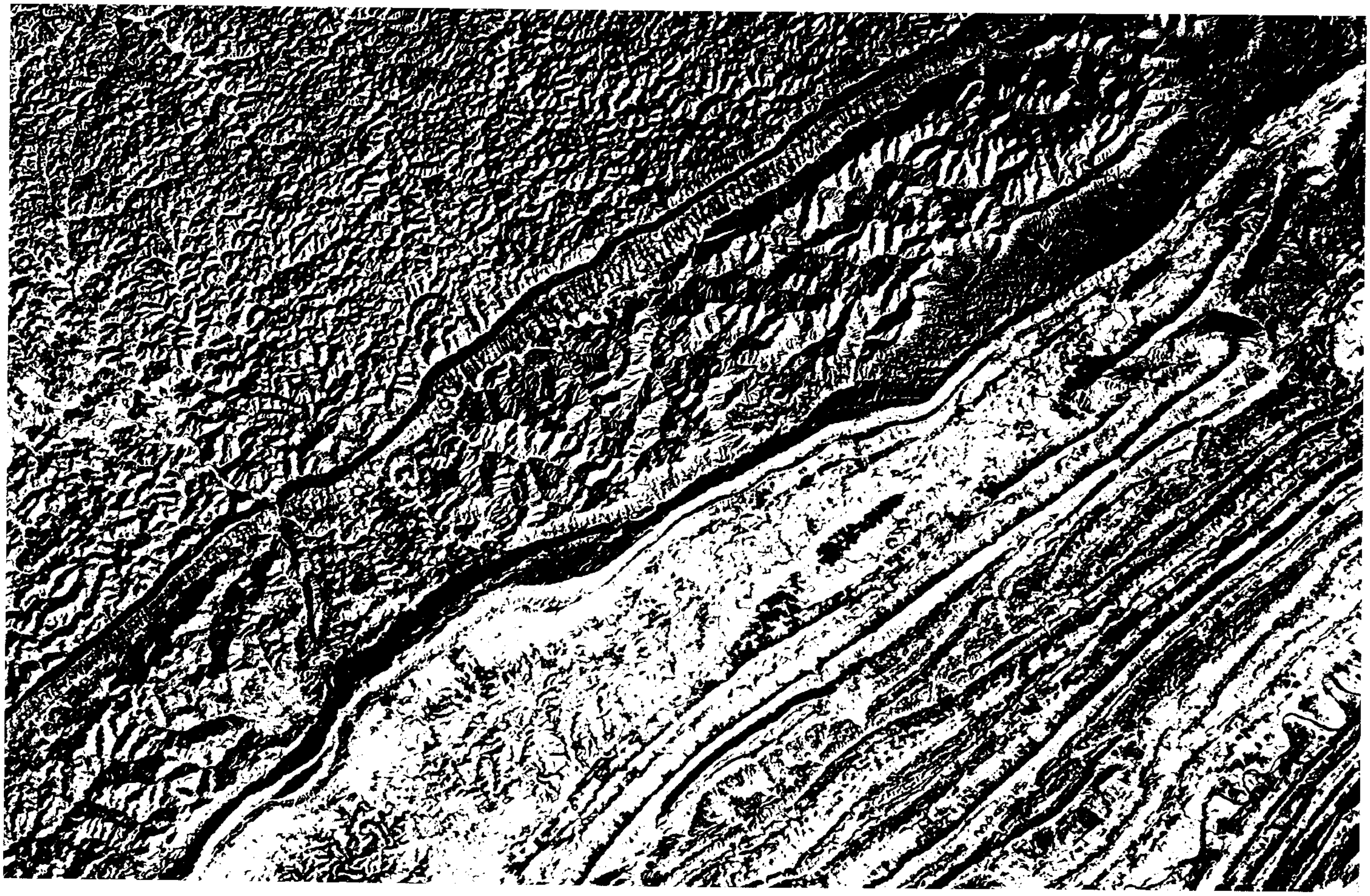
VIRGINIA DIVISION OF MINERAL RESOURCES PUBLICATION 28

LINEAMENT AND FRACTURE TRACE ANALYSIS AND ITS APPLICATION TO OIL EXPLORATION IN LEE COUNTY, VIRGINIA

THOMAS M. GATHRIGHT, II



COMMONWEALTH OF VIRGINIA
DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT
DIVISION OF MINERAL RESOURCES

Robert C. Milici, Commissioner of Mineral Resources and State Geologist

CHARLOTTESVILLE, VIRGINIA

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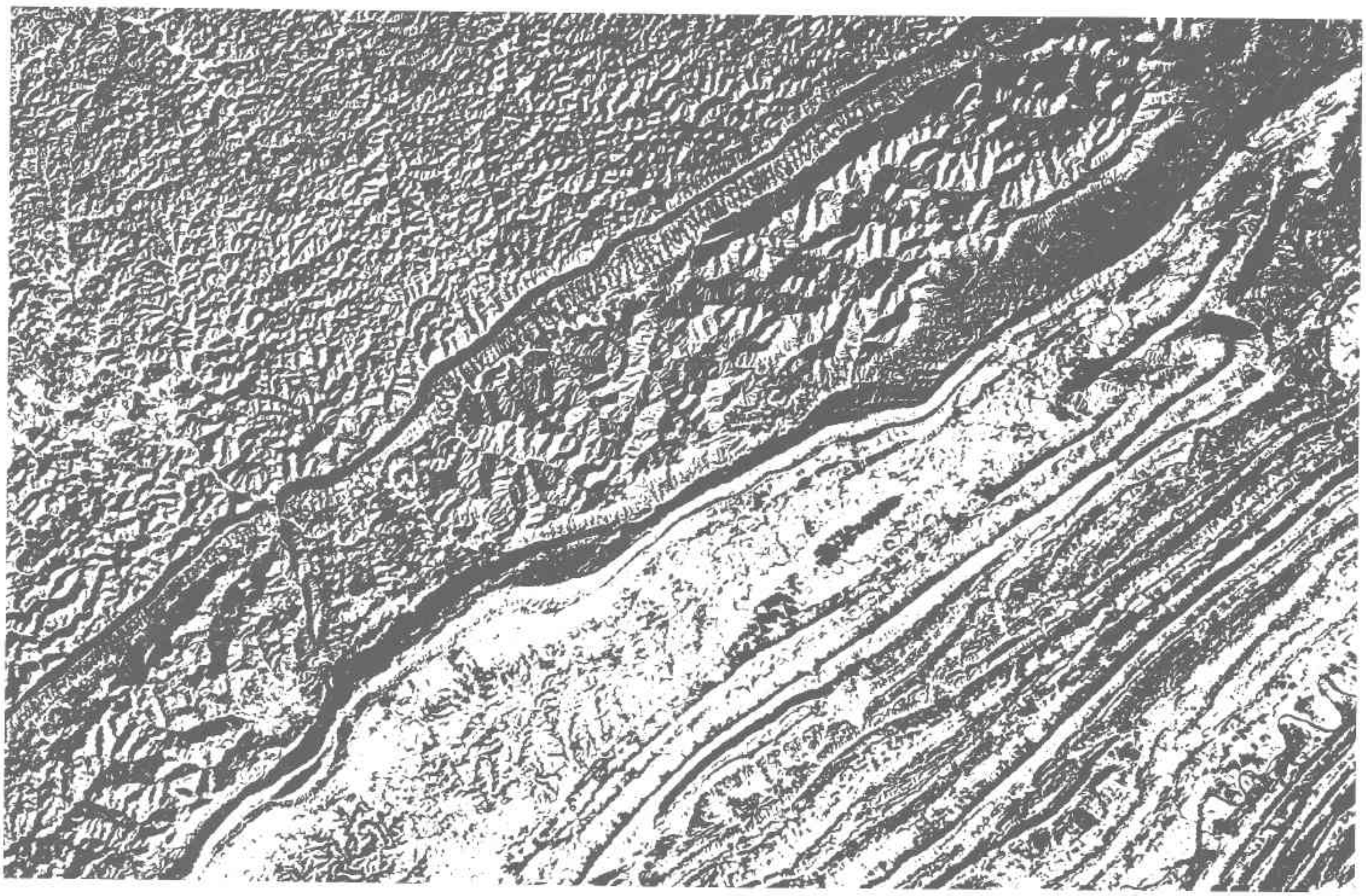

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FRONT COVER: Black-and-white photographic copy of computer-enhanced, false-color, multispectral-scanner LANDSAT imagery of Lee County, Virginia and adjacent areas in Kentucky and Tennessee. Scale is 1:250,000; original imagery provided by the General Electric Company.

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COMMONWEALTH OF VIRGINIA

DEPARTMENT OF GENERAL SERVICES

DIVISION OF PURCHASES AND SUPPLIES

RICHMOND

1981

REFERENCE NOTE

Portions of this publication may be quoted if credit is given to the Virginia Division of Mineral Resources. It is recommended that reference to this report be made in the following form: Gathright, T. M., II, 1981, Lineament and fracture trace analysis and its application to oil exploration in Lee County, Virginia: Virginia Division of Mineral Resources Publication 28, 40 p.

DEPARTMENT OF CONSERVATION
AND ECONOMIC DEVELOPMENT

Richmond, Virginia

FRED W. WALKER, Director
JERALD F. MOORE, Deputy Director

BOARD

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LINEAMENT AND FRACTURE TRACE ANALYSIS AND ITS APPLICATION TO OIL EXPLORATION IN LEE COUNTY, VIRGINIA

By

Thomas M. Gathright, II

ABSTRACT

In this study the relationship of oil production and oil occurrence to lineaments and fracture patterns in Lee County, Virginia is examined to assess the relative value of LANDSAT imagery as an oil exploration tool. Lineaments and fracture patterns were derived from LANDSAT imagery and from air photos.

The geology of the oil fields and construction and production data for 102 oil wells form the data base for evaluating the relationships between lineament trends and distributions of oil production and occurrence. LANDSAT lineament maps and air photo lineament maps were prepared for Lee County using twenty-one, 7.5-minute topographic quadrangles. Analyses included plotting lineament population densities and trend distributions as Cartesian diagrams, histograms and rose diagrams, and calculating air photo/LANDSAT lineament population ratios for each of the four structural sub-provinces in the county area. The production of individual wells and the trends of lineaments (fracture traces) and distances to them indicate that LANDSAT lineament maps derived from multiseasonal enhanced scenes or from enhanced scenes having high sun angles are useful tools in structural analysis and, therefore, in petroleum exploration. These maps do not provide the cartographic accuracy that is needed for siting test wells nor do they provide lineament population densities that correlate adequately with air-photo-derived lineament population densities.

The study was funded by the Appalachian Regional Commission under contract No. 79-166.

INTRODUCTION

The purpose of this study is to evaluate the use of lineaments and fracture patterns identified on LANDSAT imagery as a tool for petroleum exploration in Lee County, Virginia (Figure 1). This county is in a portion of NASA/ARC Applachian Lineament test site no. 3. The study was funded by the Appalachian Regional Commission, (ARC) Contract No. 79-166, CO-7115-79-1302-0725 in coperation with the National Aeronautics and Space Administration (NASA).

The first step in the study was adjusting the scales of the LANDSAT imagery, air photos, and topographic quadrangle maps (on which the oil well sites were plotted) so that the "landforms" could be compared to well sites. Another early step was the comparison of LANDSAT prints in order to evaluate the effect of seasonal changes in sun angle and ground cover on observing lineaments on these prints. Finally, data on lineaments observed on air photos and on LANDSAT imagery were related to oil production.

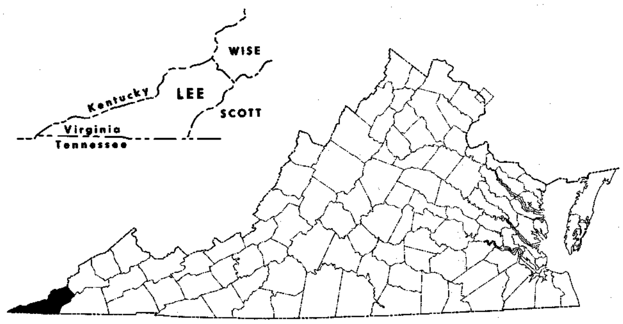

Figure 1. Index map

Two types of areal distributions of lineaments were used in the study: 7.5-minute quadrangle and regional structure distributions. Four regional structures were used for analyses of lineaments: the Powell Valley anticline, two areas of the Middlesboro syncline, and the thrust fault belt.

METHODOLOGY

LANDSAT lineament maps: The LANDSAT imagery utilized for the project comprised 12 color prints of ARC test site no. 3 at 1:250,000 scale; the test site includes Lee County, Virginia. These 12 prints include 4 different computer enhancements (reflected in the print numbers) for each of 3 scenes, December (prints 13-16), February (prints 17-20) and May (prints 21-24), and include a wide range in vertical and horizonal sun angles. The prints were examined to determine which scene(s) and which enhancement(s) provided the greatest number of lineaments per unit area and the best lineament resolution. Two prints, numbers 20 and 21, were selected for use in this study. They were examined by three observers using high- and low-oblique orthographic viewing and viewing through a diffraction grating. Linear features observed include short, straight, sharply defined boundaries between shadow and sunlight; stream segments and valleys;

and long, straight subtle textural or tonal features which are best seen by low-oblique viewing. The diffraction grating produced too much visual "noise" for observing individual linear features, but it did bring out dominant lineament trends.

All lineaments observed on prints 20 and 21 by each observer were plotted on clear mylar placed over and registered to the prints. Compilation mylars were then made from the lineament data of each observer for the two prints. The two compilation mylars (representing the two prints) then were aligned approximately with the 1:250,000-scale, Johnson City topographic map by using salient topographic and cultural features visible on both the prints and the map as registration points. State and county boundaries and 7.5-minute quadrangle boundaries were then transferred from the Johnson City map to the compilation mylars. The sites of all producing and non-producing oil wells were then plotted on the compilation mylars (scale 1:250,000) by photographically adjusting the scale of large-scale mylar maps containing the well information. These mylar maps were 7.5-minute quadrangles previously reduced to 1:50,000 scale.

The two compilation mylars (Figures 2 and 3) thus show the general spatial relations of the LANDSAT lineaments derived from prints 20 and 21 to the oil well sites. These two mylars were then combined to form a composite map of all the lineaments recognized on the two LANDSAT prints (Figure 4). Numbers of lineaments observed on LANDSAT imagery and on air photos as well as their ratios for each of the 21, 7.5-minute quadrangle areas are tabulated in Figures 5 and 6. Additionally, the azimuths (bearings) of LANDSAT-derived lineaments from four structural areas in or adjacent to Lee County are compiled in Cartesian diagrams in Figures 7-10.

Air photo lineament maps: The control imagery consists of stereopairs of quadrangle-centered, panchromatic, air photos (scale 1:80,000) for the 21, 7.5-minute topographic maps for Lee County. These air photo stereopairs were examined stereoscopically by one observer using an Old Delft Scanning Stereoscope ODSS III. All linear, topographically low landforms, except those obviously related to strike-oriented differential weathering of inclined beds, were plotted on clear mylar placed over one member of each stereopair. Each of these 21 air photos together with the superposed, plotting mylar was then photographed on 35mm high-contrast panchromatic film.

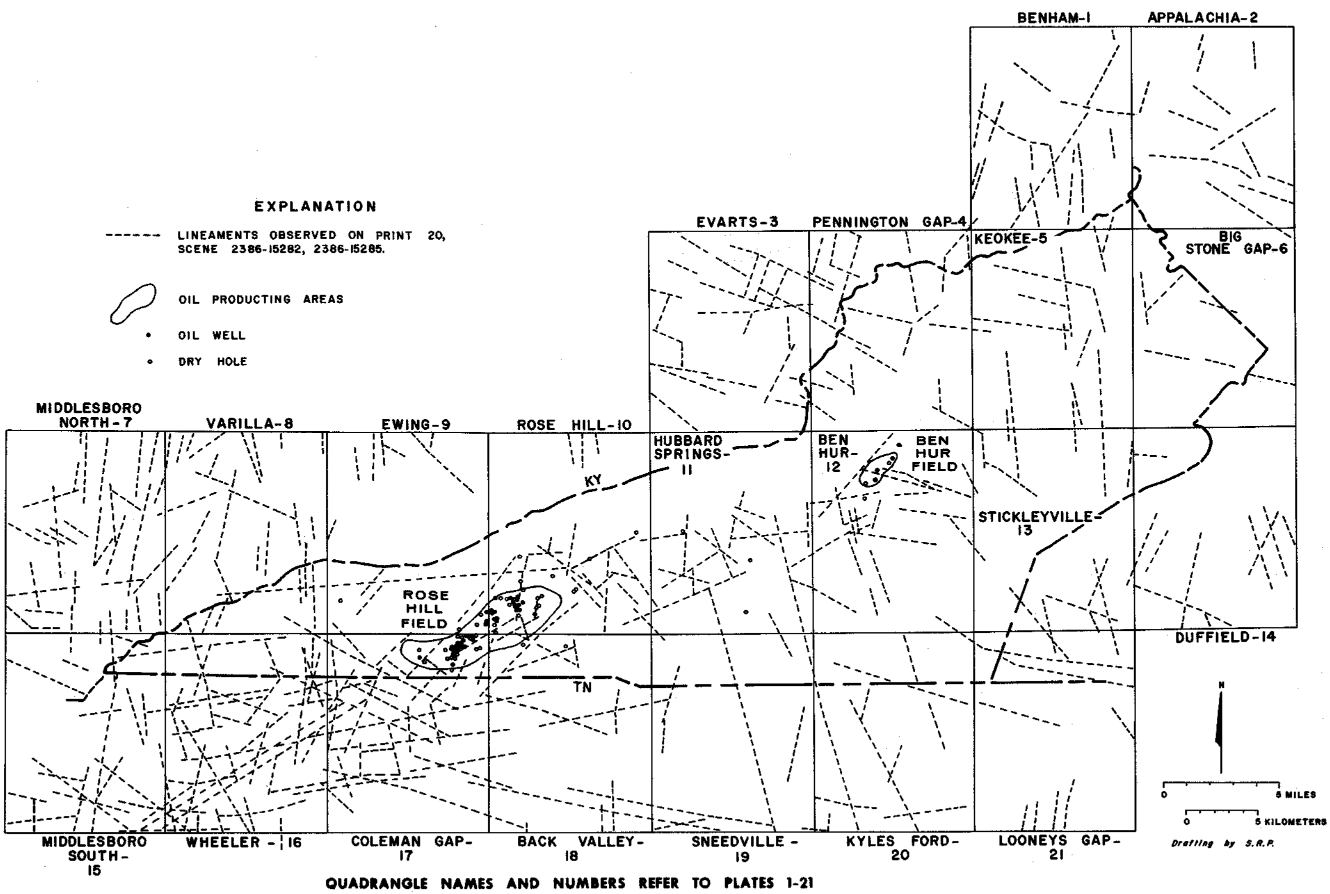

Figure 2. LANDSAT lineament map of Lee County, Virginia derived from print 20.

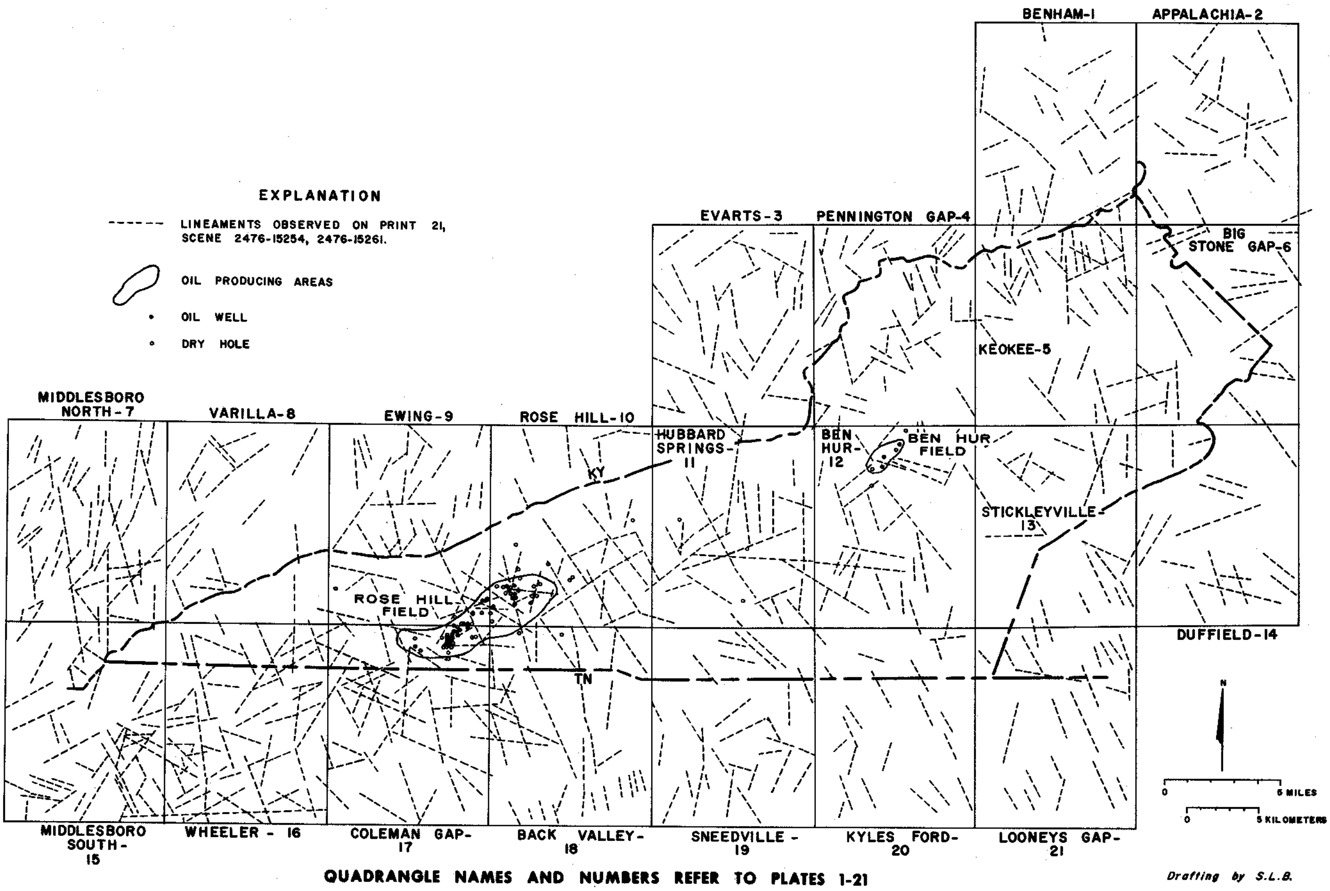

Figure 3. LANDSAT lineament map of Lee County, Virginia derived from print 21.

The composite photograph was projected onto a tilting easel on which the appropriate 7.5-minute topographic quadrangle mylar (scale 1:50,000) was mounted; image size and easel tilt were adjusted to get the best fit between the projected image and the topographic base. This projected image, now fitted to a topographic base, was printed, and the photograph was registered to the topographic mylar for a final check. The lineament traces were then transferred directly to the 1:50,000 topographic base on a light table.

Using these maps, the azimuth for each lineament having more than 50 percent of its extent in the quadrangle was recorded. Then rose diagrams were constructed from the data for each quadrangle (Figure 11). In addition, Cartesian diagrams of lineament azimuth were prepared for each of four structural regions in the study area (Figures 7-10). The data presented in Figure 7 are combined in Figure 12 for easy comparison of the lineament data from LANDSAT prints 20 and 21 and from the air photos.

Comparisons of LANDSAT prints and air photo lineament populations and trends: Lineaments in each quadrangle were counted and tabulated (Figure 5 and 6) for both LANDSAT imagery and for air photos. The number of LANDSAT-derived lineaments ranges from 7 to 49 per quadrangle (print 20), 16 to 62 per quadrangle (print 21) and 71 to 315 per quadrangle (air photos). The ratio of air photo lineaments to LANDSAT lineaments ranges from 2.70 to 18.43 per quadrangle for print 21. On comparing these ratios prepared from print 20 (Figure 5) with the rose diagrams of lineament trend frequencies derived from air photos (Figure 11), it is apparent that where northwest-trending air photo lineaments are dominant, the air photo/LANDSAT lineament ratio is large. Where the dominant air photo lineament trends are east-west or north-south, the air photo/LANDSAT lineament ratios are small. This suggests that many northwest-trending, linear topographic features that are recognized as lineaments stereoscopically on the air photos are not recognized orthoscopically on print 20 of the LANDSAT imagery.

The solar illumination direction for LANDSAT print 20 is N40°W (320° azimuth), a direction close to the orientation of the maximum frequency of the air photo lineament trends for most of the quadrangles. This suggests that the observed wide range of ratios for print 20 can be attributed to the masking effect that sun position has on the northwest-trending, linear topographic features. The low sun angle (29° degrees above the horizon) accentuates

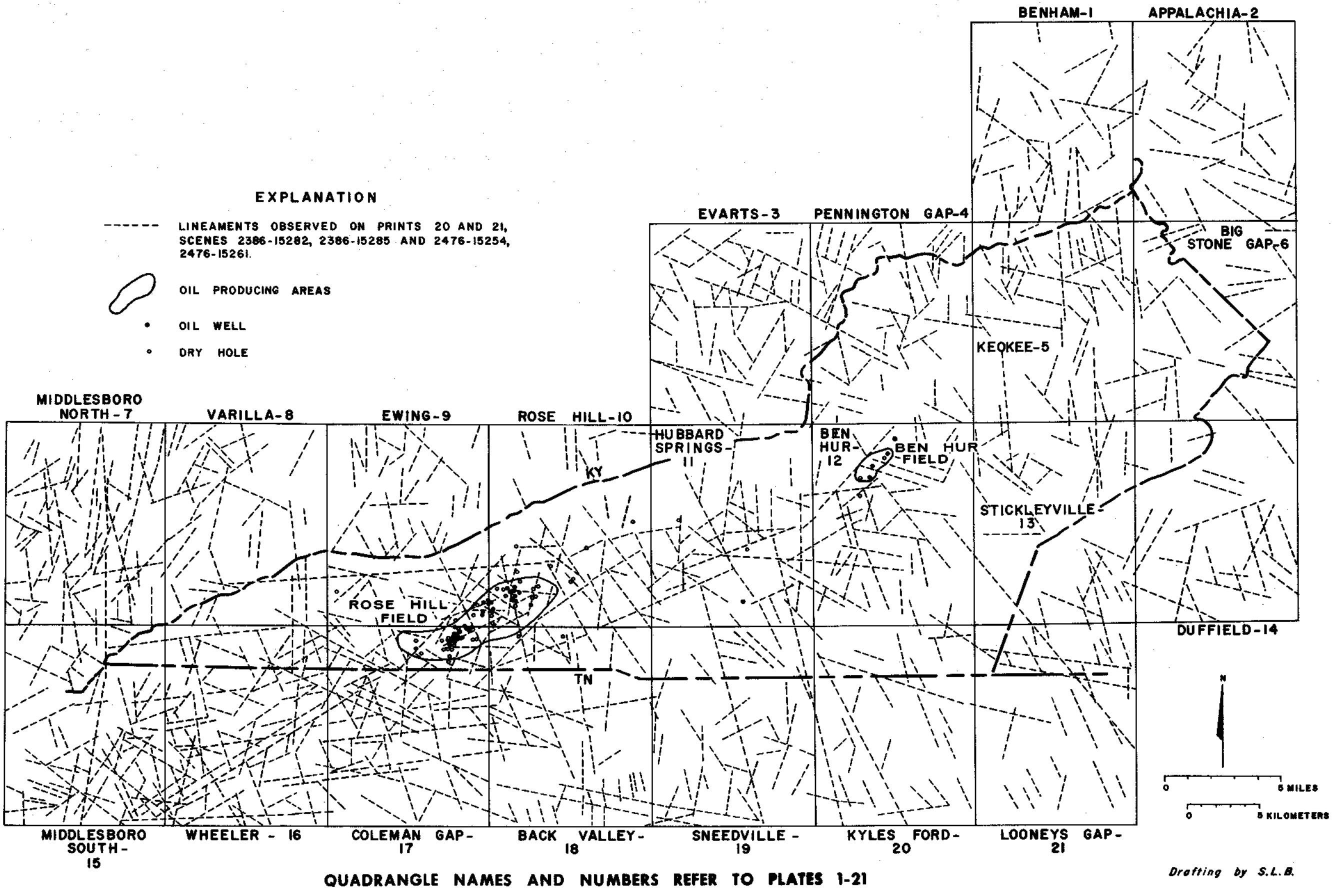

Figure 4. Composite LANDSAT lineament map of Lee County, Virginia derived from prints 20 and 21.

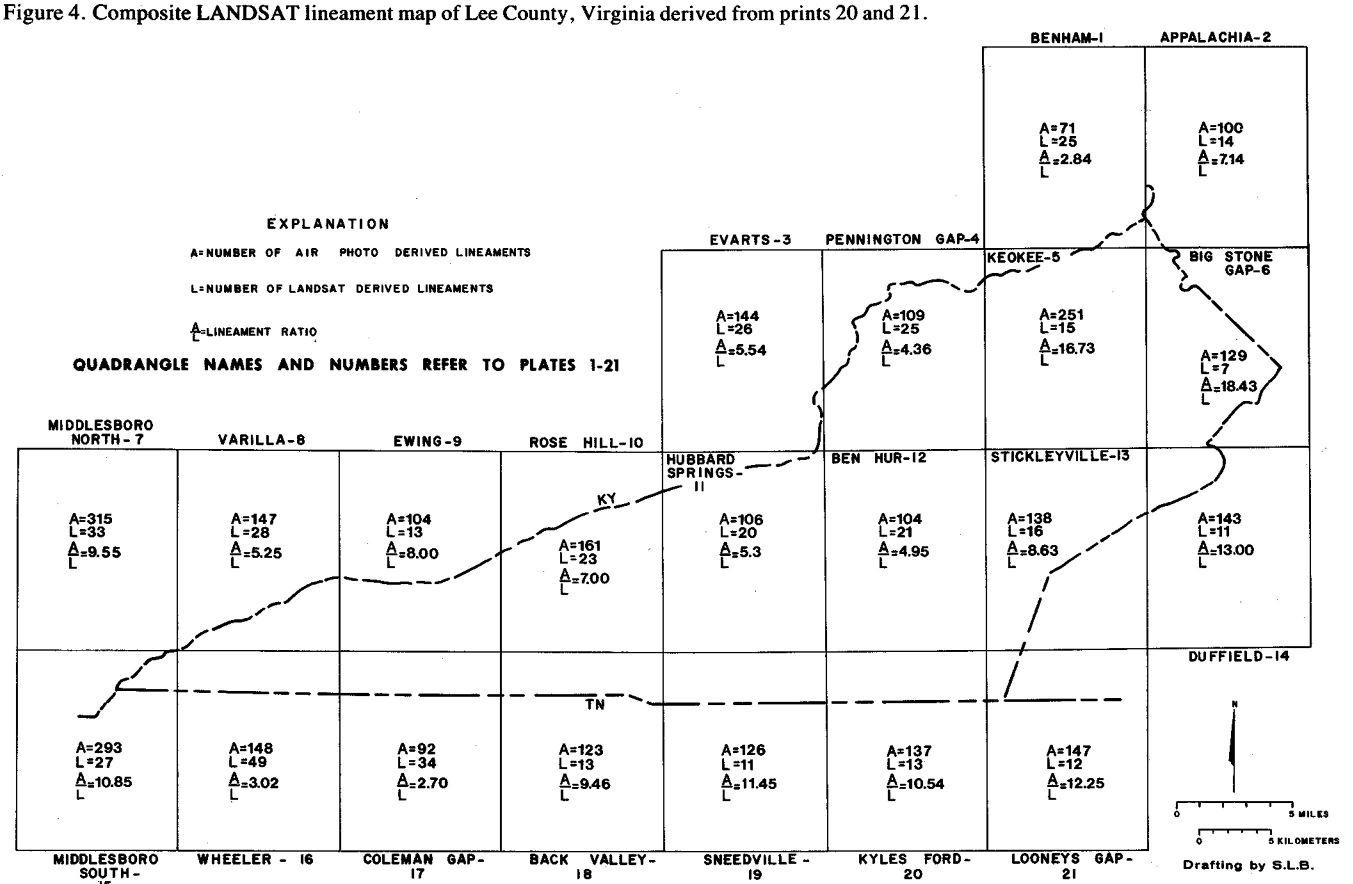

Figure 5. Comparison of air photo and LANDSAT (print 20) lineament populations.

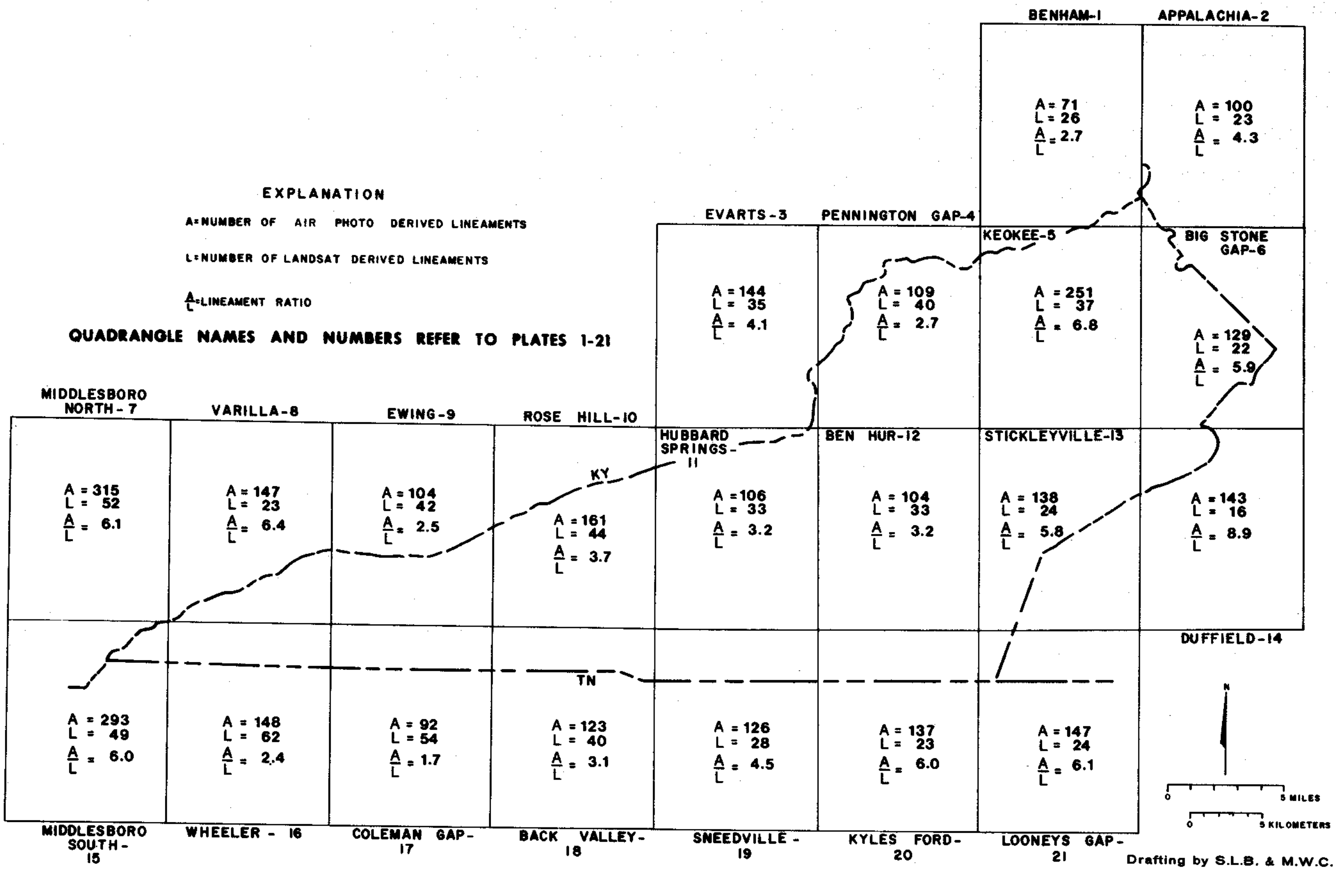

Figure 6. Comparison of air photo and LANDSAT (print 21) lineament populations.

north-, northeast-, and east-trending features and increases the probability that linear topographic forms having these orientations will be observed. These characteristics distort the LANDSAT lineament-trend frequencies with respect to those derived from the air photos.

In comparing the sun azimuth and elevation for each of three LANDSAT scenes (February, May, December) it was found that sun azimuths for the December and February scenes were closely aligned with the lineament maxima obtained from the air photos. Most LANDSAT lineaments are the expression of aligned or linear topographic features as brought out by shadows. Thus the degree of their expression is contingent on both the horizontal and vertical angle of illuminations, that is, on sun azimuth and elevation (Wise, 1969). Prints from the May scene have an illumination direction that does not coincide with the lineament-trend maxima derived from the air photos. The sun's elevation in the May scene is greater than those in the December and February scenes and is also greater than the angle of topographic slopes in the area. The resultant high illumination-angle provides a relatively isotropic lighting which reduces the shadow expression of all topographic forms. The reduction of intensity and number of shadows reduces overall subject contrast without reducing photo (gamma) contrast. This condition of isotropy aids perception of low-contrast linear features that are obscured by shadows. Isotropy also decreases the dominance of high-contrast linear forms as observed on scenes obtained at times of low sun angle. Data analysis of print 21 of the May scene not only produced lineament-trend maxima most like those derived from the air photos, but also produced larger lineament populations than any print of the winter scenes.

Long, straight, regionally extensive, tonal lineaments, only seen on low-oblique viewing, are visible on the best enhancements of all scenes. These long lineaments appear to be expressed best on the December scene.

It appears that adequate maps of LANDSAT-derived lineaments cannot be made from a single scene, but that at least two scenes, having as widely divergent illumination directions as possible, should be used. Probably the best lineament map that could be derived from the least number of the prints used in this project would be a composite map of lineaments derived from prints 14, 20 and 21 — prints from December, February and May scenes, respectively. Lineament-trend and population distribution on this composite map should approximate the real distribution of topographically and tonally expressed structural features in the study area.

The composite number of lineaments for prints 20 and 21 (Figure 4) are used for the analysis of the relationship of LANDSAT-derived lineaments to oil production in Lee County. If only one print were to be used, it should be one chosen from the scene (season) having the highest sun angle. The enhancement chosen for the scene should be the one giving the highest contrast (gamma) and the sharpest resolution.

Lineaments and geologic structures: Comparisons of Cartesian diagrams for LANDSAT prints 20 and 21 and the air photos of four major structural areas are shown in Figures 7-10. The general geographic distribution of lineaments derived from air photos is shown in Figure 11. Cartesian diagrams for LANDSAT prints 20 and 21 and the air photos of four major structural areas are shown in southwestern portion of the Middlesboro syncline (Figures 7-10). In this area the strong lineament trends to the northwest were not observed on the imagery or on the topographic maps, and probably are absent. The low sun angle and high contrast of LANDSAT print 20 accentuates the north- to east-trending linear features that form the major lineament trends seen on the air photos in this area. As a result, lineament trends on LANDSAT print 20 more closely match the lineament trends seen on the air photos than do those on print 21 (Figure 8).

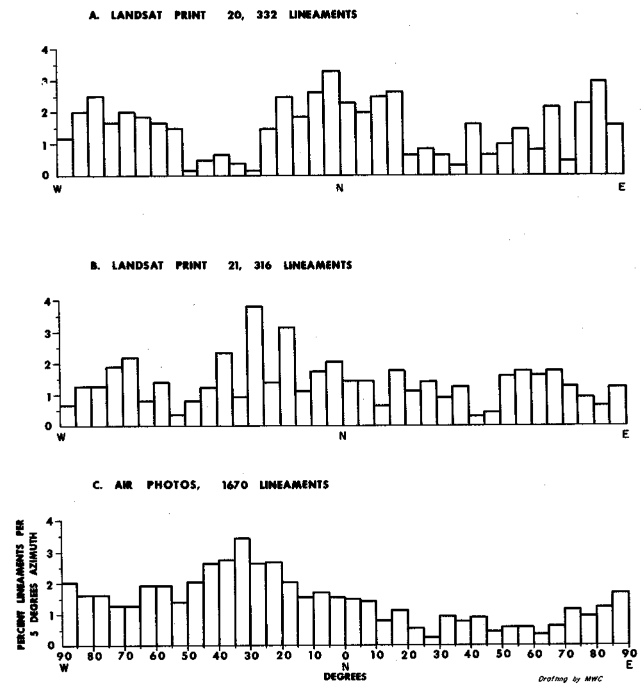

Figure 7. Cartesian diagrams of lineament azimuth distributions found along the Powell Valley anticline (Plates 4-6; 8-13; and 15-19).

The lineament-trend frequencies derived from the air photos and from print 21 correlate well for the thrust belt (Figure 10); the LANDSAT lineament populations are low here when compared to other areas (Figure 6). This can be directly attributed to the geology of the thrust belt where northeast-trending, steeply inclined strata are repeated in nearly parallel belts. Many short, straight, northwest-trending, linear valleys developed at a large angle to the strike of rock formations are visible as lineaments on the air photos, but many of these are too small or oriented too nearly parallel to the sun direction to be recognized on the LANDSAT imagery. Thus, there are large air photo/LANDSAT lineament ratios in areas of steeply inclined rocks where the strike of the rock units is perpendicular to the sun direction.

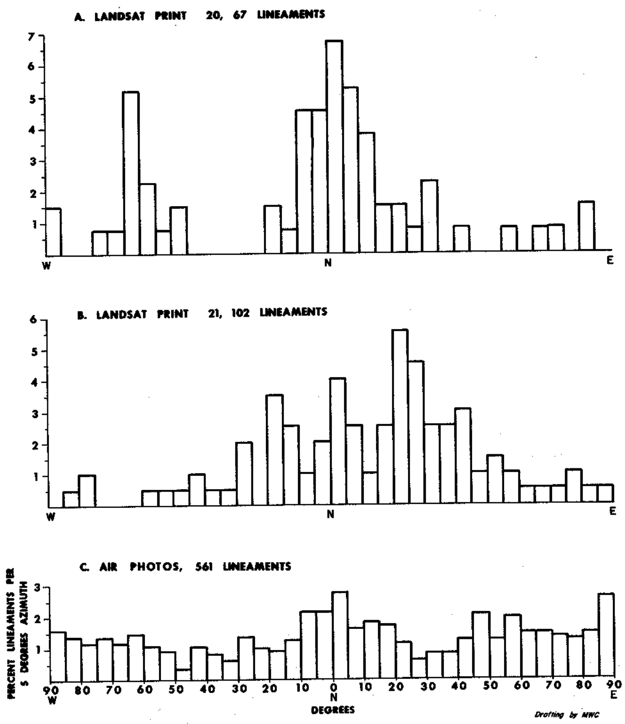

Figure 8. Cartesian diagrams of lineament azimuth distributions in the Middlesboro syncline (Plates 7-9 and 15).

A comparison of the Cartesian diagrams of lineament azimuth distribution on the Powell Valley anticline from LANDSAT print 20 and the air photos are shown in Figure 12. The frequency curves are closely similar except for observations that fall within 30 degrees of the illumination direction for the LANDSAT imagery. The degree of divergence of the curves suggests that 30 to 40 percent of the potential lineament-forming topographic features along the Powell Valley anticline are unrecognized on print 20.

LANDSAT lineament populations seem to vary with both rock type and Paleozoic structure, although the struc-

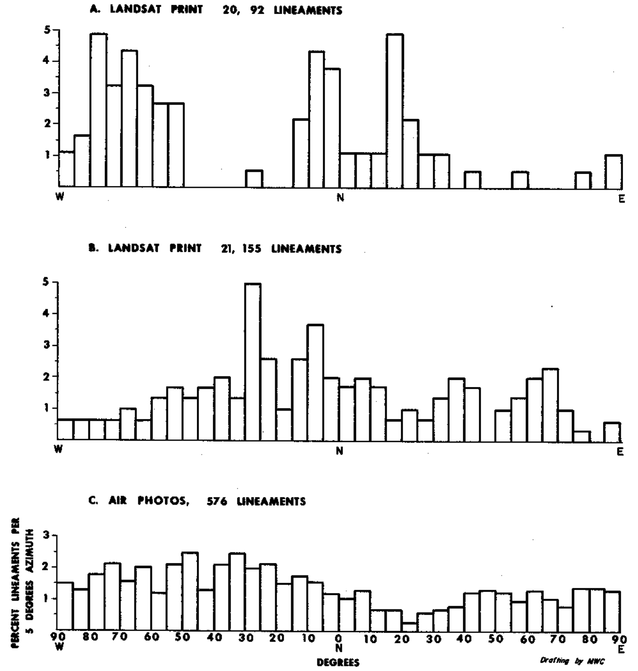

Figure 9. Cartesian diagrams of lineament azimuth distributions on the northeastern portion of the Middlesboro syncline (Plates 1-6 and 10).

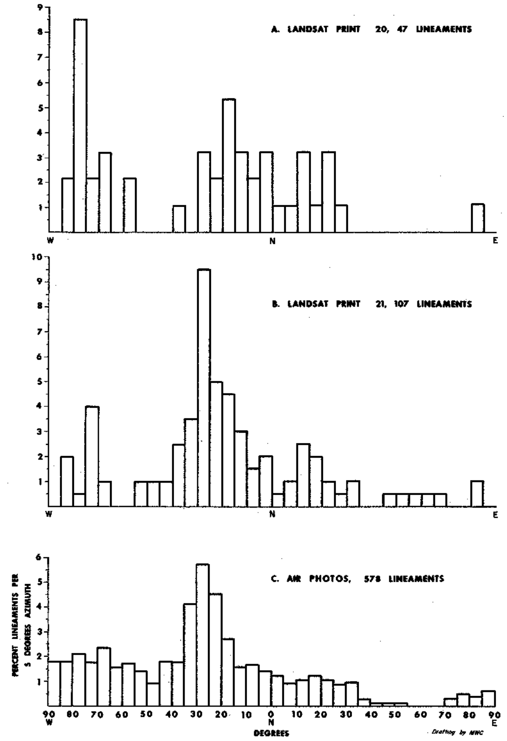

Figure 10. Cartesian diagrams of lineament distributions in the thrust belt (Plates 12-14 and 18-21).

ture may exercise the greater control. There is a dense population of very distinct lineaments on the LANDSAT imagery along the crest of the Powell Valley anticline, where gently inclined dolomite and limestone form the floor of Powell Valley. The more steeply inclined, siliciclastic and interbedded carbonate rocks along the flanks of the anticline are nearly devoid of short, straight LANDSAT lineaments.

LANDSAT lineaments are moderately numerous in the nearly horizontal Pennsylvanian age rocks of the Middlesboro syncline (Plates 1-5, and 8-10) and are sparse in the steeply inclined rocks of the thrust belt southeast of Powell Valley (Plates 13, 14 and 18-21).

Frequency-maxima of air photo lineament trends (Figure 11) generally conform well to the transverse and diagonal joint trends which would be expected in the gently to moderately plunging northeastern portion of the Powell Valley anticline. There are similar frequency-maxima in areas of nearly horizontal strata in the Middlesboro syncline, the adjacent fold structure to the northwest. In the southwestern portion of the study area, several quadrangles (Plates 7, 8, 9, and 16) contain north-south and east-west trend-maxima that can be related to fracturing associated with the north-trending Rocky Face fault or the northeast-trending Doublings fault zone and associated parallel flexures. Northwest-trending frequency-maxima do not appear to be present in this area. The southeastern portion of the area is characterized by imbricated thrust faults and moderately to steeply inclined, northeast-trending fold limbs. The strongest northwest maxima occur in this area (Plates 13, 14, and 18-21) and may be the result of masking of longitudinal and diagonal fracture systems by the well-defined, steeply inclined beds of the thrust belt.

OIL PRODUCTION AND GEOLOGY

Oil exploration began in Lee County, Virginia in 1915 with the D.C. McClure number 1 well. Sporadic drilling, based on little geologic knowledge of structure or stratigraphy, continued through 1945 with some small success. The proven presence of oil in Lee County together with higher oil prices sparked an increase in drilling in 1946 so that by 1950, 76 wells had been completed or abandoned. Since then, 26 additional wells were drilled and several more are currently being drilled or completed. Production is from the Rose Hill and Ben Hur fields.

Information for 102 wells drilled for oil in Lee County was obtained from Miller and Fuller (1954) and files of the Virginia Division of Mineral Resources and the Virginia Division of Mines and Quarries. These data are in the Appendix.

In 1978, 2390 barrels of oil were produced from 5 wells in the Lee County fields bringing the cumulative production of the two fields to more than one-quarter million

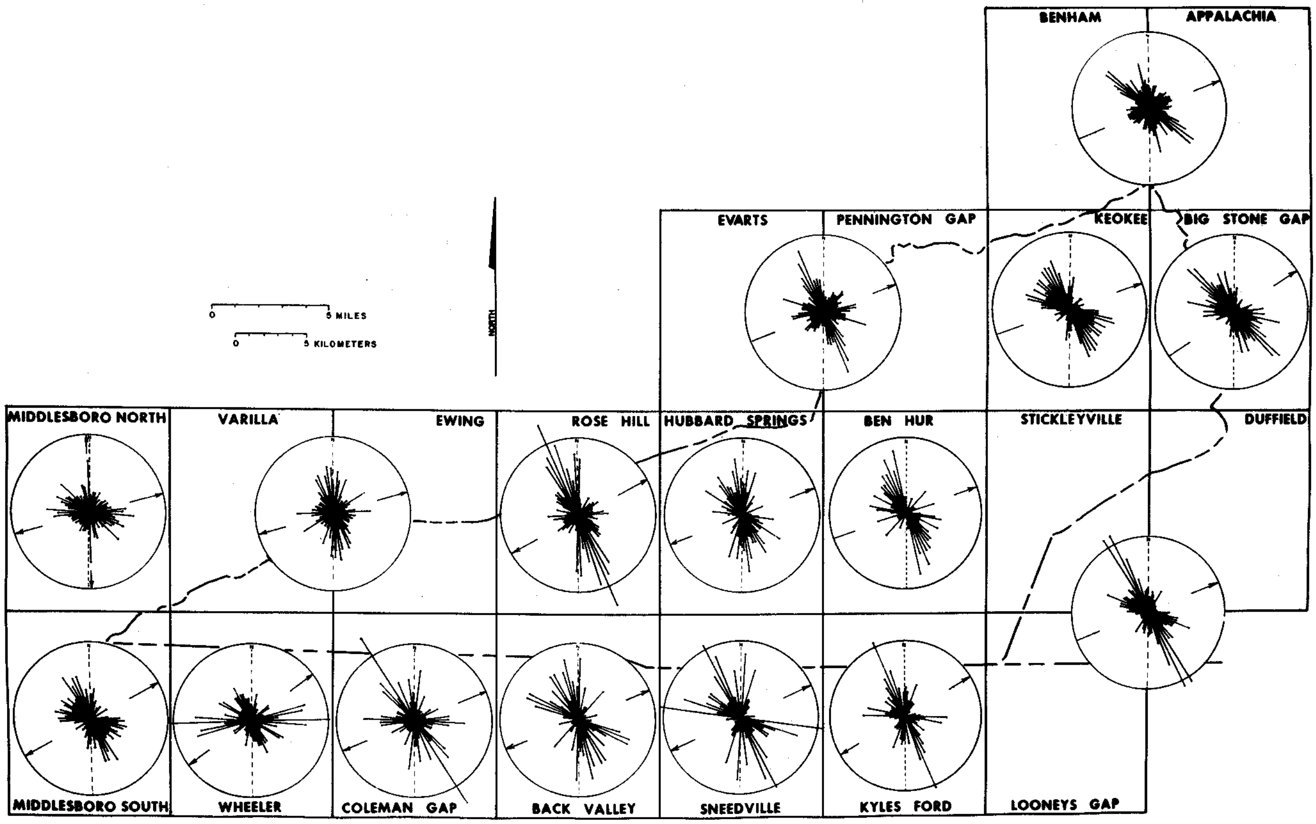

Figure 11. Lineament-trend frequency map of Lee County, Virginia derived from lineaments observed on air photos. Lengths of line in the diagrams are porportioned to the percentages of the total lineament frequency (360°) lying within 5 degrees intervals. Arrows in circles depict approximate fold trends and plunge directions.

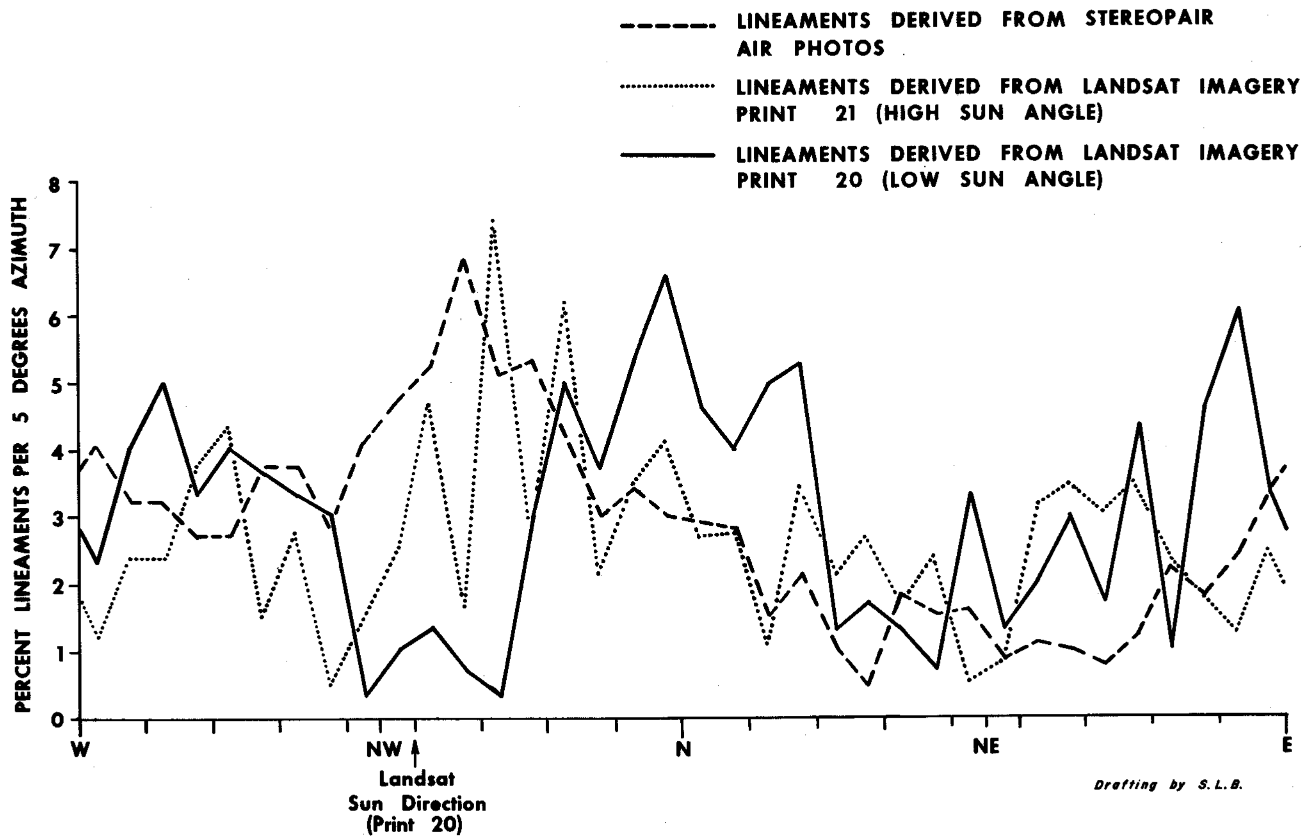

Figure 12. Lineament-trend frequency curves derived from LANDSAT prints 20 and 21 and stereopair air photos of the Powell Valley anticline in Lee County, Virginia.

barrels. Oil production is from shallow and inexpensive wells; relatively few wells are dry. Production from individual wells generally decreases rapidly and may cease after a few weeks or months. Such production characteristics are common to oil wells in fracture reservoirs. Because oil production in Lee County is associated with fractures and because the traces of fractures are visible on remote-sensing imagery, this imagery may be a useful tool for selecting productive oil well sites in Lee County.

Geologic investigations: Early geologic studies of Lee County oil fields include the works of Butts (1927), Miller and Fuller (1954), and Miller and Brosge (1954). In these works, the basic stratigraphic and structural framework of the rocks in Powell Valley was established, and the oil-producing formations of the area and the anticlinal structure of the rocks beneath the Pine Mountain thrust sheet in Powell Valley were recognized. Geologic maps for about 95 percent of the area of Lee County at scale 1:24,000 (7.5-minute quadrangles) have been published (Miller and Fuller, 1954; Miller and Brosge, 1954, Harris, 1965; Harris and Miller, 1958, 1963; Harris and others, 1962; Englund, 1964; Englund and others, 1961, 1963, 1964; Miller, 1965; Miller and Roen 1971, 1973). The remaining 5 percent of the area is included on a 1:250,000 scale map (Butts, 1933). New concepts of the development of the Pine Mountain thrust and the associated Powell Valley anticline have been proposed by Harris (1967) and Harris and Milici (1977). In these concepts, strata of the Powell Valley anticline are considered to have been locally flexed at least two different times. Arching accompanied movement along separate thrust planes of the Pine Mountain thrust system. Figures 13 through 15 provide a graphic summary of the geology of Lee County; a generalized stratigraphic column for the county is shown in Table 1.

Fracture systems visible on LANDSAT imagery and on air photos probably include ones developed during flexing of strata in the Powell Valley anticline. It is anticipated that these fracture systems are characterized by fracture trends that lie parallel, normal and diagonal to the local trends of the axial trace of the Powell Valley anticline.

In addition to these fractures, which are related to Alleghanian deformation, there are numerous post-Alleghanian features which are transverse to the regional structural grain of the Appalachian thrust belt of this area. These transverse fractures extend into the Plateau province.

The Rose Hill and Ben Hur oil fields (Figure 15) are situated in Powell Valley on the crest of the Powell Valley anticline. This broad, northeast-plunging anticlinorial structure includes the Chestnut Ridge and Sandy Ridge anticlines and the Cedars syncline (Figure 13 and 14). The Powell Valley anticline is the major fold of the Pine Mountain thrust sheet, a sheet with a nearly horizontal lower boundary. The rocks of the block were arched upward to form the anticline by movement along the Bales fault slice, which lies beneath Powell Valley. The Pine Mountain thrust sheet is comprised of rocks ranging in age from Middle Cambrian to Pennsylvanian (Figure 13). Locally in Powell Valley, the entire stratigraphic sequence of the upper sheet has been eroded. Ordovician to

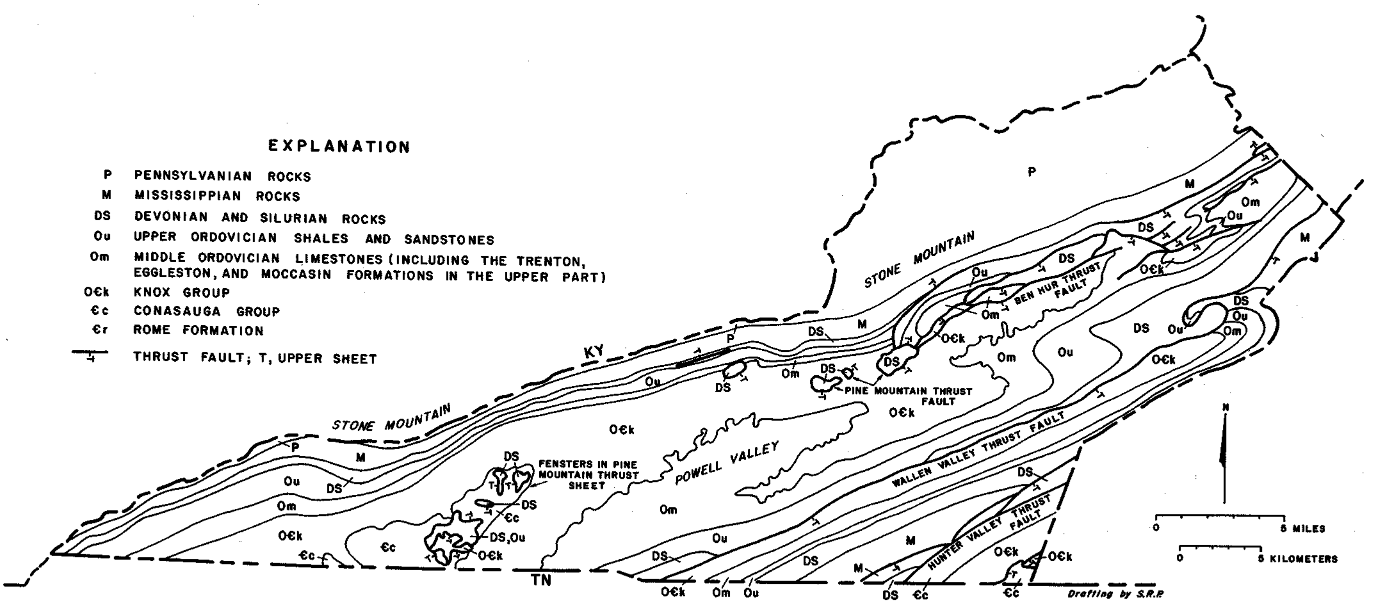

Figure 13. Generalized geologic map of Lee County, Virginia. Map compiled from Butts (1933); Englund (1964); Englund and others (1961, 1963, 1964); Harris (1965); Harris and Miller (1958, 1963); Harris and others (1962) Miller (1965); Miller and Brosge (1954); Miller and Fuller (1954); and Miller and Roen (1971).

Table 1. Generalized stratigraphic column for Lee County, Virginia with key to geologic formations shown in Figures 13 and 15.

System	Group	Formation and rock type	Approx. Average Thickness (feet)	Composite Thickness	Symbol Key to Figures 13 and 15
Pennsylvanian		Harlan Formation: sandstone, minor amounts of shale and coal	650	5400'	P
		Wise Formation: sandstone, shale and coal	1900		
		Gladeville Sandstone: sandstone	50		
		Norton Formation: sandstone, shale and coal	1150		
		Lee Formation: sandstone, minor amounts of shale and coal	1680		
Mississippian		Bluestone Formation: sandstone and shale	300	1850'	M
		Hinton Formation: sandstone and red shale	500		
		Bluefield Formation: shale and calcareous shale	360		
		Greenbrier (Newman) Limestone: limestone	360		
		Fort Payne Chert: chert	15		
		MacCrady Shale: red shale	85		
		Price Formation (Grainger Formation): sandstone	225		
Devonian—Silurian		Chattanooga Shale: black shale	800	1600'	DS
		Wildcat Valley Sandstone: calcareous sandstone	25		
		Hancock dolomite: dolomite and limestone	200		
		Rose Hill Formation: ferruginous sandstone	325		
		Clinch Sandstone: sandstone and shale	260		
Ordovician		Sequatchie Formation: sandstone and shale	275	600'	Ou
		Reedsville Shale: shale	340		
		*Trenton Limestone: granular, fossiliferous limestone	550	2000'	Om
		*Eggleston Formation: limestone and mudstone	150		
		*Moccasin Formation (Hardy Creek and Ben Hur limestones)	290		
		Woodway Limestone: impure limestone	270		
		Hurricane Bridge Limestone: limestone	325		
		Martin Creek Limestone: fossiliferous limestone	120		
		Rob Camp Limestone: thick-bedded limestone	75		
		Poteet Limestone: limestone with chert	70		
		Dot Limestone: limestone and dolomite	150		
	Knox Group	Mascot Dolomite: dolomite, sandy	370 ± 150	2100'	OꞒK
		Kingsport Dolomite: dolomite, minor amounts of chert	185		
Cambrian		Chepultepec Dolomite: dolomite, sandy	740		
		Copper Ridge Dolomite: dolomite	825		
		Maynardville Limestone: limestone and dolomite	300	850'	Ꞓc
		Conasauga Shale: red and green shale, limestone	550		
		Rome Formation: sandstone, shale and dolomite	1600		Ꞓr

* Indicates oil production from fracture reservoirs in these formations.

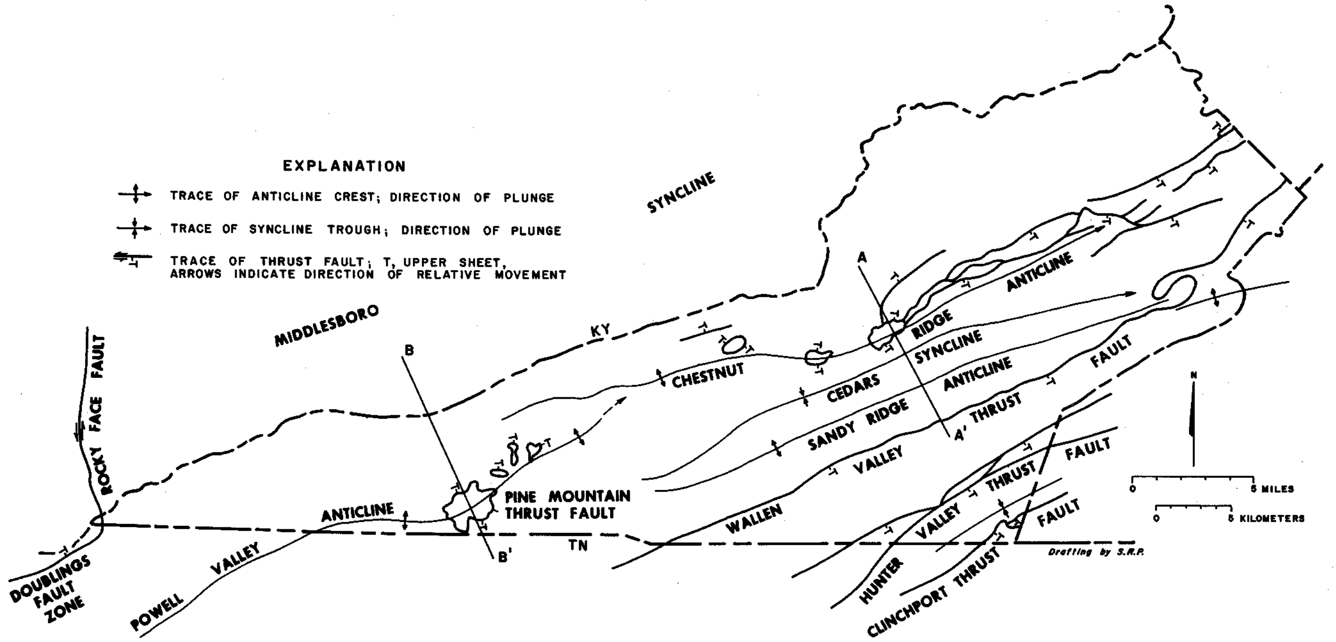

Figure 14. Generalized structural map of Lee County, Virginia. Map compiled from sources listed in caption to Figure 13.

Devonian age rocks of the underlying block are exposed in several fensters which lie along the crest of the Powell Valley anticline (Butts, 1927; Miller and Brosge, 1954; Miller and Fuller, 1954).

The oil fields and most of the exploratory drilling sites are in or near the fensters, where drilling depths to the oil-bearing Middle Ordovician formations are less than 3000 feet (914 m) and where structural closure may be present. Most of the early productive wells were drilled in the Rose Hill field in and around the Chestnut Ridge fenster (Miller and Fuller, 1954), but since 1950 a few have been drilled in the Sulfur Springs fenester (Miller and Brosge, 1954). These latter wells form the Ben Hur field. Oil or gas shows have been encountered in Middle Ordovician through Devonian age rocks beneath the Pine Mountain thrust, but production has been from only the Middle Ordovician Trenton (the major producer), Eggleston, and Moccasin formations (upper part of "Om" in Figures 13 and 15). These formations, named in order from youngest to oldest, are the only known oil reservoir beds near the fensters and may be the source of oil or oil shows found in the Ordovician, Silurian and Devonian age rocks (Miller and Fuller, 1954). The Upper Devonian-Mississippian black shales are probably source beds for oil and gas in the western portion of the Pine Mountain thrust sheet. In Powell Valley these shale beds are intensely deformed, and because they lie in the Pine Mountain thrust zone, are at least partially faulted out. Gas shows and small quantities of gas have been obtained in a few wells from the Silurian Hancock dolomite (Table 1). This

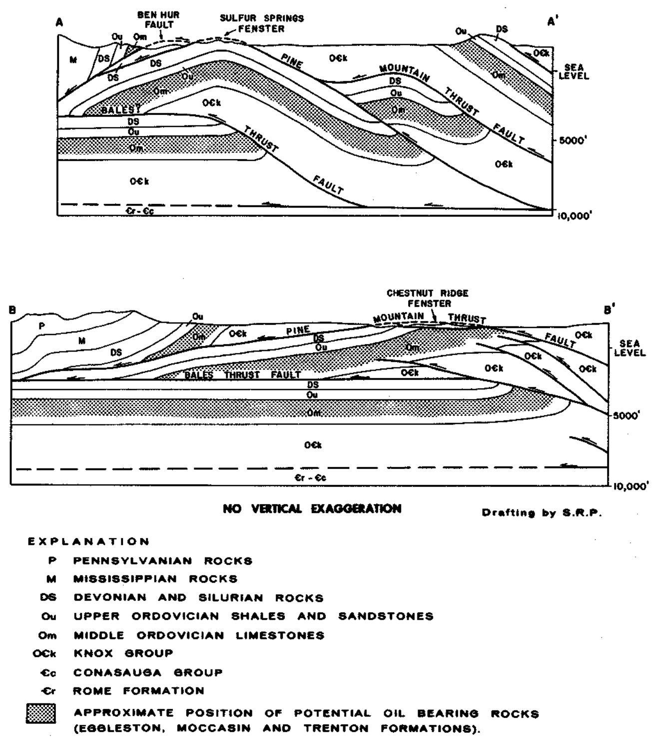

Figure 15. Generalized structure sections across the Ben Hur (A-A') and Rose Hill (B-B') oil fields. Structure sections derived from Harris (1967); Harris and Milici (1977); Miller and Brosge (1954); and Miller and Fuller (1954). All oil production has been the Chestnut Ridge and Sulfur Springs fenster areas and from depths of less than 3000 feet (900m).

formation lies immediately beneath the Devonian black shale beds, suggesting that the shales may also be a hydrocarbon source locally.

The rock sequence exposed in the fensters is a portion of a thrust sheet beneath the Pine Mountain sheet (Figure 15). The lower sheet moved up and westward along the underlying Bales thrust fault following emplacement of the Pine Mountain sheet (Harris, 1967). This later thrusting formed the Powell Valley anticline by repeating the upper Cambrian through lower Devonian rock sequence beneath the Pine Mountain thrust (Harris, 1967). At present all oil production in Lee County is from the Bales thrust sheet. Formations below the Bales fault, including the Trenton Formation and the Devonian black shales (Figure 15), have not been drilled. The black shales are nearly 8000 feet (2438 m) below sea level.

Relation of oil production to lineaments: From study of geologic maps and structure sections, drilling depths of the test wells, and other published data relating to the Lee County oil fields, it is evident, in retrospect, that many of the test wells in Lee County could not be expected to produce oil — either because they did not reach oil-bearing rock units, or because they were drilled too far from structural closure. Production data for the Lee County wells vary in reliability and therefore are generally inadequate for a quantitative study. Accordingly, the production data were reduced to the lowest common denominator for all wells, whether or not the well produced oil.

The 85 oil wells that appear to penetrate the Moccasin, Eggleston and/or Trenton formations (see Appendix) where the formations lie beneath the Reedsville shale (cap rock) and the Pine Mountain thrust fault were selected for analysis. The history of oil exploration in Lee County strongly suggests that only these wells had any chance of producing oil.

By using the data compiled on Plates 1-21, bar graphs depicting the relation between well production and the trend of the nearest air photo lineament were constructed both for wells that were very close to lineaments (within 100 feet, 30.5 m) and for those more distant (>100 feet) from the lineaments (Figure 16 A and B). (For details of the process for adjusting scales and plotting data see "Methodology"). These graphs suggest that lineament trends are not so well correlated to oil production as is the distance from a given lineament to the well. More wells were drilled along lineaments having certain directions, for example, northeast, northwest and north, than along others, but for all wells likelihood of production falls off significantly where a well is sited more than 100 feet from a fracture trace. A bar graph depicting the percentage of producing wells relative to their distance from the nearest lineament (Figure 17) strongly suggests that the probability of oil production from a given well site is increased if the well site is on an air photo lineament.

This relationship between oil well production and proximity of well sites to air photo lineaments is not firmly established because of the sensitivity of the distance relationship. It may be that wells and lineaments need be plotted to within 50 feet (15 m) of true values for relationships to be meaningful. Additionally, data on the

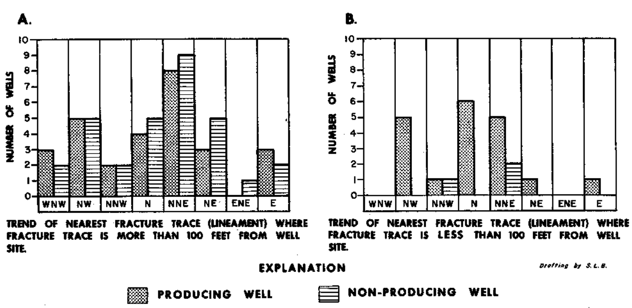

Figure 16. Distribution of producing and non-producing oil wells in relation to the trend of the fracture trace (lineament) nearest to the well site in the Pine Mountain thrust sheet. Each well penetrated potentially oil-bearing rock units (Moccasin, Eggleston, and Trenton formations) under the thrust sheet.

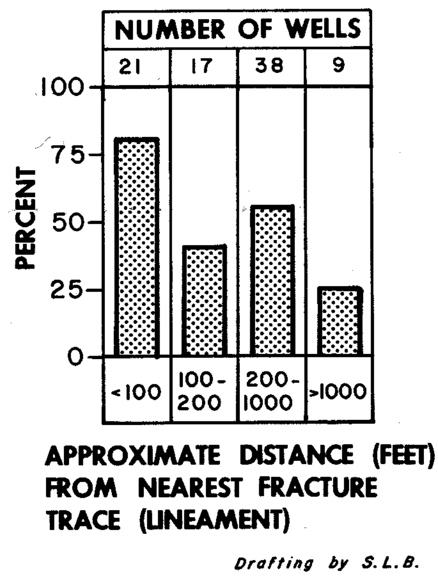

Figure 17. Percentages of producing wells in Trenton Formation vs. distace from fracture trace.

width, depth and attitude of lineament-forming fracture systems, which is not available, would allow a better assessment of possible relationships between air photo lineaments and production.

The relationship between LANDSAT lineaments and sites of producing oil wells plotted on 1:250,000 scale (Figure 4) is likewise not definitive, but it seems to hold true that dry holes are located largely between, rather than on or near, these lineaments. In many of the dry holes that were located on lineaments or lineament intersections, wells did not reach pay zones or reached them off structure or at depths so shallow as to have allowed hydrocarbons to escape to the surface (see Appendix).

There have not been many wells drilled into the Powell Valley and Chestnut Ridge anticlines in the area between the Rose Hill and Ben Hur fields (Figure 4: Plates 10-12). The possibility of local structural closure along the anticlines in this area was suggested by Miller and Fuller 1954) and by Miller and Brosge (1954). Likewise, there has been no drilling on the Sandy Ridge anticline (Figure 14), a structure which may outline a second subsurface thrust sheet similar in origin to the one exposed in the fensters (Harris and Milici, 1977). The possible association between well production and lineaments (fracture zones) should be systematically tested as drilling is continued in the areas where structural closure and oil-bearing rocks occur together.

Because the Lee County oil fields are small, have inadequate production data for the wells and are traversed by only a few lineaments as seen on either air photos or LANDSAT imagery, the usable sample size is too small to provide statistically valid results. Analysis of LANDSAT lineaments derived from multiseasonal, large-scale, enhanced imagery may provide a useful tool for recognizing the shape and extent of subsurface structures. Analysis should include the trends, lengths and population densities of the various types of lineaments. The extent of the Bales thrust block, which is only exposed in the fensters, for example, may be defined by the area of greatest LANDSAT lineament density in the Powell Valley anticline.

OBSERVATIONS AND CONCLUSIONS

The value of LANDSAT imagery as a tool in petroleum exploration is summarized in the following six observations and conclusions:

(1) The dominant trend of air photo lineaments in Lee County correlates well with the trend of fracture patterns that stress-strain analysis suggests should have developed in the area during the Alleghanian orogeny.

(2) The probability of oil production from wells within about 100 feet (30 m) of air photo lineaments appears to be appreciably greater than for wells more distant from the lineaments.

(3) Most short, straight LANDSAT lineaments generally can be recognized as linear topographic forms on air photos or topographic maps.

(4) The population densities of short, straight LANDSAT lineaments do not correlate well with population densities of air photo lineaments. For the two LANDSAT scenes tested (print 20 and 21), the air photo/LANDSAT lineament ratios for 21 quadrangles ranged from 1.7 to 18.4. This extreme range is due in part to unequal conditions of lighting on the prints and to unequal detail of observation due to the difference in scale of the two types of imagery, but mostly it is due to real differences arising from structural and stratigraphic control of lineament length and prominence at different scales.

(5) The statistical trends of short, straight LANDSAT lineaments derived from scenes having high sun angles, or from multiseasonal scences having a wide range of sun direction and angle, correlate with trends of air photo lineaments.

(6) Long, straight, textual or tonal lineaments visible on the LANDSAT imagery may mark zones of strike-slip fracturing that post-dates the Alleghanian orogeny (Fouse and Brigham, 1979).

These observations indicate that LANDSAT lineament maps and derivative lineament data are useful tools in structural analysis which is directly applicable to petroleum exploration, particularly in areas where other imagery or geologic maps are not available. LANDSAT lineament maps do not provide the cartographic accuracy or topograhic resolution necessary for locating well sites on specific linear features, and single LANDSAT scenes do not provide lineament population densities that correlate well with air-photo-lineament population densities.

It is not known whether the lineament population densities derived from LANDSAT imagery is more significant to oil exploration than those derived from air photos.

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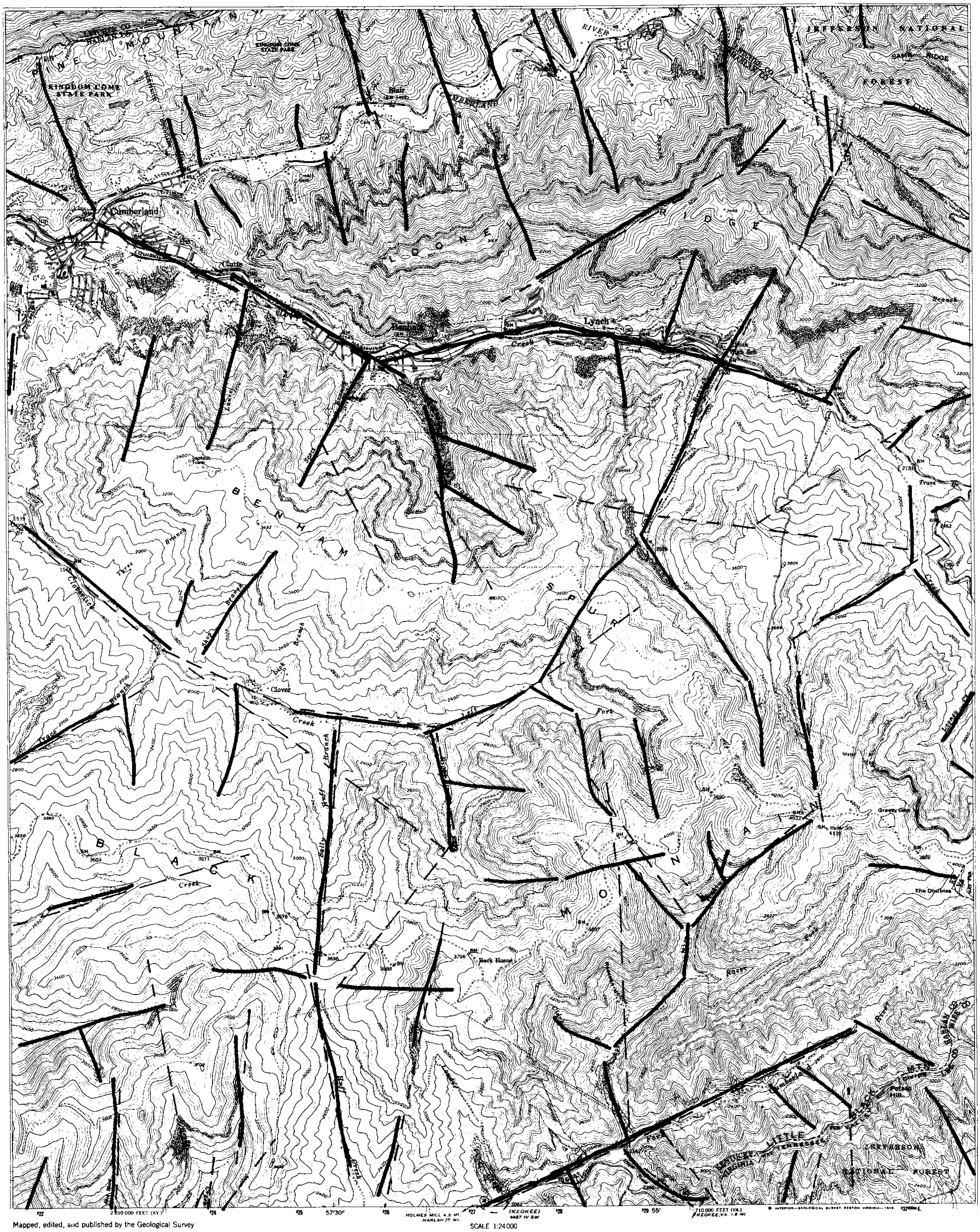
EXPLANATIONS FOR PLATES 1-21

LINEAMENT OBSERVED ON STEREOPAIR, 1:80,000 SCALE, QUADRANGLE-CENTERED AIR PHOTOGRAPHS.

LINEAMENT OBSERVED ON ENHANCED LANDSAT PHOTO PRINTS 17, 18, 19, 20 AND 21.

● 23 OIL WELL HAS PRODUCED OIL OR HAD LARGE GAS SHOW (PLATES 9, 10, 12, 17). WELL NUMBER KEYED TO APPENDICES 1 AND 2.

⊙ 78 OIL WELL, NONPRODUCTIVE DRY HOLE (PLATES 9, 10, 11, 12, 17, 18).



Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography from aerial photographs by stereophotogrammetric methods. Aerial photographs taken 1952. Field check 1954

Polyconic projection. 1927 North American datum
10,000-foot grids based on Kentucky coordinate system, south zone, and Virginia coordinate system, south zone

Red tint indicates areas in which only landmark buildings are shown

Contours in strip mine areas compiled from 1952 photography

UTM GRID AND 1979 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

PLATE 1

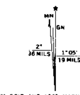
BENHAM, KY.—VA.
NW/4 BIG STONE GAP 15' QUADRANGLE
N3652.5—W8252.5/7.5

Mapped and edited by Tennessee Valley Authority
Published by the Geological Survey

Control by USC&GS, USGS, and TVA

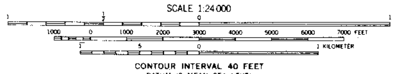
Topography by multiplex methods from aerial photographs taken 1953. Field examination by TVA, 1955

Polyconic projection. 1927 North American datum
10,000 foot grid based on Virginia (South) and Kentucky (South) rectangular coordinate systems
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue

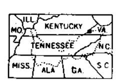


UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000



CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL



QUADRANGLE LOCATION

PLATE 2

APPALACHIA, VA.–KY.
NE/4 BIG STONE GAP 15' QUADRANGLE

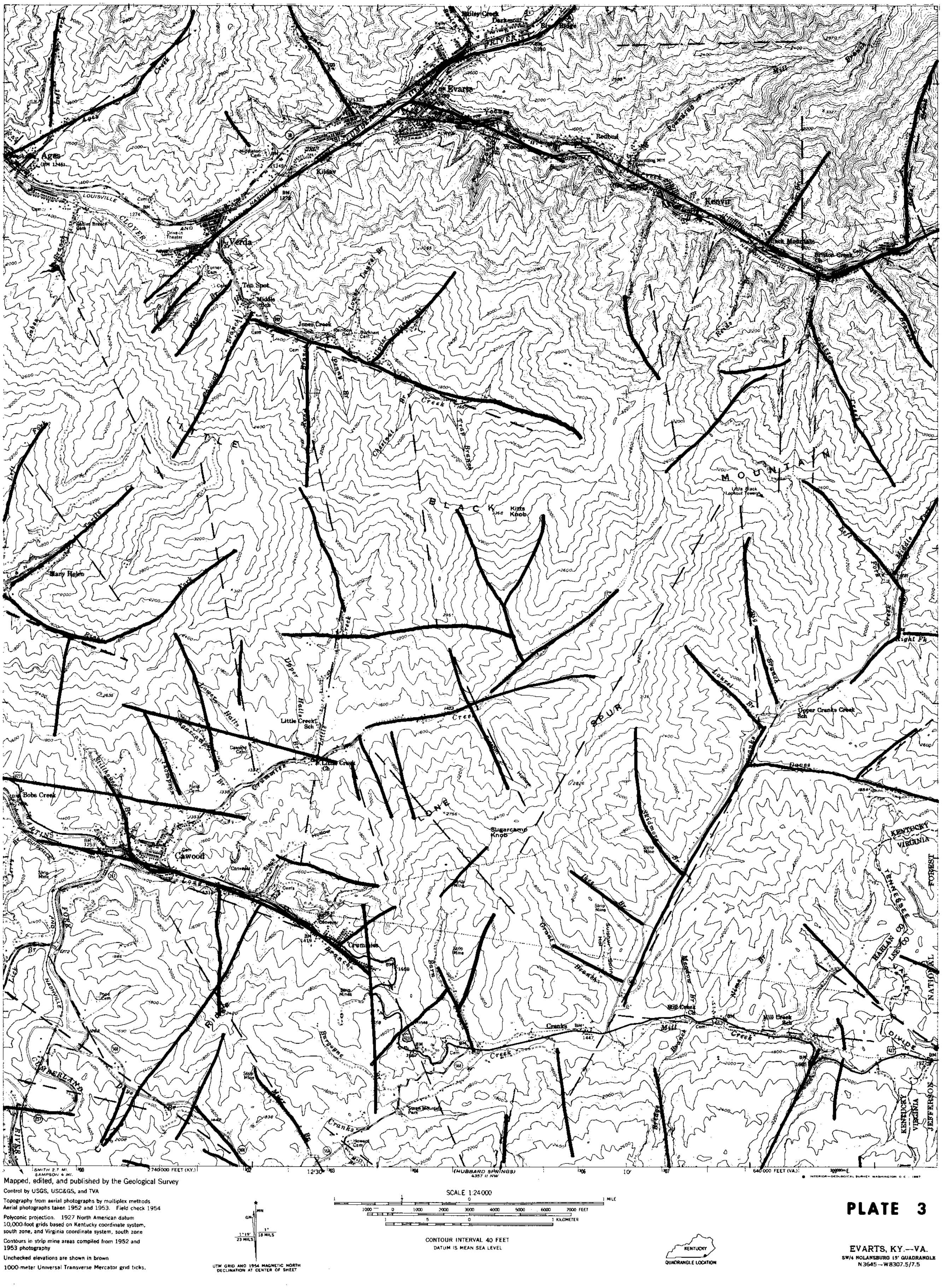

Mapped, edited, and published by the Geological Survey
Control by USGS, USC&GS, and TVA
Topography from aerial photographs by multiplex methods
Aerial photographs taken 1952 and 1953. Field check 1954
Polyconic projection. 1927 North American datum
10,000-foot grids based on Kentucky coordinate system, south zone, and Virginia coordinate system, south zone
Contours in strip mine areas compiled from 1952 and 1953 photography
Unchecked elevations are shown in brown
1000-meter Universal Transverse Mercator grid ticks.
UTM GRID AND 1954 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
SCALE 1:24000
CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL
KENTUCKY
QUADRANGLE LOCATION
EVARTS, KY.—VA.
SW/4 NOLANSBURG 15' QUADRANGLE
N3645—W8307.5/7.5
Ages
Evarts
Verda
Kildav
Black Mountain
BLACK MOUNTAIN
Kitts Knob
Mary Helen
Little Creek Sch
Bobs Creek
Cawood
Crummies
Sugarcamp Knob
LONE MOUNTAIN SPUR
Upper Cranks Creek Sch
Cranks
Mill Creek
KENTUCKY
VIRGINIA
JEFFERSON NATIONAL FOREST
CUMBERLAND RIVER

PLATE 3

PLATE 4

PENNINGTON GAP, VA.-KY.
SE/4 NOLANSBURG 15' QUADRANGLE
N3645—W8300/7.5


JEFFERSON NATIONAL FOREST
KENTUCKY
VIRGINIA
POOR VALLEY
Dryden
Keokee
WOODWAY 2.4 MI.
57'30"
(STICKLEYVILLE 179-NW)
55'
© INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1970
KY. 2 840 000 FEET
VA. 690 000 FEET
Mapped and edited by Tennessee Valley Authority
Published by the Geological Survey
Control by USC&GS, USGS, and TVA
Topography by multiplex methods from aerial photographs taken 1953. Field examination by TVA, 1955
Polyconic projection. 1927 North American datum
10,000-foot grid based on Virginia (South) and Kentucky (South) rectangular coordinate systems
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue
Revisions shown in purple and recompilation of woodland areas compiled by the Geological Survey in cooperation with Commonwealth
UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
SCALE 1:24 000
CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL
QUADRANGLE LOCATION
KEOKEE, VA.–KY.
SW/4 BIG STONE GAP 15' QUADRANGLE
N3645—W8252.5/7.5

PLATE 5

Mapped and edited by Tennessee Valley Authority
Published by the Geological Survey

Control by USC&GS, USGS, and TVA

Topography by multiplex methods from aerial photographs taken 1953. Field examination by TVA, 1957

Polyconic projection. 1927 North American datum
10,000-foot grid based on Virginia (South) rectangular coordinate system

1000 meter Universal Transverse Mercator Grid ticks, Zone 17, shown in blue

Fine red dashed lines indicate selected fence and field lines

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24000

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

QUADRANGLE LOCATION

PLATE 6

BIG STONE GAP, VA.
SE/4 BIG STONE GAP 15′ QUADRANGLE
N3645—W8245/7.5

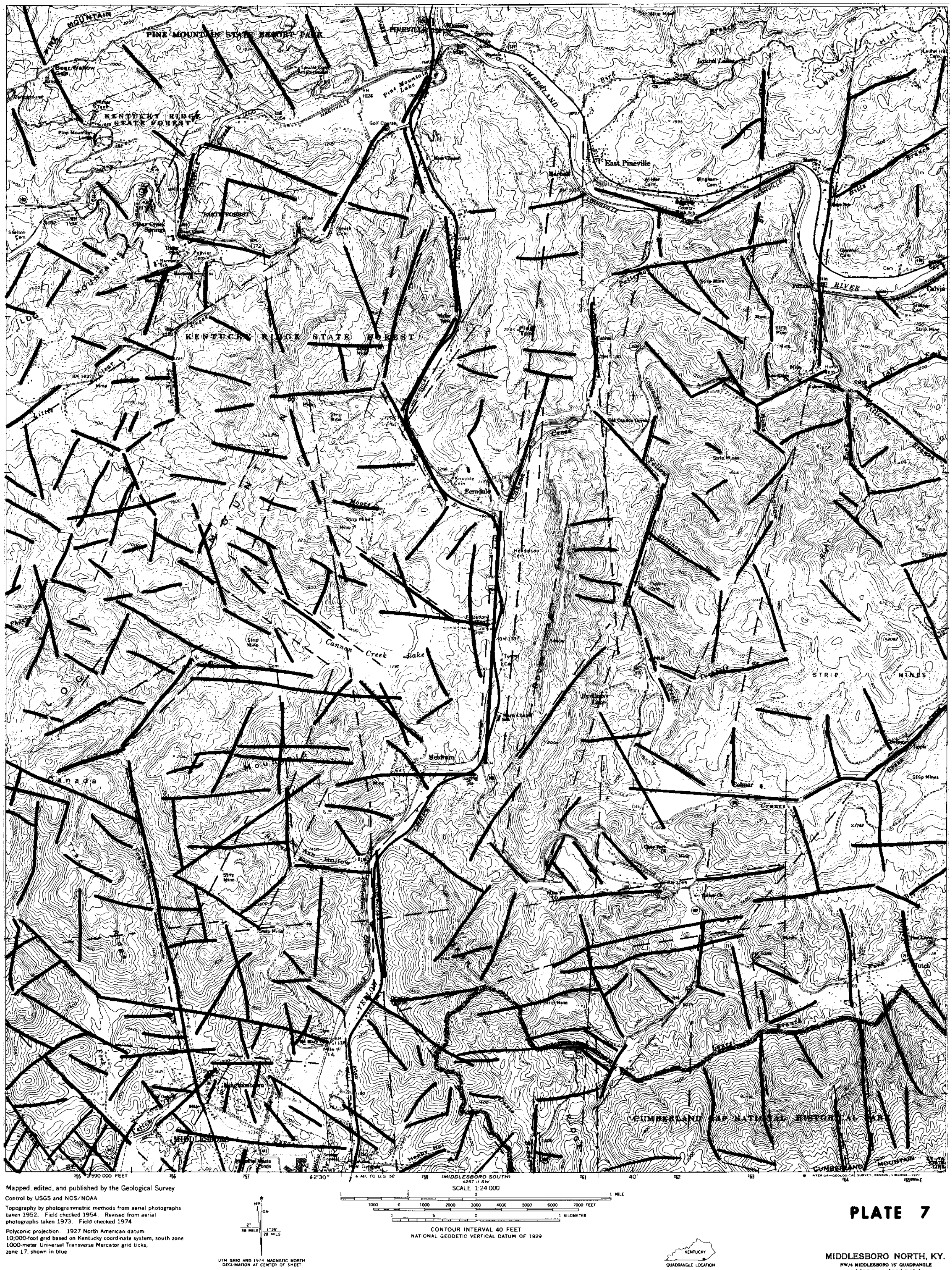

Mapped, edited, and published by the Geological Survey
Control by USGS and NOS/NOAA
Topography by photogrammetric methods from aerial photographs taken 1952. Field checked 1954. Revised from aerial photographs taken 1973. Field checked 1974
Polyconic projection. 1927 North American datum
10,000-foot grid based on Kentucky coordinate system, south zone
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue
UTM GRID AND 1974 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
SCALE 1:24 000
CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929
QUADRANGLE LOCATION
MIDDLESBORO NORTH, KY.
N3637.5—W8337.5/7.5

PLATE 7

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Control by USGS and NOS/NOAA

Topography by photogrammetric methods from aerial photographs taken 1952. Field checked 1954. Revised from aerial photographs taken 1973. Field checked 1974

Polyconic projection. 1927 North American datum
10,000-foot grids based on Kentucky coordinate system, south zone, and Virginia coordinate system, south zone
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue

Fine red dashed lines indicate selected fence and field lines where

UTM GRID AND 1974 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 20-FOOT CONTOURS
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

PLATE 8

VARILLA, KY.—VA.
NE/4 MIDDLESBORO 15′ QUADRANGLE
N3637.5—W8330/7.5

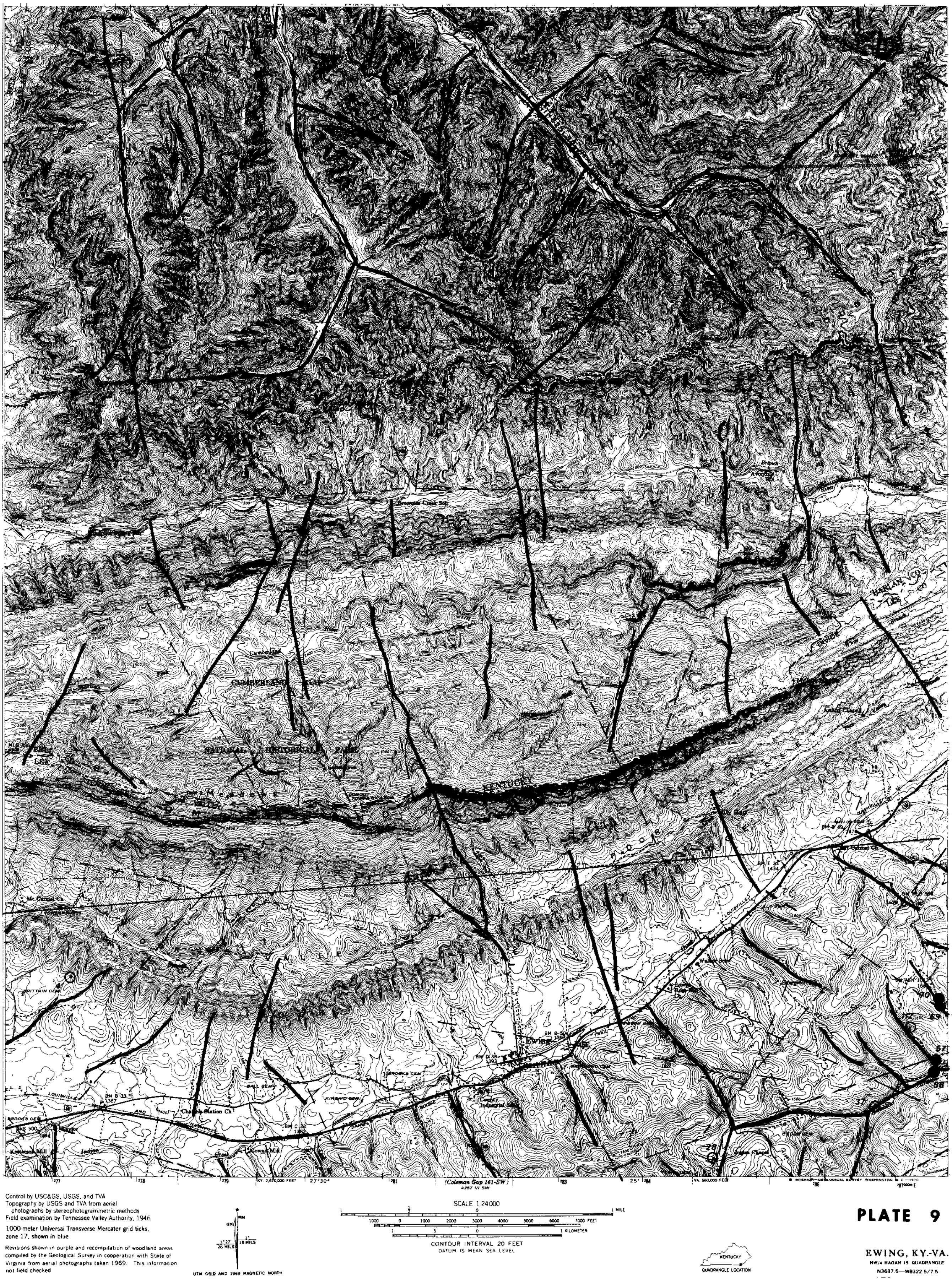
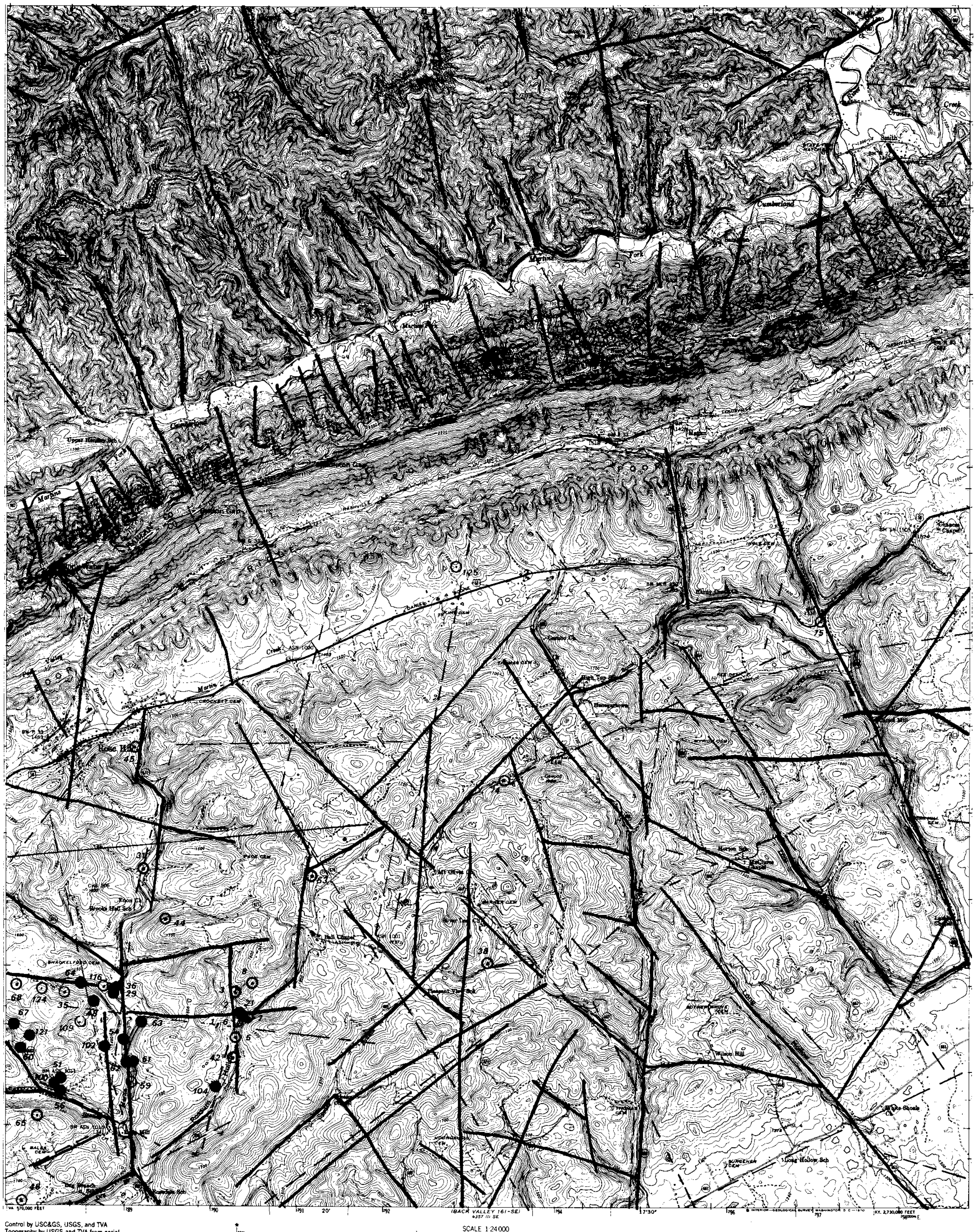

Control by USC&GS, USGS, and TVA
Topography by USGS and TVA from aerial photographs by stereophotogrammetric methods
Field examination by Tennessee Valley Authority, 1946
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue
Revisions shown in purple and recompilation of woodland areas compiled by the Geological Survey in cooperation with State of Virginia from aerial photographs taken 1969. This information not field checked
UTM GRID AND 1969 MAGNETIC NORTH
SCALE 1:24000
CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL
KENTUCKY
QUADRANGLE LOCATION
EWING, KY.-VA.
NW/4 HAGAN 15' QUADRANGLE
N3637.5—W8322.5/7.5
(Coleman Gap 161-SW)
INTERIOR—GEOLOGICAL SURVEY WASHINGTON D C—1970

PLATE 9



Control by USC&GS, USGS, and TVA
Topography by USGS and TVA from aerial photographs by stereophotogrammetric methods
Field examination by Tennessee Valley Authority, 1946

Revisions shown in purple and recompilation of woodland areas compiled by the Geological Survey in cooperation with State of Virginia from aerial photographs taken 1969. This information not field checked

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

Contour interval 20 feet
Datum is mean sea level

QUADRANGLE LOCATION

PLATE 10

ROSE HILL, VA.-KY.

NE/4 HAGAN 15' QUADRANGLE

N3637.5-W8315/7.5

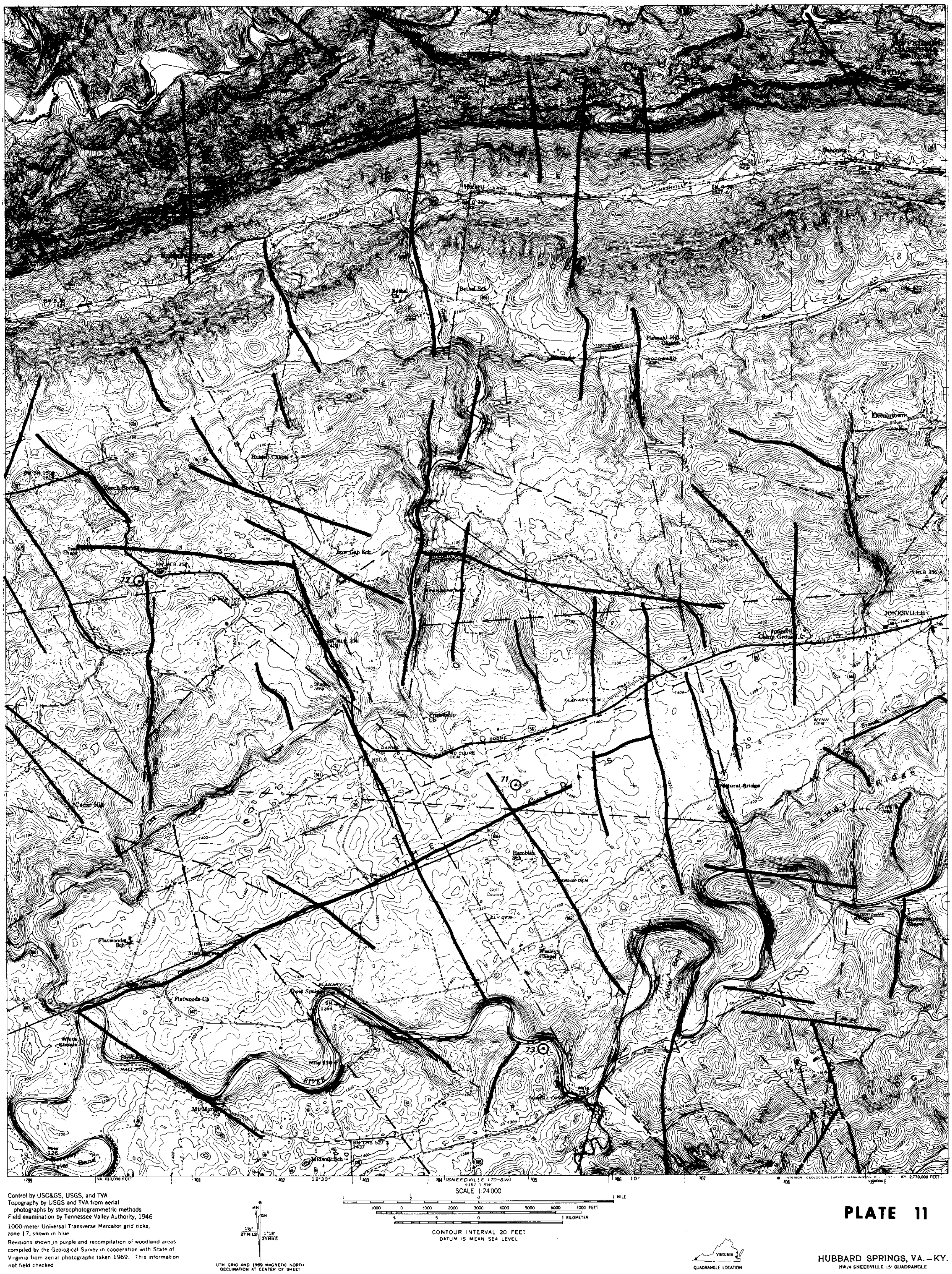


PLATE 11

HUBBARD SPRINGS, VA.–KY.
NW/4 SNEEDVILLE 15' QUADRANGLE

Control by USC&GS, USGS, and TVA
Topography by USGS and TVA from aerial photographs by stereophotogrammetric methods
Field examination by Tennessee Valley Authority, 1947

Revision shown in purple and recompilation of woodland areas compiled in cooperation with State of Virginia from aerial photographs taken 1969. This information not field checked

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

QUADRANGLE LOCATION

PLATE 12

BEN HUR, VA.
170-NE
N3637.5-W8300/7.5

PLATE 13

STICKLEYVILLE, VA.
179-NW
N3637.5—W8252.5/7.5


Duffield
(Plum Grove 179-SE)
Control by USC&GS, USGS, and TVA
Topography by USGS and TVA from aerial photographs by stereophotogrammetric methods
Field examination by Tennessee Valley Authority, 1947
SCALE 1:24000
CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL
UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
VIRGINIA
DUFFIELD, VA.
179-NE
1947
PHOTOREVISED 1969

PLATE 14

Mapped by the Tennessee Valley Authority
Edited and published by the Geological Survey

Control by USGS, NOS/NOAA, and Tennessee Valley Authority

Topography by photogrammetric methods from aerial photographs taken 1953. Field checked 1955. Revised from aerial photographs taken 1973. Field checked 1974

Polyconic projection. 1927 North American datum
10,000-foot grids based on Tennessee coordinate system, Kentucky coordinate system, south zone, and Virginia coordinate system, south zone
1000-metre Universal Transverse Mercator grid ticks, zone 17, shown in blue

UTM GRID AND 1974 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

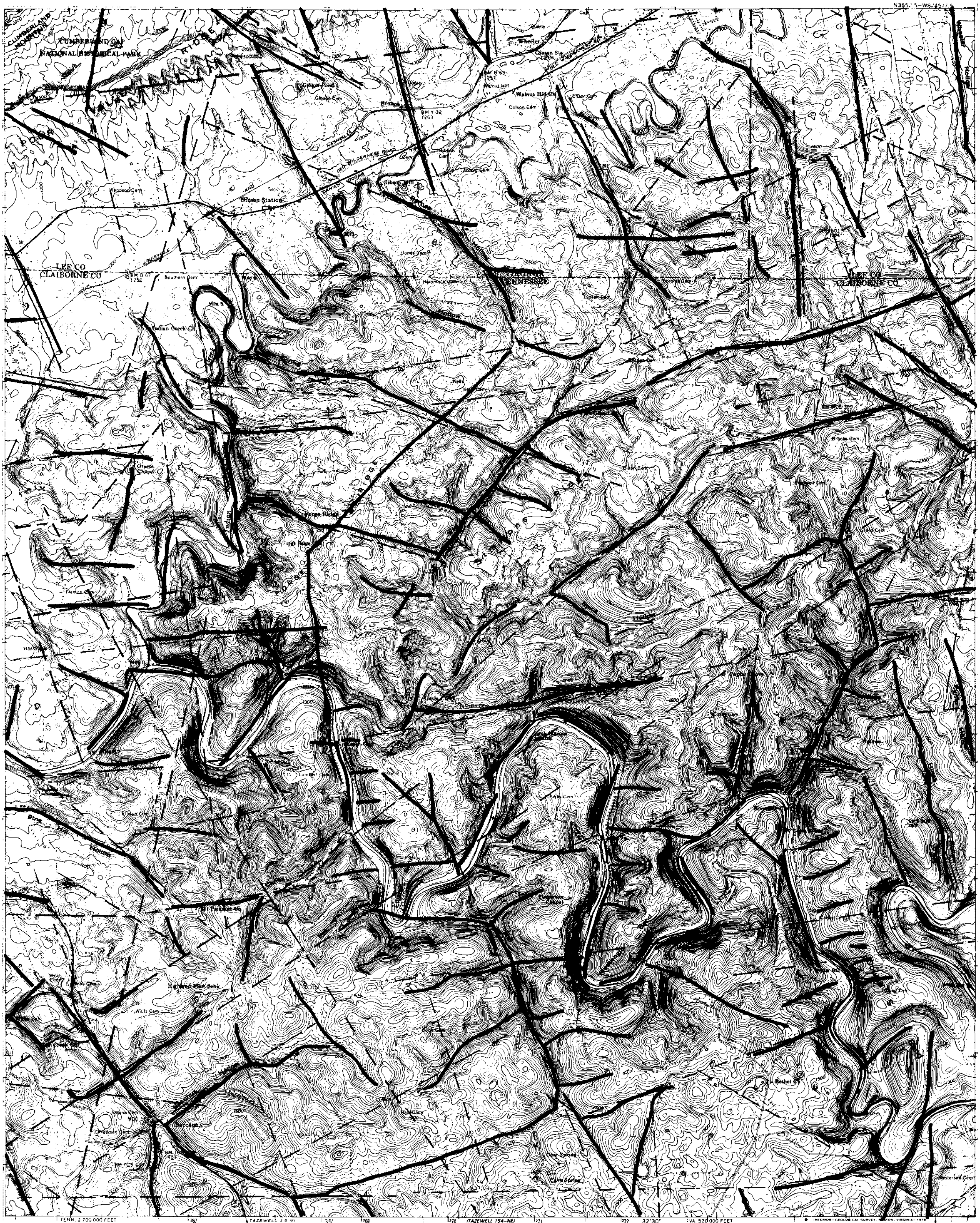
SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

PLATE 15

MIDDLESBORO SOUTH, TENN.—KY.—VA.
SW/4 MIDDLESBORO 15' QUADRANGLE
N3630—W8337.5/7.5



Mapped and edited by Tennessee Valley Authority
Published by the Geological Survey

Control by NOS/NOAA, USGS, and TVA

Topography by photogrammetric methods using aerial photographs taken 1953. Map field checked by TVA, 1956

Polyconic projection. 1927 North American datum
10,000 foot grid based on Tennessee and Virginia (South) rectangular coordinate systems
1000 meter Universal Transverse Mercator Grid ticks, Zone 17, shown in blue

Revisions shown in purple and recompilation of woodland areas

UTM GRID AND 1978 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

PLATE 16

WHEELER, TENN.-VA.

PLATE 17

COLEMAN GAP, TENN.-VA.

N3630—W8322.5/7.5

Mapped, edited, and published by Tennessee Valley Authority

Control by USGS, USC&GS, and Tennessee Valley Authority

Topography by photogrammetric methods from aerial photographs. Field checked 1946

Polyconic projection. 1927 North American datum
10,000-foot grids based on Tennessee coordinate system and Virginia coordinate system, south zone
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue

Revisions shown in purple and recompilation of woodland areas

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

Contour interval 20 feet

Datum is mean sea level

TENNESSEE
QUADRANGLE LOCATION

PLATE 18

BACK VALLEY, TENN.-VA.
161-SE
N3630—W8315/7.5

Control by USC&GS, USGS, and TVA
Topography by USGS and TVA from aerial photographs by stereophotogrammetric methods
Field examination by Tennessee Valley Authority, 1946

1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue

Revisions shown in purple and recompilation of woodland areas compiled by the Geological Survey in cooperation with Commonwealth of Virginia from aerial photographs taken 1969. This information not field checked

MN GN 1½° 27 MILS 1°18' 23 MILS
UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 KILOMETER
CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

TENNESSEE
QUADRANGLE LOCATION

PLATE 19

SNEEDVILLE, TENN.-VA.
170-SW
N3630-W8307.5/7.5

Mapped, edited, and published by Tennessee Valley Authority

Control by USGS, USC&GS, and Tennessee Valley Authority

Topography by photogrammetric methods from aerial photographs. Field checked 1947

Polyconic projection 1927 North American datum
10,000-foot grids based on Tennessee coordinate system and Virginia coordinate system, south zone
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue

Revisions shown in purple and recompilation of woodland areas

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24000

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

TENNESSEE
QUADRANGLE LOCATION

PLATE 20

KYLES FORD, TENN.-VA.
170-SE
1947

Mapped, edited and published by Tennessee Valley Authority

Control by USGS, USC&GS, and Tennessee Valley Authority

Topography by photogrammetric methods from aerial photographs Field checked 1947

Polyconic projection 1927 North American datum
10,000-foot grids based on Tennessee coordinate system and Virginia coordinate system, south zone
1000-meter Universal Transverse Mercator grid ticks, zone 17, shown in blue

Revisions shown in purple and recompilation of woodland areas compiled by the Geological Survey in cooperation with State of

MN GN 1½° 27 MILS 1°09' 20 MILS
UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000
1 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
.5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

TENNESSEE
QUADRANGLE LOCATION

PLATE 21

LOONEYS GAP, TENN.–VA.
N3630—W8252.5/7.5

APPENDIX
OIL WELL INFORMATION

Well No.	Well Name	Operator	Year started	Total Depth	Field and (Quadrangle)	Probable Position on Sub-surface Anticline	Negative Location Factors Affecting Production	Production or (Show) Formation	Distance from Nearest Fracture Trace (Feet)	Trend of Nearest Fracture Trace
1	Gilbert Lee No. 1	L. E. Bales et al.	1922	303*	R.H. (R.H.)	East limb	Edge of field	Clinch-Clinton	<100’	N
2	Gilbert Lee No. 2	L. E. Bales et al.	1924	1400	R.H. (R.H.)	East limb	Edge of field	Trenton, (Trenton)	100-200’	E
3	Lon Montgomery	Lon Montgomery?	1925?	2400?	R.H. (R.H.)	Crest	Edge of field	(Undet.)	100-200’	N
4	Billy Parkey No. 1	Johnson, Head, and Gilmore	1928 or 9	2650?*	W.C. (E.)	Off structure	Low on west limb	(Undet.)	200-1000’	NE
5	Jack Asher	Jack Asher?	1929?	900?*	R.H. (R.H.)	East limb	Edge of field	(Undet.)	<100’	N
6	W. B. Fulton	W. B. Fulton	1934	1498	R.H. (R.H.)	East limb	Edge of field		<100’	N
7	Pritchard	?	1937	463**	R.H. (R.H.)	East limb	Edge of field		100-200’	E
8	Ingram	Ingram or Holcombe	1938	1870	R.H. (R.H.)	Crest	Edge of field		200-1000’	N
9	B. C. Fugate No. 1	Walker et al.	1942	1115	R.H. (C.G.)	West limb		Trenton	100-200’	NNE
10	B. C. Fugate No. 2	Walker et al.	1942	2003	R.H. (C.G.)	West limb		(Trenton)	>1000’	NNE
11	B. C. Fugate No. 3	Virginia Lee Oil Co.	1943	1773	R.H. (C.G.)	West limb		Trenton, (Trenton)	< 100’	NNW
12	Bob Lemons No. 1	O. A. Larazola	1939	3261	R.H. (C.G.)	West limb		(Moccasin)	< 100’	NNE
13	Eli Brooks No. 1	Virginia Lee Oil Co.	1943	4079	W.C. (C.G.)	Crest	Down plunge	Cayuga, (Cayuga, gas)	200-1000’	NW
14	Bob Lemons No. 2	Fred Seal et al.	08/14/45	1222	R.H. (C.G.)	West limb		Trenton, (Trenton, oil & gas)	< 100’	NNE
15	Bob Lemons No. 3	Fred Seal et al.	10/30/45	1590	R.H. (C.G.)	West limb		(Trenton, oil & gas)	200-1000’	NNE
16	Fugate Estate No. 1	Rouge Oil Co.	02/15/46	1609	R.H. (C.G.)	West limb		Moccasin, (Trenton)	< 100’	NNE
17	B. C. Fugate 2-B	Rouge Oil Co.	04 1946	1908	R.H. (C.G.)	West limb		(Reedsville)	200-1000’	NNE
18	Fugate Estate No. 2	Rouge Oil Co.	05/17/46	1215	R.H. (C.G.)	West limb		Trenton, (Trenton?)	200-1000’	NE
19	Fugate Estate No. 3	Rouge Oil Co.	07/15/46	1320	R.H. (C.G.)	West limb		Trenton, (Trenton, oil & gas)	200-1000’	NE
20	Fugate Estate B-2	Rouge Oil Co.	09/16/46	1769	R.H. (C.G.)	West limb		Trenton-Eggleston	200-1000’	NNW
21	Gilbert Lee No. 3	Sheaffer et al.	1946	1869	R.H. (R.H.)	East limb	Edge of field	Trenton, (Trenton?)	100-200	E
22	Fugate Estate B-3	Rouge Oil Co.	12/04/46	2037	R.H. (C.G.)	West limb		Trenton?, (Undet.)	< 100’	NNE
23	Fugate Estate No. 4	Rouge Oil Co.	10/15/46	1526	R.H. (C.G.)	West limb			100-200’	NE
24	L. E. Bales No. 1	Rouge Oil Co.	10/10/46	1766+	R.H. (C.G.)	West limb		Trenton?, (Undet.)	< 100’	NNE
25	Stacey Nelson No. 1	Rouge Oil Co.	11 1946	1575	R.H. (C.G.)	West limb		Trenton?, (Undet.)	> 1000’	NNE
26	G. C. Dean No. 1	Rouge Oil Co.	1946 or 7	1766+	R.H. (C.G.)	West limb		Trenton?, (Undet.)	200-1000’	NNW
27	Josh Dean No. 1	Rouge Oil Co.	11/03/46	1806	R.H. (C.G.)	West limb		Trenton?, (Undet.)	200-1000’	NE
28	George S. Yeary No. 1	E. R. Morris	01 1947?	3034	R.H. (E.)	West limb low	Edge of field	(Eggleston?)	200-1000’	NNE
29	Charles Hobbs No. 1	Rouge Oil Co.	?	?	R.H. (R.H.)	Crest		Trenton, (Undet.)	200-1000’	N
30	Henly Sutton	Rouge Oil Co.	12 1946	2707 deepen-ed to 4000	W.C. (C.G.)	West limb	Down plunge	(Trenton, gas)	>1000’	NW
31	H. B. Nolan No. 1	E. R. Morris	05/20/47	2373	R.H. (R.H.)	Low on west limb	Edge of field		200-1000’	N
32	Joe Dean No. 1	Rouge Oil Co.	01/20/47	1574	R.H. (C.G.)	West limb		Trenton?, (Undet.)	< 100’	NNE
33	Patton Ely No. 1	Stacy et al.	01/24/47	2900+	R.H. (C.G.)	West limb		(Trenton)	>1000’	NNW
34	Andy Ely No. 1	Rouge Oil Co.	01/27/47	2166	R.H. (C.G.)	West limb		Trenton?, (Trenton?)	>1000’	NNE
35	W. S. Riley No. 1	Rouge Oil Co.	03/10/47	355±**	R.H. (R.H.)	West limb			200-1000’	E

APPENDIX
OIL WELL INFORMATION

Well No.	Well Name	Operator	Year started	Total Depth	Field and (Quadrangle)	Probable Position on Sub-surface Anticline	Negative Location Factors Affecting Production	Production or (Show) Formation	Distance from Nearest Fracture Trace (Feet)	Trend of Nearest Fracture Trace
36	R. L. Bales No. 1	Rouge Oil Co.	04/07/47	1867	R.H. (R.H.)	Crest		Trenton, (Trenton, gas)	<100'	N
37	Joe Chadwell No. 1	Rouge Oil Co.	04/13/47	2015	R.H. (E.)	West limb	Edge of field	(Sequatchie, gas)	100-200'	NE
38	M. Davis No. 1	Robert Vorhees	04 1947?	4405	W.C. (R.H.)	East limb low		(Trenton)	200-1000'	N
39	Cleve Dean No. 1	Rouge Oil Co.	04 1947	182?**	R.H. (C.G.)	West limb			200-1000'	NNE
40	W. T. Jenkins No. 1	Rouge Oil Co.	04 1947?	210**	R.H. (C.G.)	West limb			200-1000'	NNE
41	O. Cavins No. 1	K. R. Wilson	06 1947	2001*	W.C. (B.V.)	East limb low	Near syn-cline axis	(Undet.)	>1000'	NNE
42	Gilbert Lee No. 1	American Trading Products Co.	06/07/47	2108	R.H. (R.H.)	East limb	Edge of field	(Clinton? and Trenton?)	100-200'	N
43	Logan Snodgrass No. 1	Rouge Oil Co.	06 1947	1832	R.H. (C.G.)	Crest		(Undet.)	< 100'	NNE
44	Owens No. 1	Fred Shaner et al.	07 1947	2325	R.H. (R.H.)	West limb	Edge of field	(Trenton, oil & gas)	200-1000'	N
45	E. C. H. Rosenbaum No. 1	K. R. Wilson	06 1947	1456**	W.C..(R.H.)	West limb very low			100-200'	N
46	Sensebaugh Heirs No. 1	K. R. Wilson	06/22/47	2002	R.H. (R.H.)	West limb			100-200'	ENE
47	Glen Yeary No. 1	Dunnigan and Malloy	07 1947	2835	R.H. (C.G.)	West limb		Trenton?, (Trenton?)	200-1000'	NNE
48	W. S. Riley No. 2	Rouge Oil Co.	07 1947	1840	R.H. (R.H.)	Crest		Trenton, (Undet.)	200-1000'	N
49	Clarence Dean No. 1	Ted Smith Oil Co.	07/12/47	2085	R.H. (C.G.)	West limb		(Undet.)	>1000'	
50	B. C. Fugate No. 1	H. and R. Oil Co.	08/09/47	1494	R.H. (C.G.)	West limb		Moccasin, (Trenton)	200-1000'	NNE
51	Dewey Lee No. 1	H. and R. Oil Co.	10/15/47	2156	R.H. (R.H.)	Crest		Trenton, (Clinton)	200-1000'	WNW
52	Cleve Dean No. 2	Rouge Oil Co.	10/08/47	2300±	R.H. (C.G.)	West limb		(Moccasin)	>1000'	NNE
53	Grant Smith No. 1	H. and R. Oil Co.	11/03/47	2188	R.H. (R.H.)	Crest-down plunge	Edge of field	(Trenton)	100-200'	NE
54	Jim Ray No. 1	Rouge Oil Co.	01 1948	?	R.H. (R.H.)	Crest		Trenton?, (Undet.)	<100'	N
55	Clifford Yeary No. 1	H. and R. Oil Co.	01 1948	3130?	R.H. (C.G.)	Steep SW plunge		(Undet.)	200-1000'	NNE
56	J. R. Osborn No. 1	Rouge Oil Co.	12 1947	?	R.H. (R.H.)	Crest		Trenton, (Undet.)	100-200'	WNW
57	J. W. Campbell No. 1	Rouge Oil Co.	02 1948?	?	R.H. (E.)	Crest		Trenton?, (Undet.)	< 100'	NW
58	Charles Marcum No. 1	H. and R. Oil Co.	01 1948	1718?	R.H. (E.)	Crest		Trenton, (Trenton, gas)	< 100'	NE
59	Beatty Harris No. 1	James Webb	06/17/48	?	R.H. (R.H.)	Crest			100-200'	N
60	Abney Heirs No. 1	Cardwell and Stacy	06 1948	1798	R.H. (R.H.)	Crest		Trenton, (5 shows: Trenton to surface)	100-200'	NW
61	C. B. Hobbs No. 1	H. and R. Oil Co. & Rouge Oil Co.	05 1948	1850	R.H. (R.H.)	Crest		Trenton, (Undet.)	100-200'	N
62	Jim Ray No. 2	Rouge Oil Co.	05/14/48	?	R.H. (R.H.)	Crest		Trenton, (Undet.)	< 100'	N
63	C. E. Hobbs No. 2	Rouge Oil Co.	05/17/48	2200+	R.H. (R.H.)	Crest		Moccasin, (Undet.)	200-1000'	E
64	M. E. McCurry No. 1	Rouge Oil Co.	09/13/48	2318	R.H. (R.H.)	West limb		Trenton, (Undet.)	< 100'	E
65	Lee Marcum No. 1	?	1949?	?	R.H. (R.H.)	Crest		(Undet.)	200-1000'	E
66	L. E. Bales No. 2	Rouge Oil Co.	02 1949?	2252?	R.H. (C.G.)	West limb		(Undet.)	200-1000'	NNE
67	C. H. Frye No. 1	Adam Stacy	09 1949?	1695	R.H. (R.H.)	West limb		Trenton, (Trenton)	200-1000'	NW
68	Alfred Shackleford No. 1	Adam Stacy	11 1949	2780	R.H. (R.H.)	West limb		(Undet.)	200-1000'	E
69	Myrtle Campbell No. 1	Rouge Oil Co.	01/05/50	1320?	R.H. (E.)	West limb		Trenton?, (Undet.)	< 100'	NW
70	Sibbie Ramsey No. 1	Adam Stacy	11 1949	2100±	R.H. (E.)	West limb		Reedsville (Undet.)	< 100'	NW
71	D. C. McClure No. 1	Cedar Valley Oil Co.	1915	3250±*	W.C. (H.S.)	Syncline trough	Cedars, syncline		200-1000'	NNW
72	Charles Phipps	Clarence Ellison	1947	1902*	W.C. (H.S.)	Near crest	Down plunge		200-1000'	N

APPENDIX
OIL WELL INFORMATION

Well No.	Well Name	Operator	Year started	Total Depth	Field and (Quadrangle)	Probable Position on Sub-surface Anticline	Negative Location Factors Affecting Production	Production or (Show) Formation	Distance from Nearest Fracture Trace (Feet)	Trend of Nearest Fracture Trace
73	M. H. Snodgrass	C. F. Deaton	1947	1706**	W.C. (H.S.)	Crest?	Sandy ridge anticline	(Undet.)	200-1000'	NNE
74	Candy Cawood	Herbert Gardener	1947	150**	W.C. (R.H.)	Crest?	Down plunge?		200-1000'	NNW
75	Anthony Ely	R. R. Murray	1947	2532	W.C. (R.H.)	West limb	Down plunge?	(Reedsville, gas)	< 100'	NNW
100	G. D. Lee No. 1	G. D. Lee	1948	2254	R.H. (R.H.)	Crest		Production, (Gas 3), Undet.	200-1000'	NW
101	Grover C. Dean No. 2	Rouge Oil Co.	1953	4451	R.H. (C.G.)	West limb		(Oil and gas), Undet.	200-1000'	NW
102	C. E. Hobbs No. 3	National Supply Inc. (Rouge Oil)	1952	1698	R.H. (R.H.)	Crest		Production, (Undet.)	< 100'	N
103	L. E. Bales	Ewing Oil Co.	1953	2167	R.H. (C.G.)	West limb		Production, (Undet.)	200-1000'	NNE
104	Manford Lee No. 6	Ewing Oil Co.	1953	2000	R.H. (R.H.)	East limb		Production, (Undet.)	200-1000'	N
105	C. F. Dean No. 3	Ewing Oil Co. (T. B. Smith)	1954	2000	R.H. (C.G.)	West limb		(Undet.)	>1000'	NW
106	Mrs. Stacy Nelson No. 1	White Moore (Rouge Oil Co.)	1954	1812	R.H. (C.G.)	West limb		(Undet.)	100-200'	NNE
107	W. C. Martin, Heirs No. 1	Rouge Oil Co.	1955	4072	W.C. (C.G.)	West limb	Down plunge	(Undet.)	200-1000'	NW
108	Roy E. Blesoe No. 1	J. W. Miloncus	1963	2207	B.H. (B.H.)	Crest		Undet., (Undet.)	< 100'	N
109	Ryland Ramsey No. 1	J. W. Miloncus	1964	2114	R.H. (R.H.)	Crest		(Undet.)	200-1000'	N
110	Browning Wynn No. 1	J. W. Miloncus	1964	2000*	B.H. (B.H.)	West limb	Down plunge	(Undet.)	100-200'	NNW
111	L. S. Bales No. 1	Shell Oil Co.	1965	8020	W.C. (B.V.)	East limb low		(Oil and gas), (Undet.)	200-1000'	NE
112	Fred B. Fugate No. 1	M. L. McGinnis	1965	610**	R.H. (E.)	West limb		(Undet.)	< 100'	NW
113	Dewey M. Livesay	David Law	1967	1200*	B.H. (B.H.)	East limb	Down plunge	(Undet.)	200-1000'	NNW
114	Grace Cobb	Wilshire Oil Co.	1967	2572	B.H. (B.H.)	West limb		Undet. (Undet.)	200-1000'	WNW
115	J. V. Graham No. 1	Wilshire Oil Co.	1967	2781	B.H. (B.H.)	West limb		Initial gusher, (Oil and gas)	< 100'	NW
116	Ikey Bacon No. 2	Trans-State Oil	1967	1670±	R.H. (R.H.)	Crest		?, (Undet.)	100-200'	WNW
117	J. V. Graham No. 3	Wilshire Oil Co.	1967	2725	B.H. (B.H.)	West limb		(Undet.)	200-1000'	NW
118	J. V. Graham No. 2	Trans-State Oil	1968	3115	B.H. (B.H.)	West limb		(Undet.)	200-1000'	NW
119	Josh A. Dean No. 2	Trans-State Oil	1970	2007	R.H. (C.G.)	West limb		Probable Trenton prod., (Undet.)	< 100'	NW
120	Logan Snodgrass No. 101	Tamik Oil	1974	2135	R.H. (C.G.)	Crest		Undet., (Undet.)	200-1000'	NNE
121	Wolfe-Snodgrass No. 1	Lee Oil Drilling Co.	1975	2166	R.H. (R.H.)	Crest		Undet. gas, (Trenton and below)	200-1000'	NW
122	Roy E. Bledsoe No. 102	Tamik Oil	1975	2379	B.H. (B.H.)	West limb		(Undet.)	200-1000'	N
123	Logan Snodgrass No. 103	Tamik Oil	1975	1853	R.H. (C.G.)	Crest		Trenton & Moccasin, (Undet.)	100-200'	NNE
124	Wayne Burgan No. 1	Lee Oil Drilling Co.	1976	3998	R.H. (R.H.)	West limb		(Undet.)	200-1000'	WNW
125	Don Grabeel No. 1	Lee Oil Drilling Co.	1977	7209	W.C. (R.H.)	Low on west limb		(Undet.)	>1000'	NE
126	Lloyd Harris No. 1	Lee Oil Drilling Co.	1977	1762	R.H. (C.G.)	West limb		(Undet.)	100-200'	NNE

Explanation

a. Data for well numbers 1-25 is from Miller and Fuller (1954, Table 11).

b. All holes penetrated Trenton Limestone except:
*Hole bottomed in unspecified formation
**Hole abandoned before reaching Trenton Limestone

c. Abbreviations for oil fields and 7.5-minute quadrangles are:
B. H. Ben Hur quadrangle, Plate 12; Ben Hur Field
B. V. Back Valley quadrangle, Plate 18
C. G. Colemap Gap quadrangle, Plate 17
E. Ewing quadrangle, Plate 9
H. S. Hubbard Springs, quadrangle, Plate 11
R. H. Rose Hill quadrangle, Plate 10; Rose Hill field
W. C. Wild cat Well

d. Where formation name is repeated, show is at different level than production. Production and shows are oil unless otherwise stated. Undet. — Undetermined.

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LINEAMENT AND FRACTURE TRACE ANALYSIS AND ITS APPLICATION TO OIL EXPLORATION IN LEE COUNTY, VIRGINIA