 2(1).
- 37) Bass, N.W., 1942. Subsurface Geology and Oil and Gas Resources of Osage County, Oklahoma, Part 11. Summary of Subsurface Geology with Special Reference to Oil and Gas. *U.S. Geological Survey Bulletin* 900-K.
- 38) Denison, R.E., 1981. *Basement Rocks in Northeastern Oklahoma*. Oklahoma Geological Survey, Circular 84.

REFERENCES

- 39) Luza, K.V., and J.E. Lawson, Jr. 1982. *Seismicity and Tectonic Relationships of the Nemaha Uplift in Oklahoma, Part IV*. Oklahoma Geological Survey Special Publication 82-1.
- 40) Wagner, O.E., Jr., and J. Maruchek, 1983. *Maps of Osage County, Oklahoma*. United States Department of the Interior. Bureau of Indian Affairs, Map-1 to Map-17.
- 41) Havertz, M.J., and R.M. McCoy, 1985. Combining Remote Sensing and Geochemistry to Estimate Oil Production in the Uinta Basin. *Association of Petroleum Geochemical Explorationists Bulletin*. 1(1).
- 42) White, D., et al. 1922, *Structures and Oil and Gas Resources of the Osage Reservation, Oklahoma*. United States Geological Survey Bulletin 686.
- 43) Friedman, M., and D.E. McKiernan, 1994. Extrapolation of Fracture Data From Outcrops of the Austin Chalk in Texas to Corresponding Petroleum Reservoirs at Depth. HWC94-36, presented at the Canadian SPE/CIM/CANMET International Conference on Recent Advances in Horizontal Well Applications, Calgary, Canada. March 20-23.
- 44) Berger, Z. 1994. *Satellite Hydrocarbon Exploration, Interpretation and Integration Techniques*. Berlin: Springer-Verlag.
- 45) Holm, D.A. 1938. *Report on The Oil Possibilities of Arizona*. Phoenix, Arizona: Arizona State Land Department.
- 46) Arizona Development Board. 1961. *Oil, Gas and Helium in Arizona, Its Occurrence and Potential*. Arizona Oil and Gas Conservation Commission.
- 47) Pye, W.D. 1967. Arizona: A New Exploration Frontier. *Oil & Gas Journal*, May 8, 1967.
- 48) Pierce, H.W., S.B. Keith, and J.C. Wilt, 1970. *Coal, Oil, Natural Gas, Helium and Uranium in Arizona*. The Arizona Bureau of Mines Bulletin 182.
- 49) Turner, D.S. 1968. Natural Gas in Black Mesa Basin, Northeastern Arizona. *AAPG Memoir* 9. V. 2, 3357-1370.
- 50) Gutman, S.I., and G.A. Heckmann, 1977. *An Integration of Landsat and Geophysical Data in Northeastern Arizona*. Report of Work Performed Under USGS Contract Number 94599 for United States Geological Survey.
- 51) Reeves, T.K. In Press. *A Review of History of and Future Potential for Exploratory Drilling for Oil and Gas in the Black Mesa Basin*. Bartlesville, Oklahoma: BDM-Oklahoma.
- 52) Werme, D.R., 1981. *Precambrian Geology of the Defiance Uplift, Arizona*, M.S. Thesis, Northern Arizona University, Flagstaff, Arizona
- 53) Davis, G.H. 1975. *Tectonic Analysis of Folds in the Colorado Plateau of Arizona*. University of Arizona, OALS Bulletin 9.

- 54) Jenkins, R.D., and G.R. Keller, 1989. Interpretation of Basement Structures and Geophysical Anomalies in the Southeastern Colorado Plateau. *New Mexico Geological Society Guidebook, 40th Field Conference, Southeastern Colorado Plateau*. 135-42.
- 55) Lucchitta, I. 1978. *Basement Control of Structural Features Near the Boundaries of the Colorado Plateau in Arizona*. Basement Tectonic Contribution 46. 3rd International Conference on Basement Tectonics, Durango, Colorado.
- 56) Shoemaker, E.M., R.L. Squires, and M.J. Abrams, *Bright Angel and Mesa Butte Fault Systems of Northern Arizona*. Geological Society of America. Memoir 152: 341-67.
- 57) Huntoon, P.W. 1981. Grand Canyon Monoclines: Vertical Uplift or Horizontal Compression? *University of Wyoming Contributions to Geology*. 19(2): 127-34.
- 58) Hodgson, R.A. 1965. Genetic and Geometric Relations Between Structures in Basement and Overlying Sedimentary Rocks, with Examples from Colorado Plateau and Wyoming. *AAPG Bulletin*. 49(7): 935-49.
- 59) Lepley, L.K. 1977. *Landsat Lineament Map of Arizona with Emphasis on Quaternary Fractures*. University of Arizona Bureau of Geology and Mineral Technology Open-File Report 77-2.