SUBSURFACE STRUCTURE OF THE EASTERN KENTUCKY GAS FIELD

BY

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ABSTRACT

The Eastern Kentucky (or Big Sandy) gas field is a coelescence of many small gas fields. Parts of the field have produced continuously for more than 60 years. The Devonian Ohio Shale is the principal producing horizon, but production also comes from the Mississippian Newman Limestone, and several Pennsylvanian sandstones.

The purpose of this study is to locate subsurface structures that may affect shale gas production in the Eastern Kentucky field.

Detailed structure contour maps drawn on the top and bottom of the Ohio Shale, using data from 4,200 wells, show that the. Ohio Shale in the southwestern portion of the field dips regionally to the south, whereas in the northeast portion of the field, the Devonian dips regionally to the southeast. The divergence in dip creates a broad structural arch in Pike and Floyd Counties that plunges southeastward.

The structures found in this study formed during several episodes of deformation, responding to stress and strain involving the basement and cover, as well as just the sedimentary cover.

The Paint Creek Uplift, a broad, low basement arch in Morgan, Magoffin, and Breathitt Counties was apparently active throughout the Paleozoic and influenced the development of structures in the gas field on its northwestern boundary.

The D'Invilliers anticlinal-synclinal structure in eastern Pike County is located over a southern extension of a proposed basement fault in West Virginia and along the New York-Alabama Lineament. The D'Invilliers structure was later cut by a strike-slip fault.

The Warfield fault in Martin County is not part of the southern boundary of the Rome Trough but lies just south of the boundary, and is on the uplifted southeastern rim of the trough. Offset on the fault in the subsurface, from the Mississippian Newman Limestone to the basement,. is down to the south, whereas offset at the surface is up to the south.

Both the Warfield and D'Invilliers structures are considered basement involved, but both may also contain some detachment deformation.

Certain faults, such as the cross fault cutting the Warfield fault, showgrowth during early Mississippian sedimentation, and the Warfield fault was determined not to be the southeastern margin of the Rome Trough as was previously suspected. Several linear zones of structural disruption, at high angles to the trend of the detached Pine Mountain thrust, are interpreted to be tears limited to the sedimentary cover.

INTRODUCTION

A. Purpose of the Investigation

The Eastern Kentucky gas field produces commercial quantities of natural gas from the Devonian Ohio Shale over a wide area. Discovering the variables which control production of natural gas from the Devonian shale in the eastern Kentucky area may lead to new production in surrounding areas, as the shale covers broad areas of the Appalachian basin. Aspects such as surface fractures (Long, 1979), subsurface fractures (Evans, 19791, and production (deWys, 1979) have been investigated by previous workers at West Virginia University and other institutions.

The purpose of this study is to define and interpret the subsurface structure of the Eastern Kentucky gas field, so that any faults or folds can later be compared to the production, stratigraphy, fractures, geochemistry, etc., of the Ohio Shale. The end goal of this research is to expand gas production from the Devonian Ohio Shale into other areas.

B. Location

The giant Eastern Kentucky gas field is located in the southeast corner of Kentucky. This field is a nearly continuous area of production, covering some 3,000 square miles (4,800 square kilometers) within part or all of the counties of Breathitt, Floyd, Johnson, Knott, Lawrence, Letcher, Magoffin, 'Martin, Perry, and Pike. (Figure 1)

C. Regional Structure

Plate 1 shows the geologic setting of the Eastern

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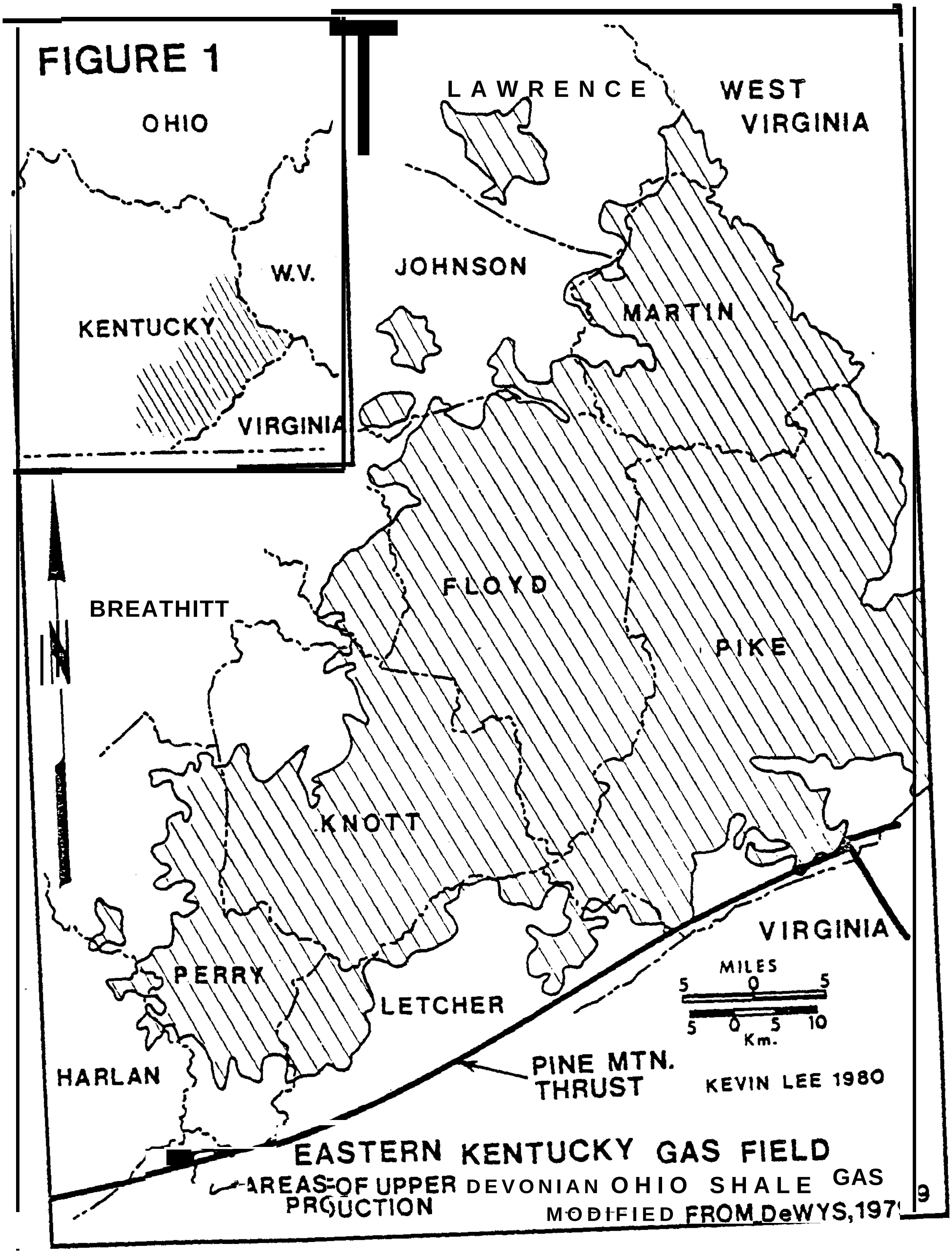

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Kentucky gas field, and all structures and cored wells mentioned or described in this study. The field is located between the eastern flank of the Cincinnati Arch and deeper parts of the Appalachin basin on the east.

Regional dip in southeastern Kentucky varies according to the stratigraphic level. Near the surface (Figure 2 and Plate 1), structural dip is to the northwest toward the eastern Kentucky syncline. The Mississippian-Devonian strata dip in the opposite direction, to the southeast (Figure 3). The basement has far more local structural relief and includes structures such as the Rome Trough, Pike and Perry County domes, and the Floyd County channel (Figure 4).

The northern border of the Eastern Kentucky field consists of a series of basement-related east-west faults, which are thought to be components of the Rome Trough fault system (Ammerman and Keller, 1979). The Rome Trough is an asymmetric graben structure thought to be associated with a Cambrian rift system (Harris, 1975). The larger faults are seen at the surface in Pennsylvanian and older rocks, indicating they have had additional movement during the Pennsylvanian and even later times.

The Eastern Kentucky field is bordered by Pine Mountain to the southeast. Pine Mountain is the surface expression Of competent Carboniferous units dipping eastward above a major ramp of adetachmentthrust, The thrust extends from the Devonian shale across more competent units to either the surface

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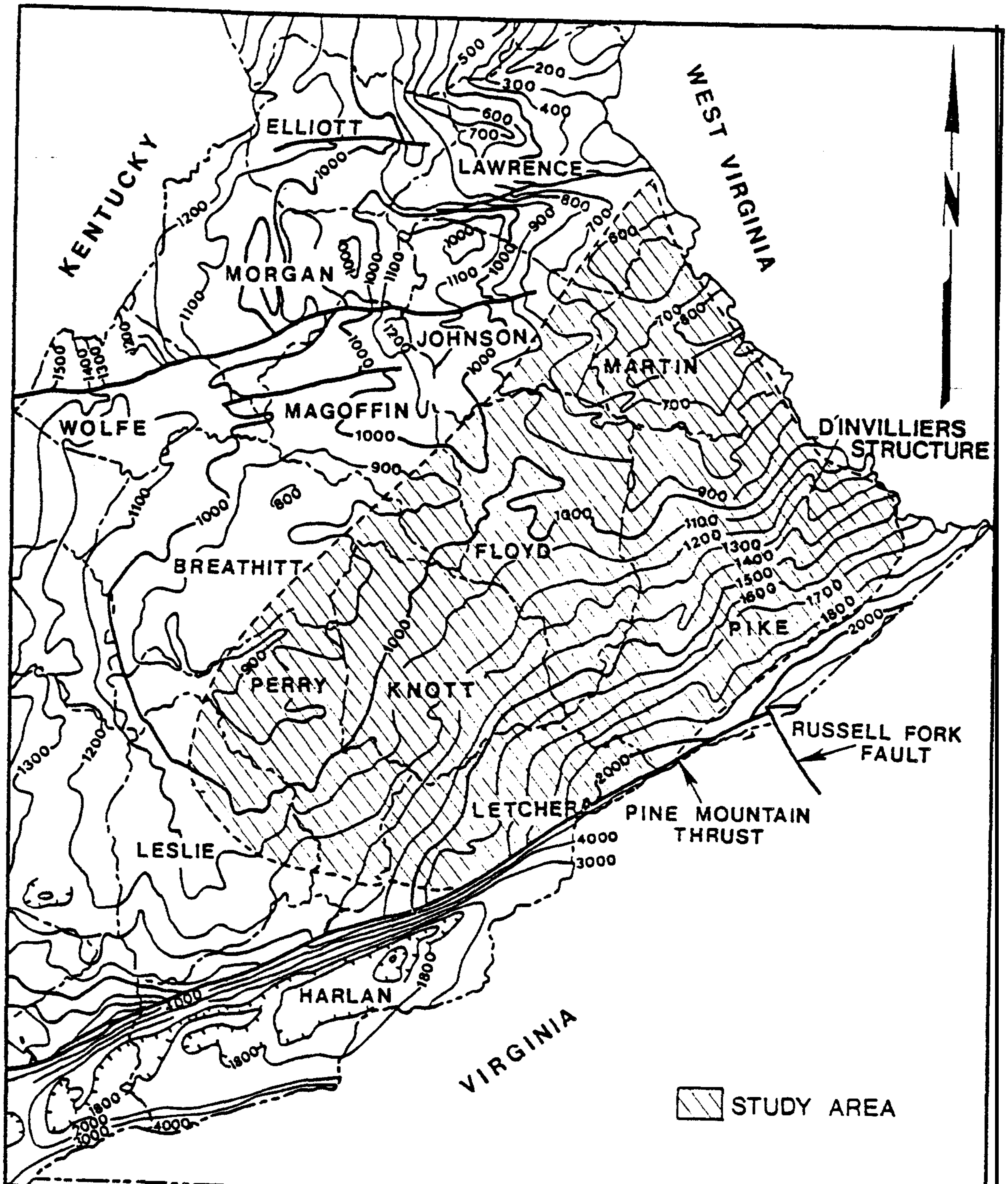

FIGURE 2. STRUCTURE CONTOUR MAP, PENNSYLVANIAN FIRE CLAY COAL after McFARLAN, 1943

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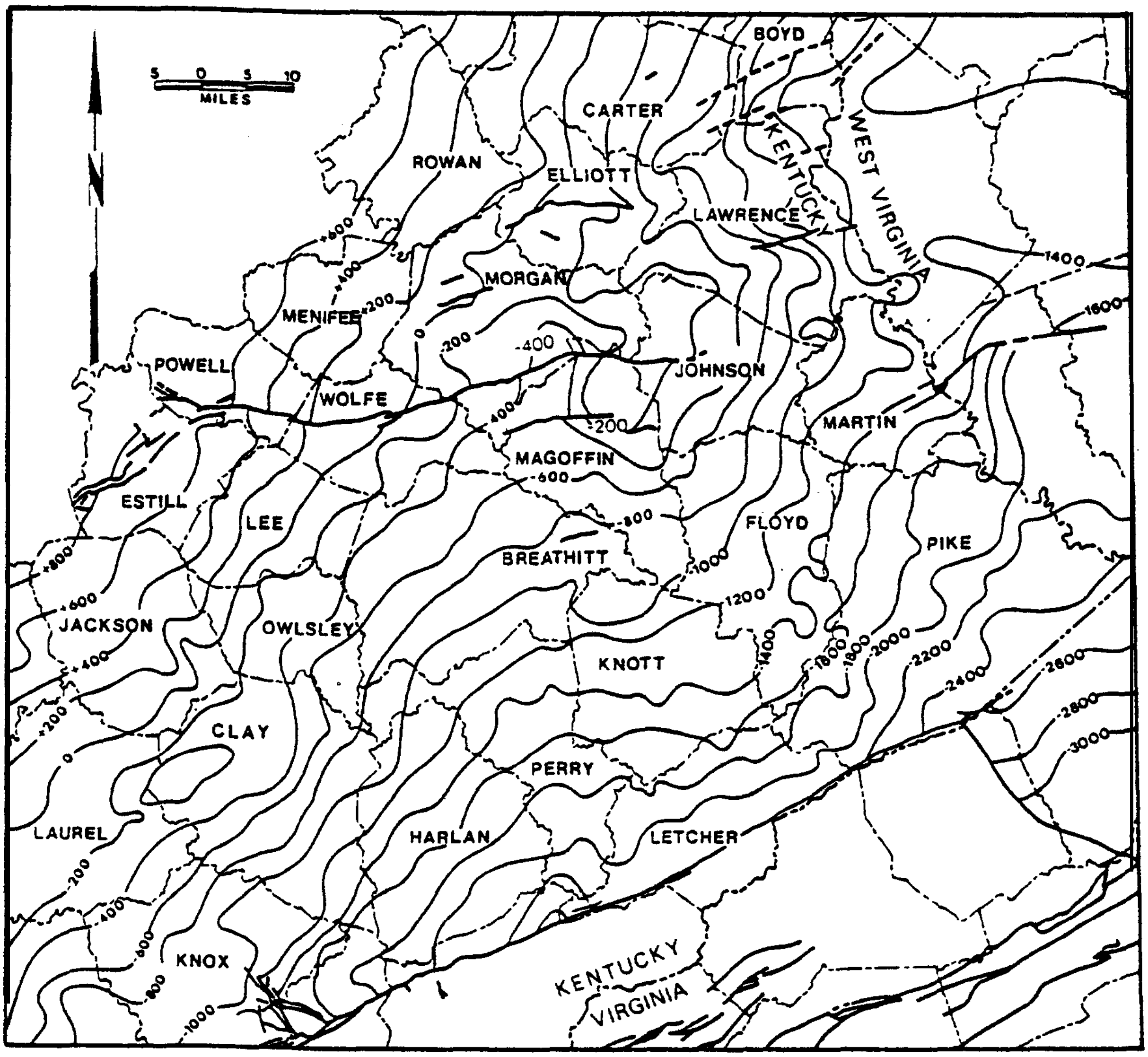

FIGURE 3 - STRUCTURE CONTOUR MAP ON TOP OF THE OHIO SHALE

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MODIFIED FROM PROVO.1977

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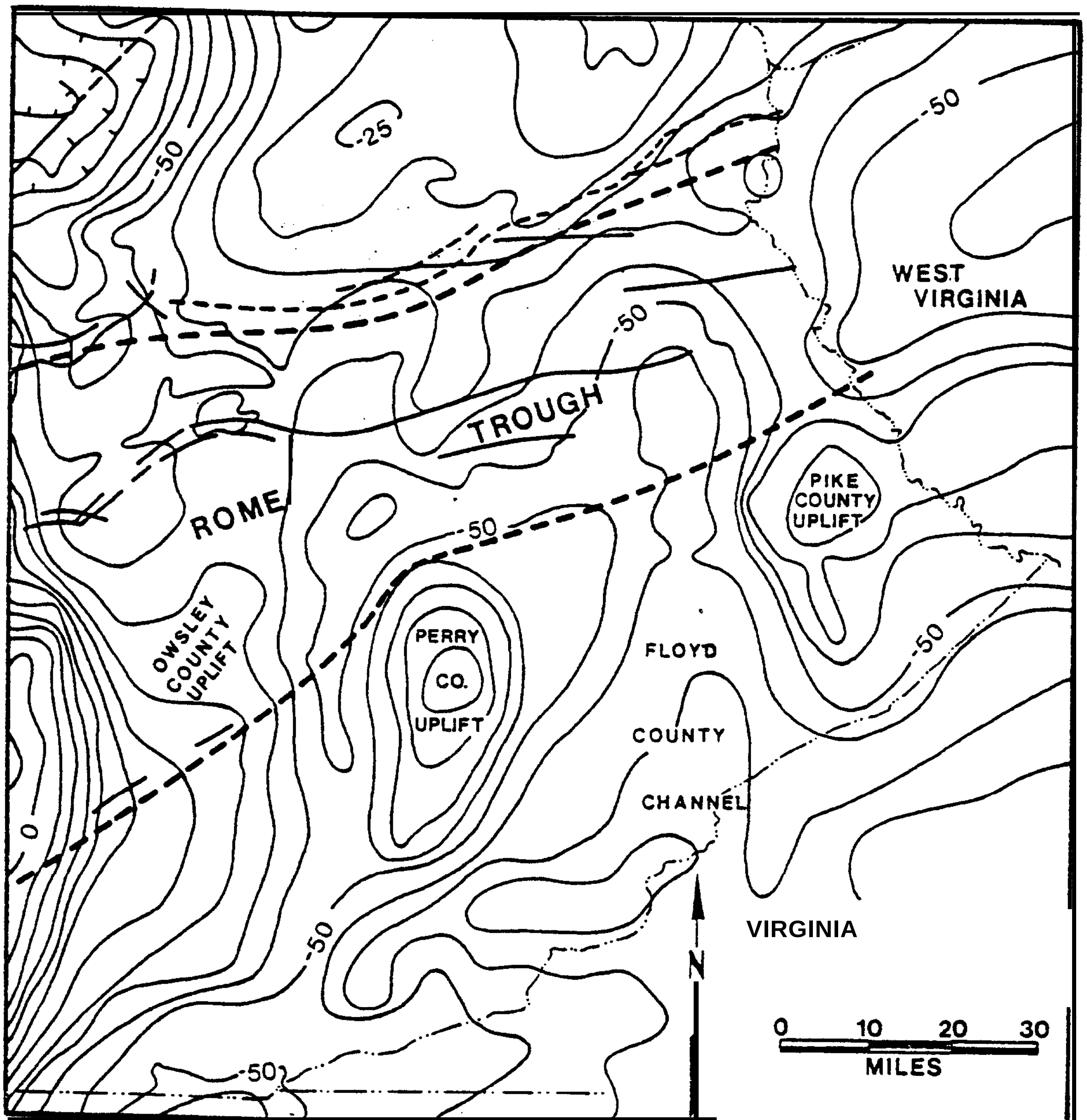

FIGURE 4. BOUGUER GRAVITY MAP OF EASTERN KENTUCKY
MODIFIED FROM AMMERMAN AND KELLER, 1979

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or to an incompetent horizon in the Pennsylvanian clastics (Harris and Milici, 1977).

D. Previous Investigations

There were no detailed regional subsurface structure maps available for eastern Kentucky at the onset of this study. The very high success ratio of shale wells drilled into the field negated the necessity and expense of producing detailed structural maps. Nearly 90% of all shale wells drilled within the Big Sandy area are economically productive (Hager, 1979).

Several workers have discussed the structure of the Big Sandy area, including Billingsley (1934), Hunter (1935), and McFarlan (1943). Hunter and Billingsley both showed Production from within the field to be from fracture porosity. McFarlan included regional geologic structure maps of eastern Kentucky drawn on top of the Fire Clay Coal (Figure 2), and on top of the Ohio Shale (from an unstated number of data points). The Fire Clay Coal map established shallow regional dip to the northwest and outlines the general trend of the D'Invilliers anticline. The Ohio Shale map showed regional dip at that level to be to the southeast.

The Kentucky Geological Survey published surface structural geology maps in the eastern Kentucky area by County, in series VI publications during the 1920's. Most of these maps were developed prior to intense drilling and are now out of print.

Subsequent workers, including Provo (1977), Fulton (1979) and deWys (1979) have drawn structural maps and cross

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sections in *the* area, but they used only several hundred data points. Those maps show regional structure, but the wide spacing of the wells used makes definition of small scale and low relief structures impossible. Provo did show that regional dip at the Devonian shale level is to the southeast, just the opposite from the dip of the Fire Clay Coal. However, small structures not capable of being defined by Provo and de Wys may be extremely important to shale-gas production, and, therefore, detailed structural analysis is paramount to a critical evaluation of the causes of the shale production.

E. Regional Stratigraphy

The rocks that make up the regional stratigraphy for the eastern Kentucky field are illustrated in Figure 5.

The "Corniferous" Limestone is a thick, hard, grey limestone. "Corniferous" is a catch-all name for the Silurian Lockport Dolomite and Salina Formation and the Devonian Eelderberg Formation and Cnondaga Limestone. The contact between the "Corniferous" Limestone and the overlying West Falls Formation is erosional (Hunter, 1935).

The Rhinestreet member of the West Falls Formation is a dark, organic-rich shale that is present only in the eastern section of the field in Pike County.

The Olentangy Shale is 100 to 200 feet (30 to 61 meters) thick and is a hard, light-colored shale. It is not as friable as the shale at the base of the Ohio Shale.

The Ohio Shale, or driller's "Brown Shale," is a thick sequence of dark, organic-rich shale alternating with non-organic shale. The thickness of the unit increases from 350 feet

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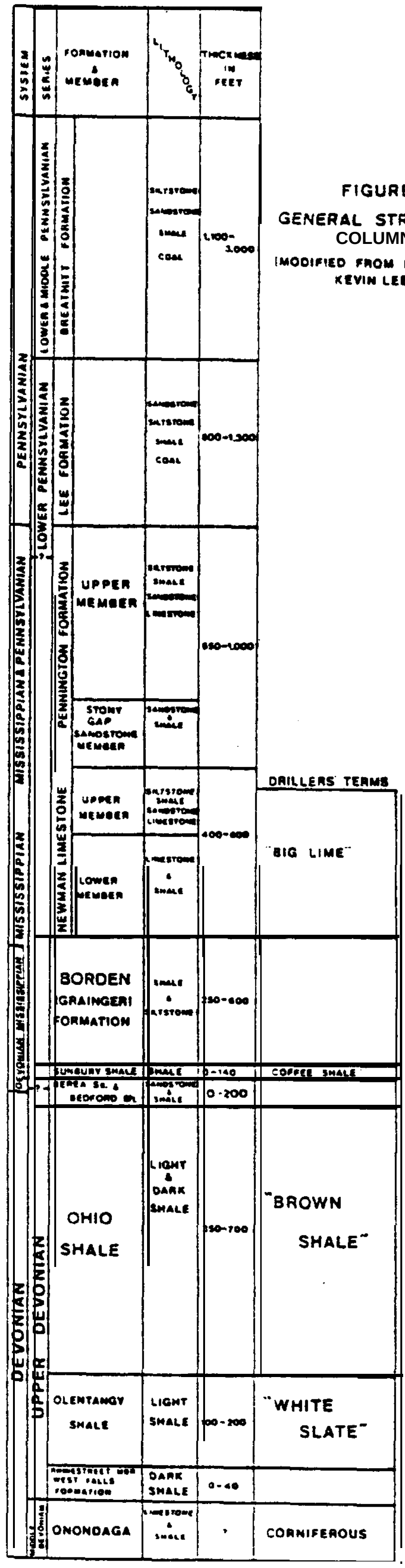

FIGURE 5
GENERAL STRATIGRAPHIC COLUMN
(MODIFIED FROM RICE & WOLCOTT, 1973)
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(137 meters) in the western portion of the field in Perry County to over 700 feet (213 meters) in Martin and Pike Counties. The Ohio Shale is considered to be Devonian, while the Devonian-Mississippian boundary is near the base of the Bedford Shale.

The Berea Sandstone is a fine-to-medium-grained sandstone, and the Bedford Shale is a light-colored shale. They have been interpreted to be the prodelta and channel sands of a prograding delta (Pepper and others, 1954). The entire sedimentary sequence is 80-220 feet (24-61 meters) thick. The Berea Sandstone, however, is absent in the western portion of the field.

The Sunbury Shale, or driller's "Coffee Shale" is 0-140 feet thick (0-43 meters). It is an organic-rich, dark grey to black shale.

The Borden Formation is 300-600 feet (91-183 meters) of green to grey to red shales and siltstone.

The Mississippian Newman Limestone, or driller's "Big Lime," is 400-800 feet (122-244 meters) thick across the field, and is known to have an erosional basal contact in some places (Shumaker, 1979; Beardsley, 1980).

The Pennsylvanian-Mississippian boundary is not precisely known, but is within the Pennington Formation (Rice and others, 1979). This formation is 650-1,000 feet (213-305 meters) thick and is made up of sandstone, siltstone, shale, and minor limestone.

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The Pennsylvanian Breathitt and Lee Formations are typical deltaic sequences of sandstone, shale, siltstone and coals. The coals are low sulphur/low ash/high B.T.U. and have great economic value (McFarlan, 1943). The sequence ranges from 1,900 to 4,300 feet (579 to 1311 meters) in thickness across the field.

Problems exist in recognizing the area1 extent of the individual stratrigraphic units of the field. Recognition of a specific shale unit in the Mississippian and Devonian section is complicated by the similarity of lithologies and because of interfingering of shale facies, especially in the Ohio Shale section. For a thorough discussion of the stratigraphy in the field, readers are referred to Provo (1977) and deWys (1979).

Map horizons had to be selected based on the reliability of driller's recognition of the units across the field. The base of the Ohio Shale is readily recognizable because of the macroscopic differences between it and the underlying Olentangy Shale and, therefore, found to be a suitable horizon to map. The top of the Ohio Shale was also selected, but was found to be unreliable in the western half of the field. Drillers were unable to differentiate between Ohio and the Sunbury Shales because of the similarities of the two units, primarily because the distinctive intervening Berea Sandstone is absent in that portion of the field. The uncertainty of drillers tops for the Ohio Shale in the western portion of the field necessitated selecting the top of the first darkcolored, organic-rich shale which the drillers recognized in that area. The top of the Ohio Shale was found to be a reliable horizon in the eastern portion of the field because of the presence of the overlying Berea Sandstone,

F. Data Base and Limitations

This study is based on approximately 4,200 drillers' logs collected from data on file at Kentucky-West Virginia Gas Company in Prestonsburg, Kentucky. A driller's log includes such items as drilling progress, tools used, etc., and the driller notes changes in the color and lithology of the units being drilled. The driller will often indicate tops Of geologic formations.

A data base of 4,200 wells is large but, in this case, does have limitations of accuracy which must be understood if valid maps are to be constructed. One of these limitations concerns the selection of tops in every well. Because the section under study is largely shale, there is extensive caving and mixing of chips in the drilling process, so change in the lithology as noted on a driller's log is approximate at best. The approximate nature of the log is especially true for the western portion of the field where overlying litholoqies are very similar to those that were chosen to be mapped and where the distinctive Berea Sandstone is absent.

It is also important to remember that these data were collected by drillers who usually had no formal geologic train-

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ing, and they did not always appreciate the importance of having a correct driller's log for geologic correlation and mapping.

Finally, company wells from Kentucky-West Virginia Gas Company were accurately surveyed, so a precise elevation of the drilling rig was usually known. However, approximately 1,800 "foreign" wells (drilled by independents or other companies) were included in the data set, and the locations of these were often spotted and elevations were estimated using topographic maps. These foreign wells could easily include errors of up to 50 feet or more. Although these data points can and do include information that is only very approximate, most wells that are significantly different can be easily detected. The density of wells is great, with up to 10 wells in a single square mile, and a single well that is anomalously high or low, when compared with many neighboring wells, can be excluded. A cut off of about 30 feet was typical for well exclusion. The detection of anomalous wells by comparison with neighboring wells was especially difficult in areas of complex structure, such as southern Floyd County, since an anomalous well was not necessarily wrong, but could be actual structure.

Although some of the data used here is approximate, the maps are considered valid because the great majority Of the wells were not found to differ markedly from other

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neighboring wells. Regional trends are adequately established to show which wells were probably in error. The contour interval of 50 feet was purposely chosen to eliminate any local errors in mapping which one or more incorrect data points, if not recognized as such, could infer.

The actual decision of whether or not to use any particular well was based on such things as density and amount Of discrepancy with neighboring wells, whether the well was foreign or company, and how difficult certain tops would have been to pick because of the stratigraphy. Approximately 90% of the wells available were actually used (about 3,800 wells).

MAJOR STRUCTURAL FEATURES OF THE EASTERN'KENTUCKY AREA

A. Introduction

The use of structural style in analysis of an area is based on the premise that certain types of deformation produce structures of predictable geometries. This type of analysis is important to the petroleum geologist because a limited amount of information on subsurface geology can be used to predict the geometry of a structure.

Once the structural style is identified, the origin and regional distrubution of structures is often more easily attained. From regional relationships in well-studied areas, models can be developed and applied to areas under investigation. The exploration geologist who can analyze available structural information and make correct associations with known

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areas should be able to better predict the geometry and distribution of structures.

Structural styles can be broadly subdivided into two categories: those associated with basement deformation and those associated wit!! detached deformation. The division between basement and detached deformation is basedonthe practical question of whether or not a surface structure extends to the crystalline basement. Detached structure does not extend to the basement so the exploration rationale must change at the stratigraphic horizon where detachment occurs. For a thorough discussion of the applications of structural style to petroleum exploration, readers are referred to Harding and Lowell (1979).

The Eastern Kentucky field is located between structures that are clearly basement (the Rome Trough [Harris, 1975; Black and others, 1976; Ammennan and Keller, 1979] and Cincinnati Arch [McFarlan, 1943; Rodgers, 1970]) and detached (Pine Mountain Thrust [Rich, 1934; Harris, 1970; Harris and Milici, 1977]). If we presume that fracture permeability within the Ohio Shale accounts for shale production (Hunter, 1934; Billingsley, 1934; Difford, 1947; McFarlan, 1943; Shumaker, 1978; deWys, 1979), then the ultimate question becomes: Are the fractures related to local or regional structure that is basement or detached in origin?: and, if porosity develops on structure, will similar porosity form over similar structures elsewhere?

This has a very serious impact on the possible extent of shale production, for if the fracture porosity relates solely to detached structure, then it is difficult to imagine natural fracture permeability outside the rather narrow confines of the zone of detached deformation.

If production is related solely to basement structure, then production can be expected from areas far removed from the zone of detached structure, in areas of known basement induced structure.

Even though the scope of this report does not include comparing production with structure, it is the intent of this work to interpret, or suggest, as far as the data permit, which structures within eastern Kentucky relate to basement deformation and which are detached. Future work will evaluate the relationships of shale-gas'production to the structures as defined here.

B. Basement Deformation in Eastern Kentucky

There are several presumed basement faults and fault zones north and west of the Big Sandy field which have been mapped at the surface, including the Warfield fault, Johnson Creek fault, Little Sandy fault, Blaine fault, the Kentucky River fault zone, and the Irvine-Paint Creek fault zone (McFarlan, 1943; Dever, et al, 1976; and Ammerman and Keller, 1979). These fault zones can be traced westward to the Cincinnati Arch which is outside (towards the craton) of the zone of orogenic detachment. Furthermore, these structures are reflected in total magnetic intensity maps that respond primarily to basement lithology changes (Shumaker, 1980). Thus, the faults are presumed to be surface expressions of larger basement faults and one might expect similar, but smaller, basement faults to occur within the field area.

The northern boundary of the Rome Trough appears to be a series of faults known as the Kentucky River fault system (Figure 6). To the west, in central Kentucky, part of the trough abuts and turns south against the north-northeast and south-southwest trending Lexington fault zone (See Plate 1). The trough also connects with the Western Kentucky trough through the Cumberland saddle (Shumaker, 1975). The trough continues and deepens to the northeast into West Virginia (Ammerman and Keller, 1979).

According to Ammerman and Keller, the trough itself is an asymmetric graben structure with the Kentucky River fault zone to the north having a much greater total aggregate throw than do the faults which form the southern boundary. Since this study produces no new evidence for structural evaluation of the Rome Trough, it is impossible from available evidence to give a precise explanation to the formation of the trough. From the geometry of the trough, and the fact that it falls below the level of regional structure, it would appear to be part of a rift system.

The main growth of the Rome Trough occurred during

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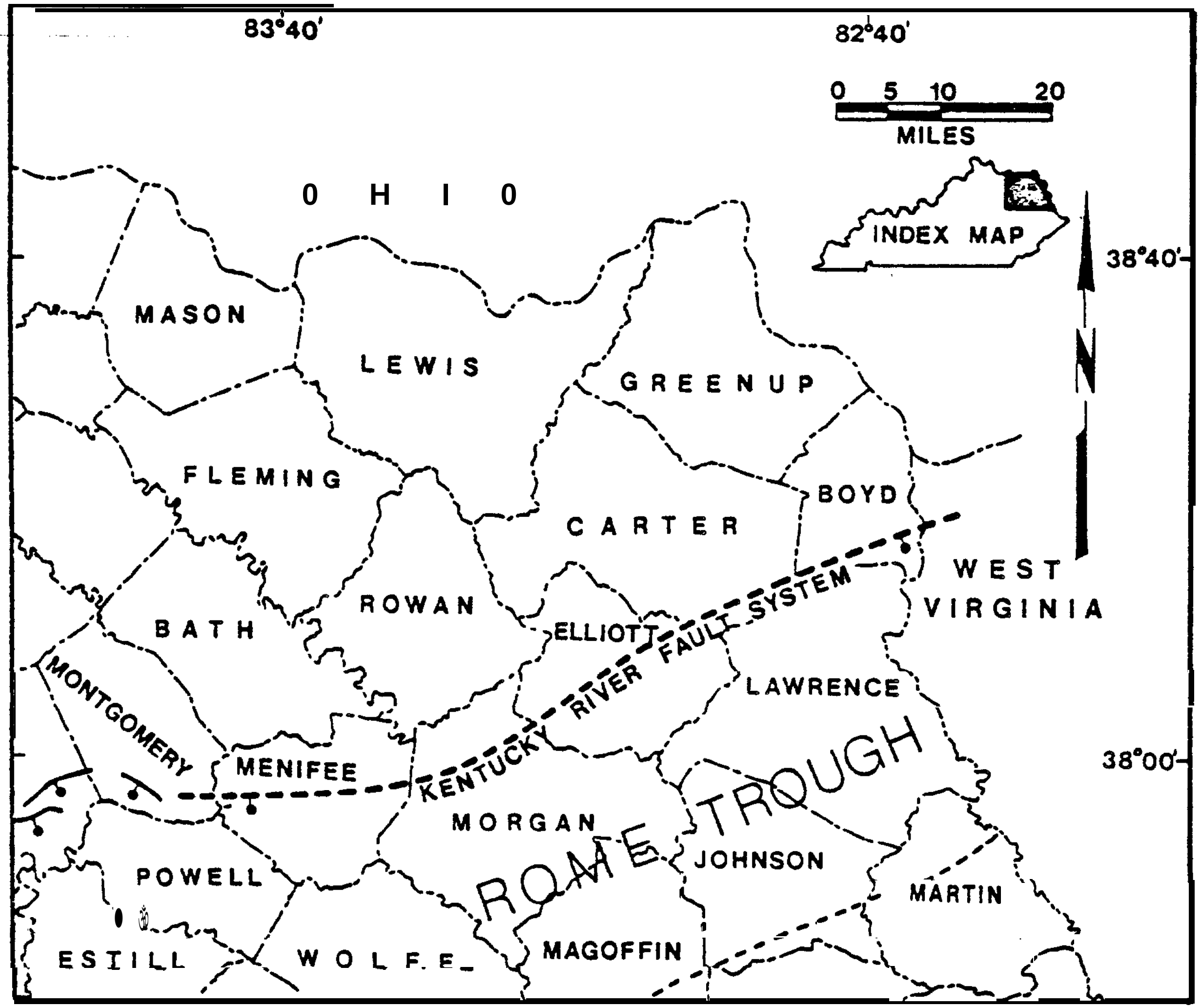

FIGURE 6 - REGIONAL EXTENT OF KENTUCKY RIVER FAULT SYSTEM
FROM DEVER ET.AL,1976

Cambrian time as evidenced by the greatly thickened sections of Cambrian strata (Harris, 1975), but intermittent growth along the trough zone continued through at least the Pennsylvanian period. There does not appear to be a large amount of horizontal, or strike-slip movement along the trough zone during the Phanerozoic (Black, 1976; Harris, 1975).

Some of the faults associated with the Rome Trough are interpreted to have been sporadically active throughout the Paleozoic (Shaefer, 1979; Dever, 1976). Basement deformation occurred within this area during deposition of -the Devonian and Mississippian, producing abnormal sedimentary patterns in association with a structural feature. All detached structures of this area are considered to have been formed after the deposition of the sedimentary rock. Therefore, detached structures should not affect sediment distribution or thicknesses (Rodgers, 1970).

C. Detached Deformation

Detachment faults, or decollements, are formed on an incompetent stratigraphic unit acting as a glide plane for slip movement between more competent units above and below. Salt and organic-rich shale are units which are suitable detachment horizons, whereas sandstone, dolomite, and thick limestone often serve as competent units (Harris, 1970).

As detachment occurs, strength of the competent autochthonous unit is exceeded, causing the unit to break to form a tectonic ramp (Figure 7). Upward movement occurs and

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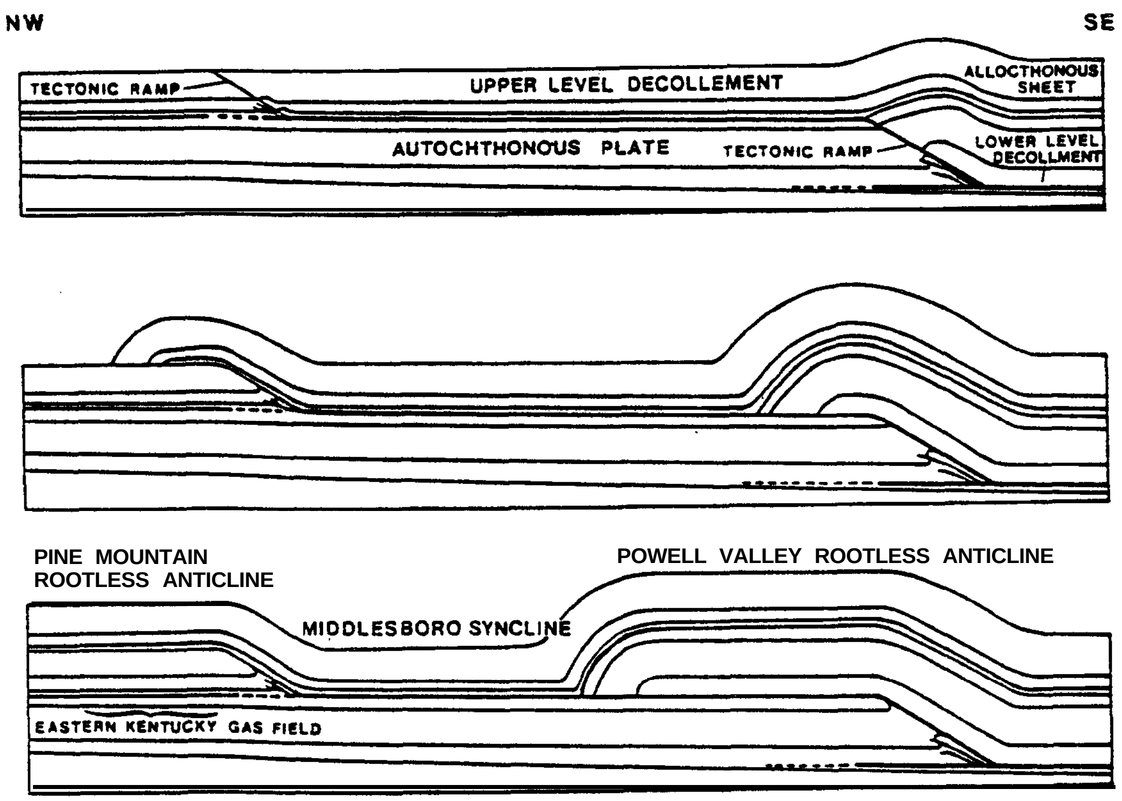

FIGURE 7-DEVELOPMENT OF THE PINE MOUNTAIN THRUST
MODIFIED FROM HARRIS & MILICI,1977
KEVIN LEE,1980

continues along the ramp until another horizontal imcompetent unit is intersected to form an upper-level decollement sheet. Movement can continue on the lower decollement and ramp, as well as within the new stratigraphically higher incompetent stratigraphic unit.

The migration of a horizontal fault plane from one incompetent unit up to another is tectonic ramping. Pine Mountain, the southern boundary of the Eastern Kentucky field, is one such ramp (Plate 1 and Figure 7).

Presumably the stress which created the Pine Mountain thrust extended into the area of the Big Sandy field (Shumaker, 1978), and the Devonian shale was a detachment horizon. If the stress and some minor movement did extend into the Devonian shales under the Eastern Kentucky field, then the stress could have created structures that effect fracture production. The deformation which created the Pine Mountain thrust and detached structure in eastern Kentucky occurred during the Alleghanian (Permian-Pennsylvanian age) orogeny.

STRUCTURE OF THE FIELD

A. Introduction

A basement structure is produced by stresses contained in the basement which effect overlying sediment. The resultant deformation will usually be similar on the top and bottom Of any given stratigraphic unit or interval.

A detached structure is produced by stresses contained within the sedimentary cover that do not involve the basement. A distinguishing characteristic of detached deformation is for a discordance of structure, such as anticlinal folds, to be present on top of a given stratigraphic unit or overlying units, but absent from the base of that unit.

The structure of the Eastern Kentucky gas field is shown by structure contour maps drawn on the top (Plate 2) and the bottom (Plate 3) of the Ohio Shale. In this study of the Ohio Shale, which is known to be a detachment horizon, (Harris and Milici, 1977), the differentiation of basement versus detached structure was based on such things as 1) whether the structure was present on top and bottom of the Ohio Shale; 2) do isopach maps show trends which correspond to structure; and, 3) is the structure near a known basement structure.

B. Paint Creek Uplift

By looking at the structure contour maps drawn on the top (Plate 2) and on the bottom (Plate 3) of the Ohio Shale, one sees the northwestern border of the field in Johnson, Floyd, and Knott Counties is against the nose of a north-south trending high called the Paint Creek Uplift. Figure 8 shows an outline of the Paint Creek Uplift.

McFarlan (1943) describes the Paint Creek Uplift as a large upwarp with north-south major axis and an associated structural closure of about 250 feet (76) meters) in Pennsylvanian rocks at the surface. An even greater closure in the

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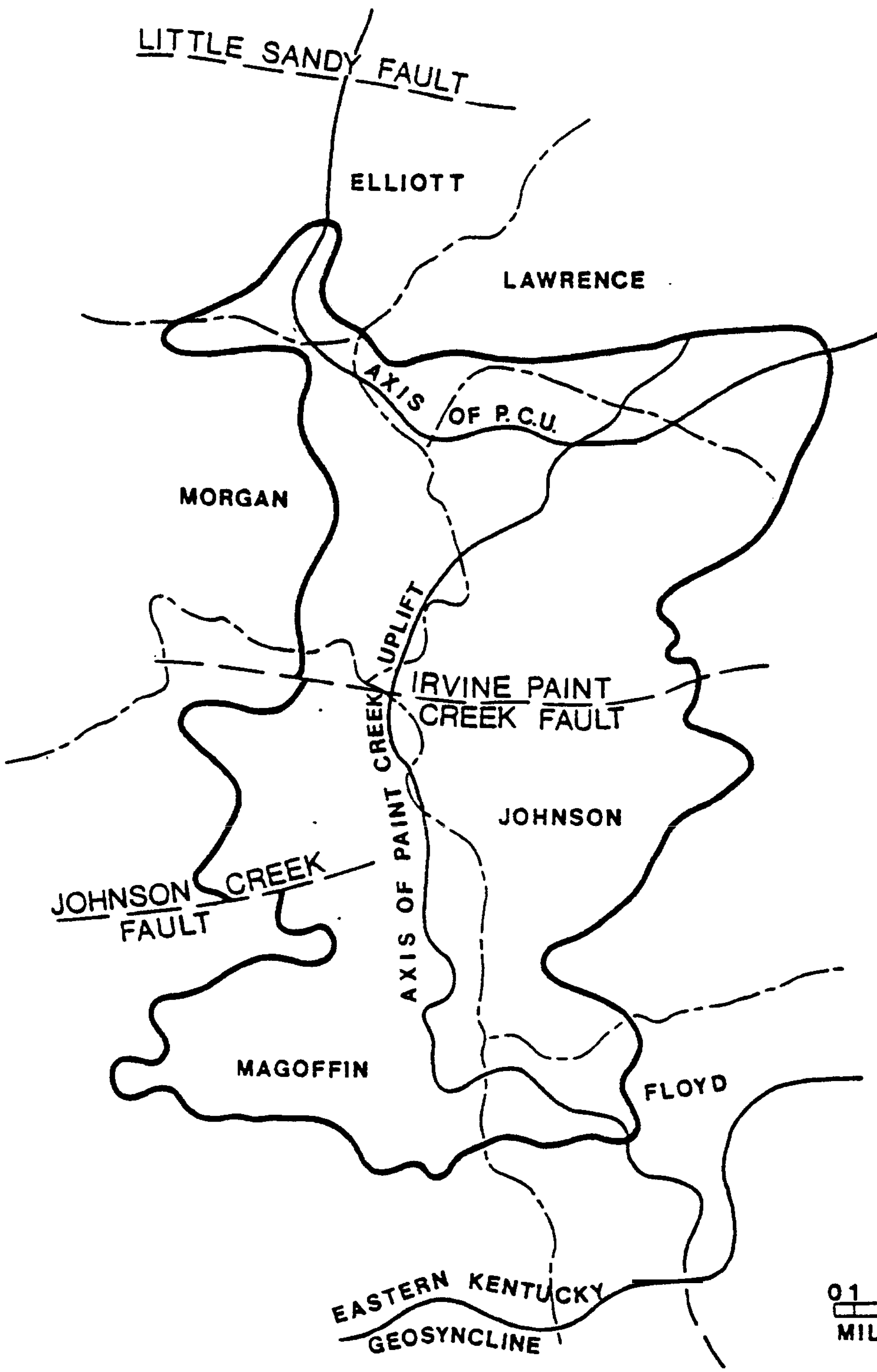

FIGURE 8: SURFACE OUTLINE OF THE PAINT CREEK UPLIFT
AFTER JILSON, 1928

subsurface is indicated in work done by Jillson (1921). Jillson called attention to a decrease in thickness over the crest of the structure in the interval between the Pennsylvanian Fire Clay Coal and the top of the Mississippian Newman Limestone, interpreting the area as a topographic high during that time. Thomas (unpublished manuscript, 1941; referenced in McFarlan, 1943), indicated that gas from the Silurian-Devonian Corniferous in Magoffin and Johnson Counties is associated with isopach thins of the Corniferous Limestone. He interpreted the evidence to indicate progressive development of the structure during Middle Silurian to Middle Devonian time.

If the interpretations by McFarlan, Jillson and Thomas are correct, the area of the Paint Creek Uplift was a topographic high from at least the Middle Silurian through the Pennsylvanian. The area1 extent and continued growth of this major structural feature during the Paleozoic suggests that it is rooted in the basement.

C. Martin County

I. Warfield Fault

The Warfield fault is the most prominent structure in Martin County, Kentucky (Plates 2 and 3). The greatest offset at the top of the Devonian is approximately 200 feet near the West Virginia border, gradually decreasing to no offset over a distance of 10 miles to the west. The state geologic map of West Virginia shows the surface trace of the fault to extend some 20 miles to the east and north (Cardwell, et al, 1968).

A structural contour map drawn on the bottom of the Newman Limestone (Figure 9) shows a similar 200-foot offset in the Newman, which would indicate the fault was 'active after deposition of the Newman. Irregularities in structural contours in the Devonian shale along the trend of the Warfield fault suggests that the fault continues westward out of the mapped area but with greatly decreased throw.

Figure 10, a seismic section across the Warfield fault and anticline in Mingo County, West Virginia (Plate 1), shows movement down to the south along the fault from the Mississippian Newman Limestone to the Pre-Cambrian basement. The seismic section does not show the surface Pennsylvanian deformation. The seismic section does show that the Warfield fault is not part of the southern boundary of the Rome Trough. An un-named basement fault north of the Warfield anticline with thousands of feet of throw, primarily active during the Cambrian period, is the southern rim of the trough (Beardsley, 1980). The Warfield anticline is seen to be a passive basement structure formed between the development of the Rome Trough and Warfield fault.

II. Strike-Slip Fault

Plates 2 and 3 show 'a north-south striking, strike-slip fault through the center of Martin County. The Warfield fault on the west side of the strike-slip fault has less throw than on the east side. Richard Beardsley (1980) of Columbia Gas

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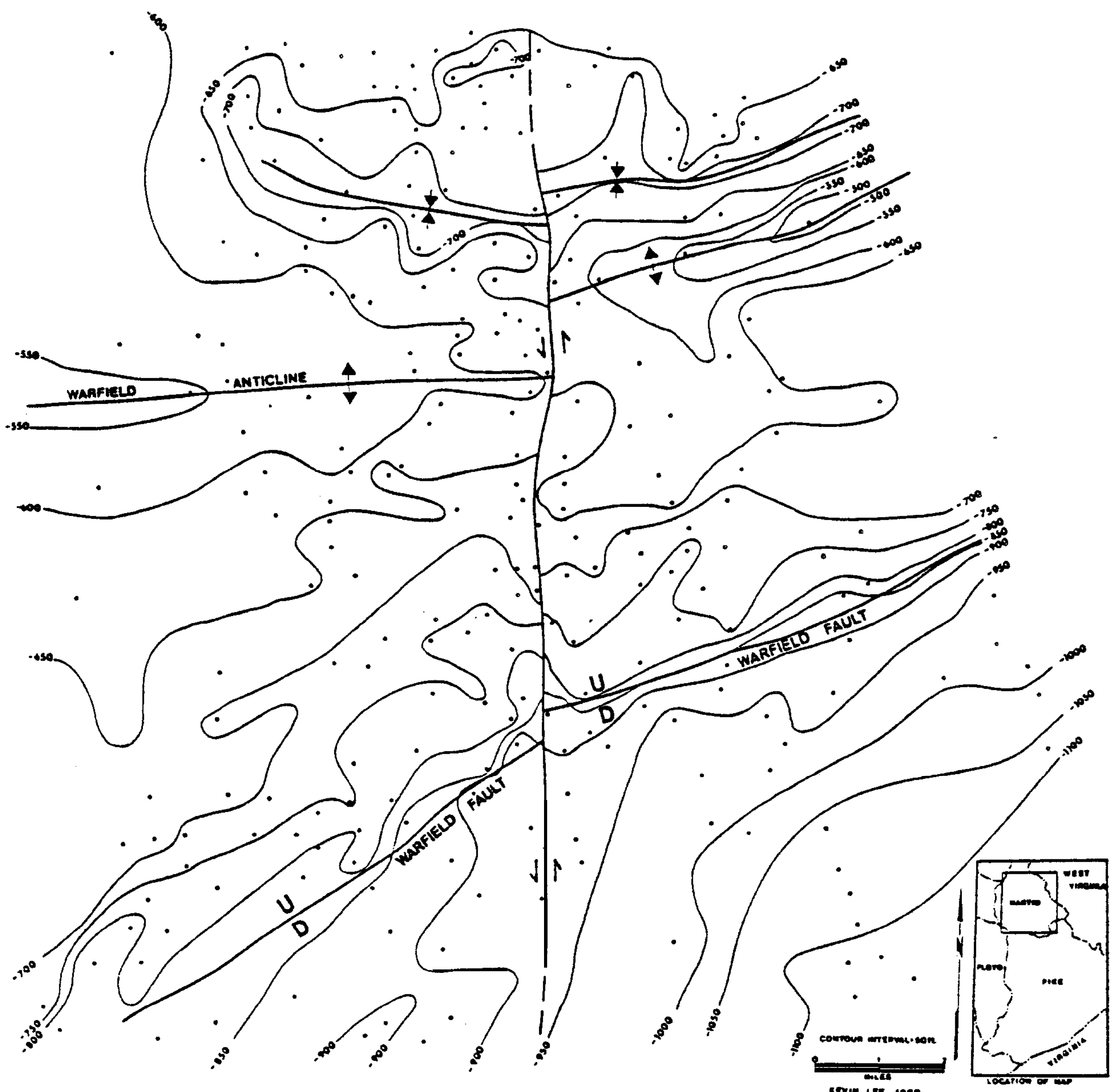

FIGURE 9

STRUCTURE CONTOUR MAP ON BASE OF NEWMAN LIMESTONE, MARTIN COUNTY, KY.

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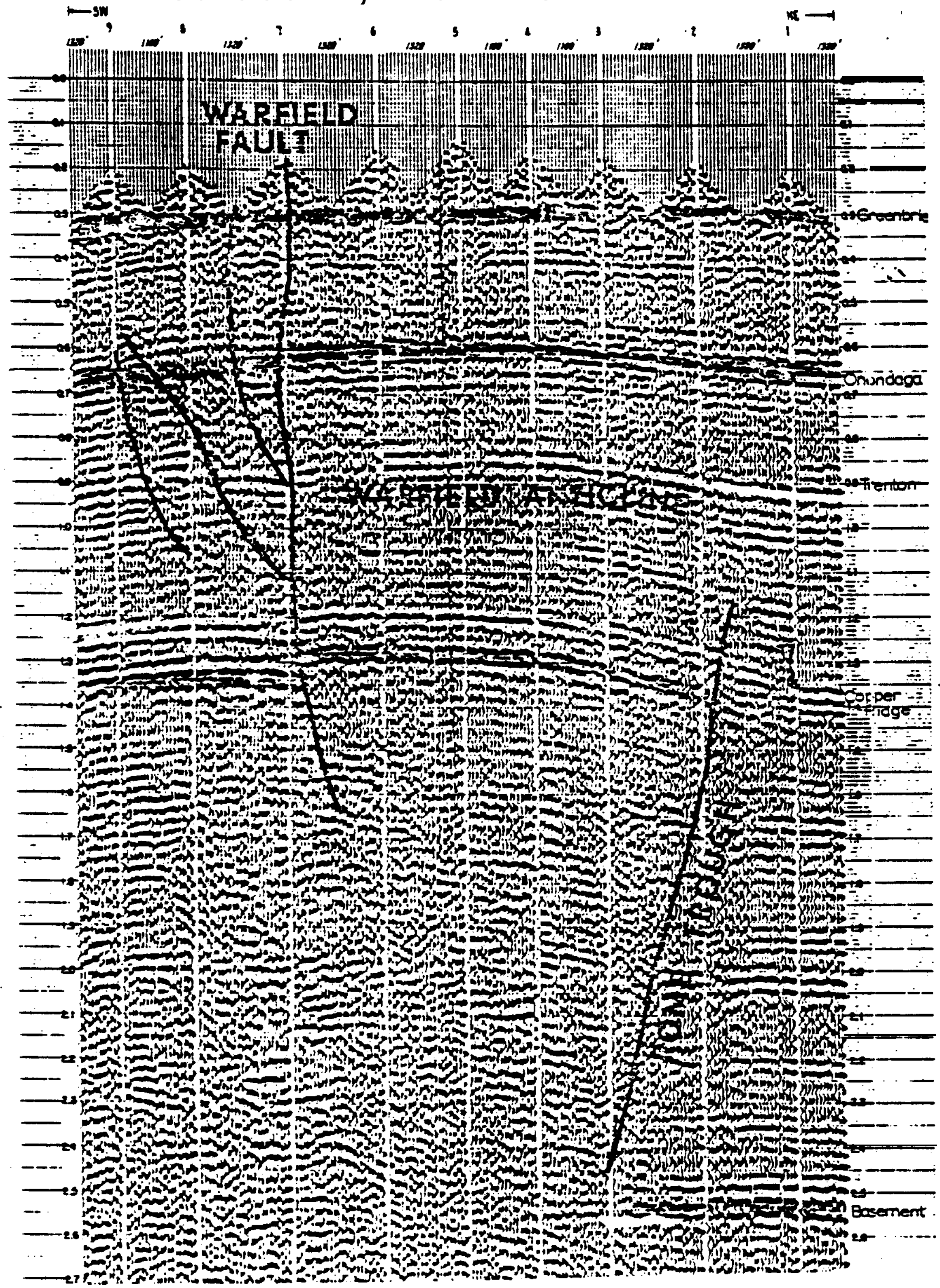
FIGURE 10

SEISMIC SECTION ACROSS THE WARFIELD STRUCTURE IN MINGO COUNTY, WEST VIRGINIA-.



Transmission Corporation has mapped basement involved strike-slip faults with the same trend that cross the Warfield fault in Mingo County, West Virginia.

The thickness map of the combined Berea Sandstone and Bedford Shale (Figure 11) shows the thickest Berea-Bedford interval generally along the trace of the strike-slip fault, suggesting that a topographic low, possibly caused by the same strike-slip fault, was present during deposition.

In addition, the thickness map of the Ohio Shale (Plate 4) shows thicks and thins in Martin County that seemingly relate to structural trends. For instance, there is a thinning of isopach lines on the Warfield anticline. This seeming adjustment to structures suggests basement movement during deposition. Of course, other possible causes for the irregular isopach contours are: flowage of the shales during structural disruption and faulting of the shale section. Similar flowage in structurally disrupted zones has been noted by Harris and Milici (1977), Lee (1979), Zafar and Wilson (1978) and Wilson (1980).

Structure contour maps drawn at the shallow Pennsylvanian Fire Clay Coal (McFarlan, 1943) and a geologic map drawn at the surface in Martin County (Huddle and Englund, 1962) show 25 to 125 feet (8 to 38 meters) of fault offset down to the north across the Warfield fault. An explanation must be found to resolve the problem of the different sense of movement between the surface and the subsurface.

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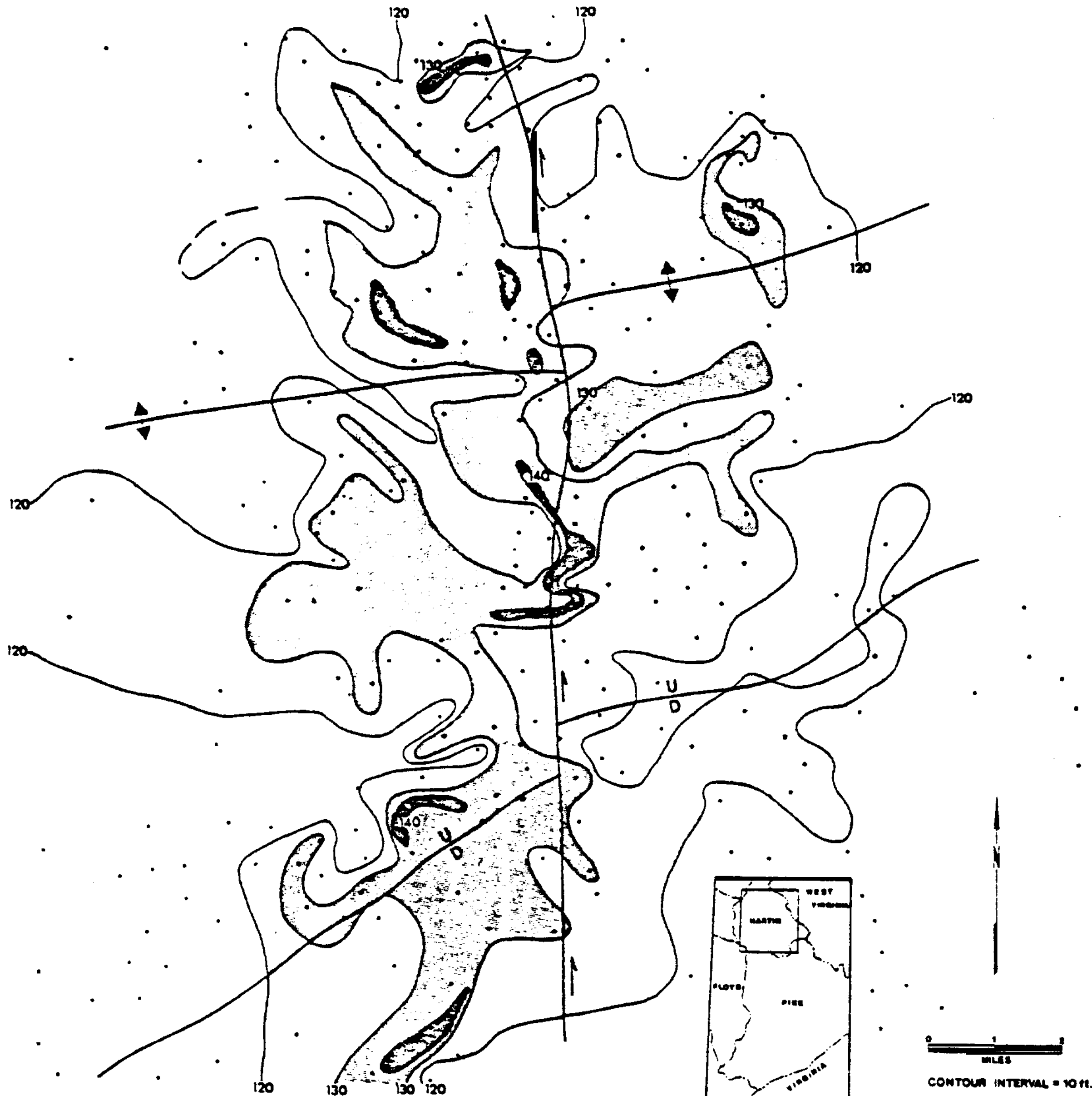

FIGURE 11: ISOPACH MAP OF THE BEREA SANDSTONE AND BEDFORD SHALE IN MARTIN COUNTY, KENTUCKY

KEVIN LEE, 1980

Evidence that bears on the problem are fractures and slickensides from an oriented core through the Ohio Shale just south of the Warfield fault that show a probable decollement zone which moved perpendicular to the Warfield fault (Evans, 1980).

The horizontal slickensides perpendicular to the Warfield fault suggest a possible explanation for the conflicting sense of movement along the Warfield fault based on surface and subsurface maps. It seems possible that the surface Warfield fault, which is up to the south, is the expression of a splay from the detachment zone in the Ohio Shale. The surface fault was initiated in the Ohio Shale from the pre-existing Warfield basement fault. This interpretation presumes that a basement fault was active prior to the detachment thrust as suggested by the evidence stated above (See Figure 12).

D. Eastern Pike County

I. D'Invilliers Folds

Mississippian and Devonian formations in eastern Pike County generally dip to the southeast. A notable feature is an anticlinal-synclinal structure which originates in West Virginia and continues south-southwestward toward the northern terminus of Pine Mountain (Plates 2 and 3). This structure, the D'Invilliers anticline of McFarlan (1943), narrows and structural relief slowly decreases to the south. It can be seen on the structure contour map on the Fire Clay Coal compiled by McFarlan from published county reports (Figure 2), but at this high stratigraphic level, it plunges to the northeast.

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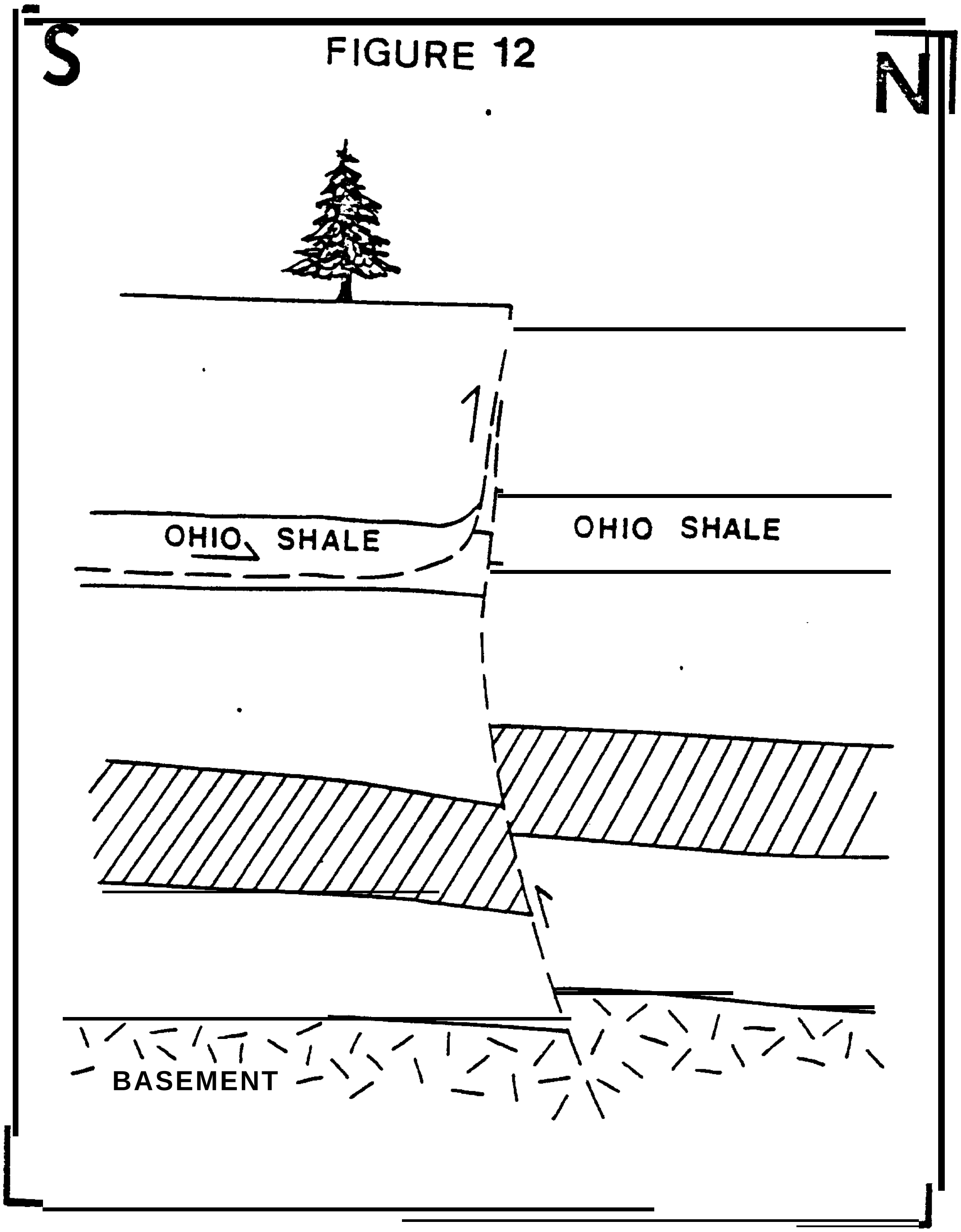
FIGURE 12



DIAGRAMATICAL SKETCH OF THE SURFACE AND SUBSURFACE WARFIELD FAULT

K.LEE 1980

Figure 13 shows the location of the New York-Alabama Lineament of King and Zeitz (1978). It is a lineament that is marked by a series of steep magnetic gradients which apparently is the boundary between basement rocks of distinctly different magnetic susceptibilities. King and Zeitz (1978) propose that the lineament is the southeastern edge of a stable crustal block that acted as a buttress 'for the strong deformation of the Appalachian foldbelt. Because of the large scale of the map (Figure 13), it is difficult to locate precisely the D'Invilliers structures, but they are in the same general area and have similar trends with the lineament, so it is likely that they are related in the same way that the Warfield fold in West Virginia follows the lineament (Shumaker, 1980). Figure 14 (Shumaker, 1977) is an interpretation of basement structure based on well data and the trends of steep magnetic gradient trends. The D'Invilliers structures are located over the southern extension of a proposed basement fault in West Virginia and along the New York-Alabama lineament. Because of the locations of these basement structures and the mapped features of the D'Invilliers folds, they are interpreted to be basement related structures.

The D'Invilliers anticlinal-synclinal structures have more structural *relief* on the base of the Ohio Shale (Plate 3) than on top of the shale (Plate 2). This may be a reflection of regional tilt, or detachment, but probably not syndeposi-tional growth because the isopach map of the Ohio Shale in the

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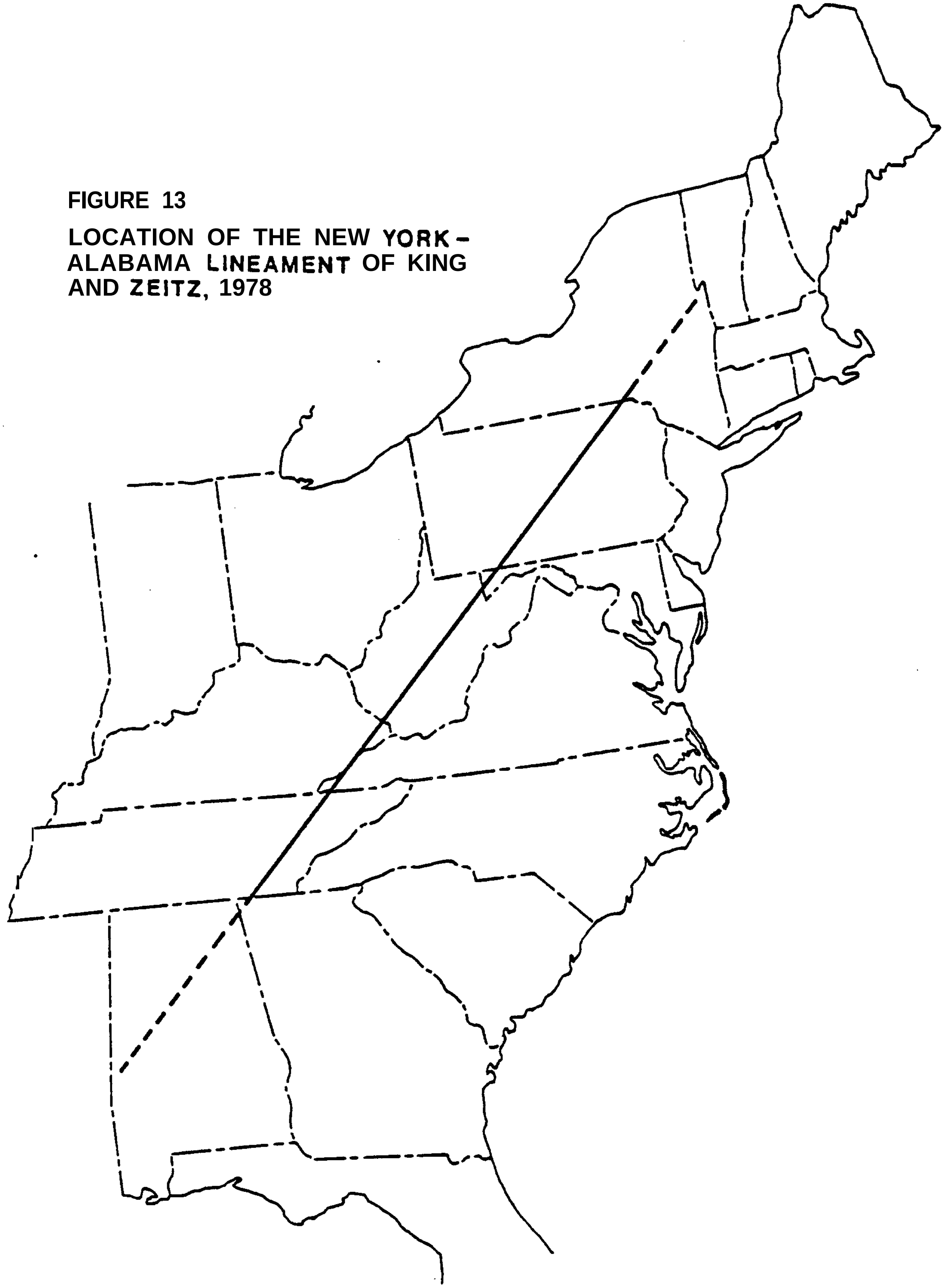
FIGURE 13

LOCATION OF THE NEW YORK-ALABAMA LINEAMENT OF KING AND ZEITZ, 1978



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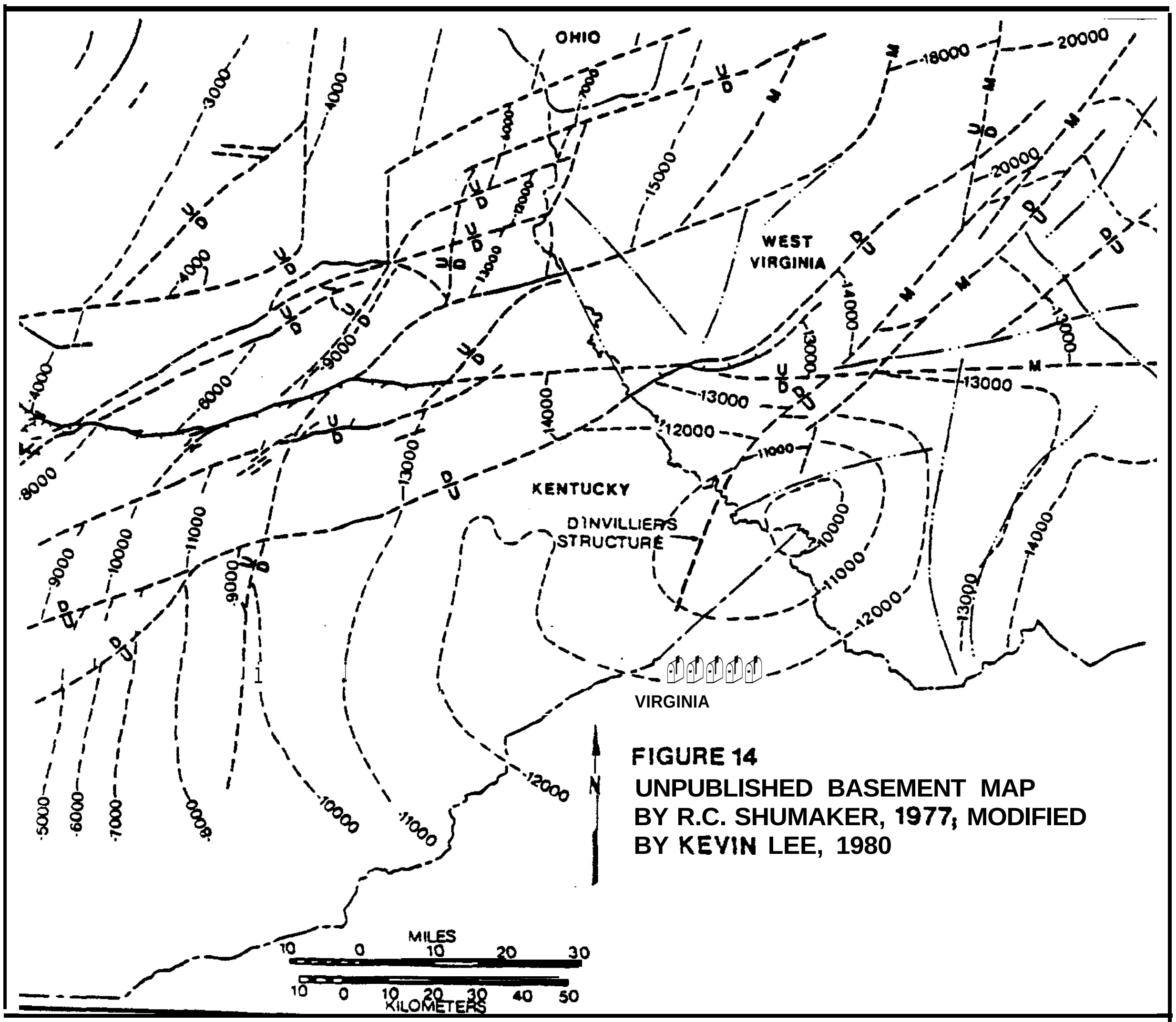

FIGURE 14

UNPUBLISHED BASEMENT MAP BY R.C. SHUMAKER, 1977; MODIFIED BY KEVIN LEE, 1980

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area of the D'Invilliers folds (Plate 4) shows no definite evidence in the form of variations in thickness of the shale supporting syndepositional growth.

II. Pikeville Fault

In central Pike County the D'Invilliers structures are cut by a strike-slip fault that is perpendicular to them. This strike-slip fault, here called the Pikeville fault, is visible on the bottom of the Ohio Shale (Plate 3) as a terminus Of structural trends. On Plate 2, the top of the Ohio Shale, the Pikeville fault shows as a disruptive pattern in the contours. The Pikeville fault is more obvious on a structure contour map of the base of the Newman Limestone in a portion of eastern Pike County (Figure 15).

All three structure contour maps of this area (Plates 2 and 3 and Figure 15) show that beds north of the Pikeville fault and west of the D'Invilliers folds dip gradually to the southeast. On the south side of the Pikeville fault, contours west of and parallel to the folds are closer together, indicating steeper dip. Whether that steeper dip of beds is caused by fault compression or by underlying basement movement is impossible to tell from evidence available in this study.

Figure 16 is a diagrammatical sketch representative of the Pikeville fault and D'Invilliers structures in eastern Pike County. The Pikeville fault cuts the D'Invilliers anticline, indicating the fault is post folding. The D'Invilliers folds are presumed to be Alleghenian.

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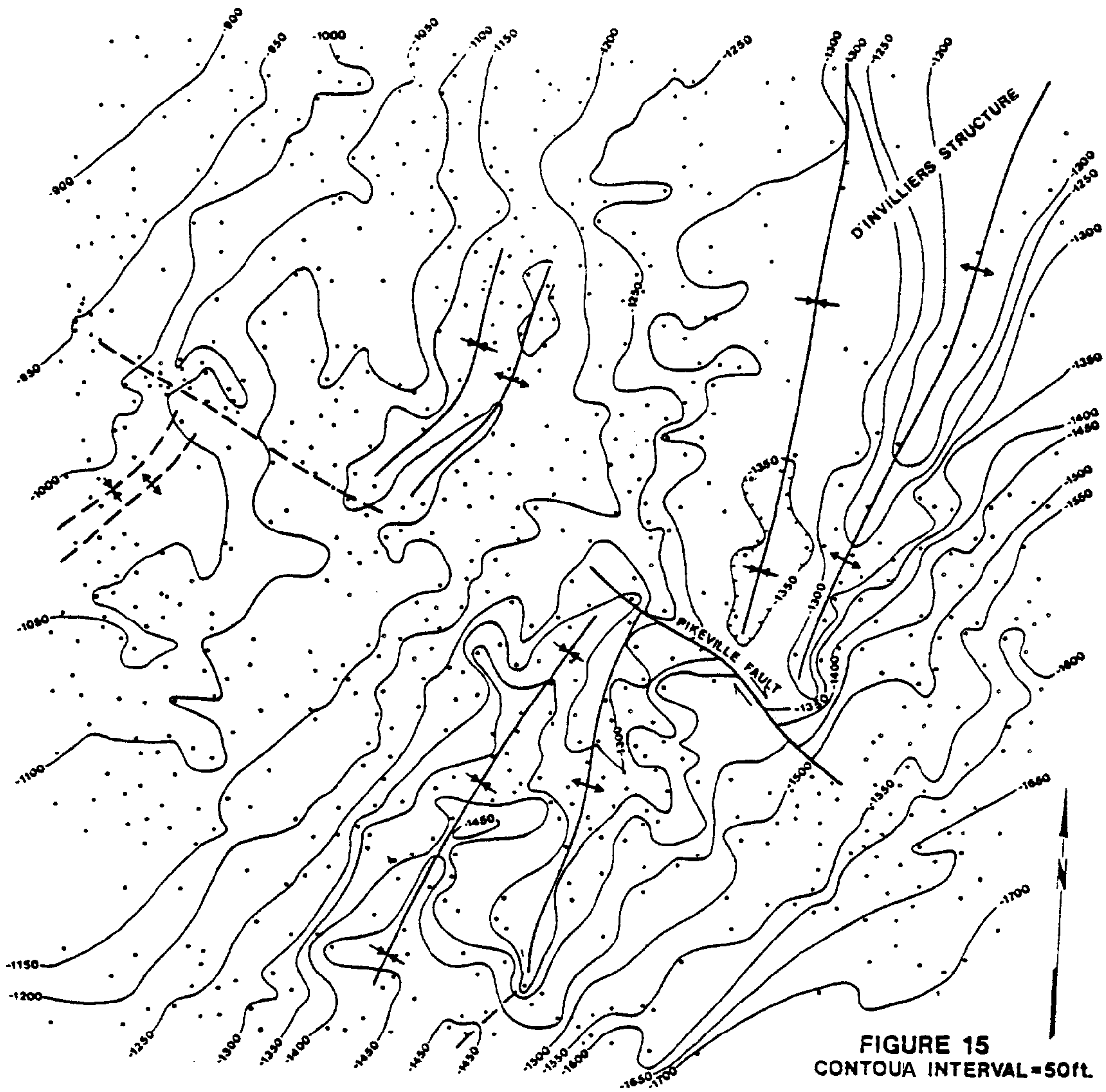

FIGURE 15
CONTOUA INTERVAL=50ft.

STRUCTURE CONTOUR MAP ON BASE OF NEWMAN LIMESTONE, PIKE COUNTY KENTUCKY

0 2 4
MILES

KEVIN LEE. 1980

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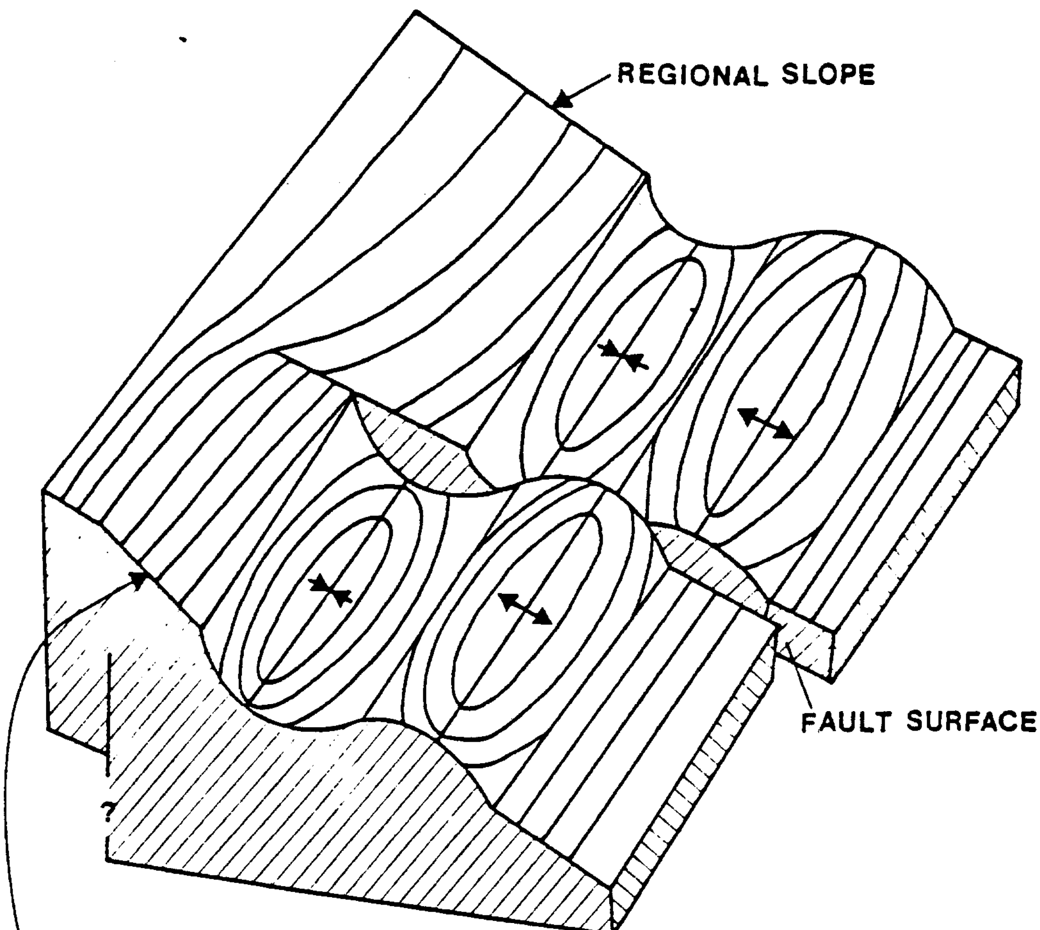

FIGURE 16

DIAGRAMMATICAL SKETCH OF THE D'INVILLIERS ANTICLINE AND PIKEVILLE FAULT

KEVIN LEE, 1980

All three maps (Plates 2 and 3 and Figure 15) show closely spaced straight contours west of the D'Invilliers structure and south of the Pikeville Fault. These consistent contours, the location of the structure on the east side of the Pike County uplift of Ammerman and Keller (Figure 4) and the proximity to the New York-Alabama Lineament (Figure 13), all suggest basement deformation was involved in formation of the structure.

E. Knott County Area

Because of problems in differentiating the Ohio Shale from the Sunbury Shale, where the intervening Berea Sandstone is missing in the western portion of the field, it was decided that the top of the first brown shale recognized by the drillers would be used as a mapping datum. The first brown shale is probably equivalent to the Sunbury (???), but further stratigraphic work is needed to establish precise correlation.

In southern Knott County and surrounding areas of eastern Perry and southern Floyd Counties, structural dip in the Devonian is to the south, as opposed to other areas of the field where structural dip is to the southeast. The arch between the two strike domains (a probable extension of the basement involved Paint Creek Uplift) plunges southeastward across Floyd and Pike Counties (see Plates 2 and 3).

The east-west trending contours in this area of Knott County are at the south end of the Paint Creek Uplift, a pre-existing structural basement high. From the Nicholas-Combs well #7239 in the Devonian in Perry County, Evans (1979) found a decollement zone indicated by horizontal slickensides, within the shale, assumed to be to the north. This supports the view of Shumaker (1977) that detachment has occurred in the shales in front of the Pine Mountain thrust. The southern end of the Paint Creek Uplift could have acted as a buttress against the advancing thrust sheets (deWys, 1979), causing the shales to trend in an east-west direction.

The north-south trending noses on the south side of the arch (the Paint Creek Uplift) are either folds or tears similar to those as mapped on the adjacent Pine Mountain block (Englund, 1968, 1971; Harris and Milici, 1977), but have far less relief or lateral offset.. The interpretation that these are structural in origin rests in their linearity, parallelism, and the coupled nature of anticlines with adjacent synclines. It seems unlikely that these are erosional features because at this low regional gradient, estimated to be less than a 2" slope, the drainage should be dendritic. Furthermore, these features do not radiate from the central high area.

The north-south noses are better defined on top of the Ohio Shalethan on the base of the shale, indicating that the tears are probably limited to the sedimentary cover.

F. Southern Floyd County

The area in central-southern Floyd County shows intense disruption of contour patterns, especially on top of the Ohio Shale. This area is on the axis of the plunging Paint Creek Uplift between the two domains of regional dips.

Drill holes are sufficiently dense to establish this map pattern, but the pattern is so irregular as to be indeterminant. The noses and troughs of this area could be erosional or structural in origin. It is also possible that the stratigraphy of the area is so complex that to establish an accurate map is impossible. Further work may resolve this problem.

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CONCLUSIONS

Detailed mapping of the subsurface structure of the Eastern Kentucky field, on top and bottom of the Devonian Ohio Shale, suggests that no one structural style predominates, but that both basement and detached structures are present. The mapping also shows that even where a particular structural style is present, interrelated structural effects are often present. The Warfield fault may be an example of this: a pre-existing basement fault may have served as a barrier to detachment and caused surface splays off of a detachment sheet.

The mapping also shows several strike-slip faults in the field that were previously unknown, and it suggests the possibility of additional strike-slip faults across the field.

Certain more specific conclusions arrived at during the investigation include:

1) Previous investigations into the structural geology of the Eastern Kentucky gas field correctly established the regional structural dip in the Devonian and Mississippian rocks, but failed to define and discover small folds and faults. The structure of the field, therefore, is not that of a simple monocline dipping to the south and east as defined in previous studies. Structure, as mapped at the surface in the field area, does not correspond to structure as mapped at the Devonian and Mississippian levels and, that structure, in turn, appears to be different from the structure on top of the basement.

2) The structure discernable in the Devonian Ohio Shale did not form in response to a simple individual stress field, nor during a single episode of deformation. Diverse trends of detached and basement structures grew during several episodes of deformation from the Cambrian through Permian. The Paint Creek Uplift in Morgan, Magoffin, and Breathitt Counties was determined to be a basement structure that was active throughout the Paleozoic.

The D'Invilliers folds and Warfield fault were determined to be basement induced structures, but both may also contain some detached deformation. The Warfield fault may have been periodically active through the Paleozoic, but the most active period of deformation for both structures is presumed to be during the Alleghenian orogeny,

Several linear zones at high angles to the Pine Mountain thrust are interpreted to be structual tears that may be limited to the sedimentary cover.

3) Details on various small structures discovered by this study include: The Warfield fault in Martin County is not part Of the southern boundary of the Rome Trough, but is a part of the uplifted block along the southern margin of the trough. Offset on the fault in the subsurface is down to the south from at least the Mississippian to the basement. The surface Warfield fault may be a splay off of detachment horizons. The Warfield fault in Martin County is offset by at least one strike-slip fault. The D'Invilliers anticlinal and synclinal

structures in eastern Pike County are located over a southern extension of a proposed basement fault in West Virginia, and they are along the trend of the New York-Alabama lineament as mapped by King and Zeitz (1978). The D'Invilliers structures are cut by a strike-slip fault that postdated, or was contemporaneous with fold development.

Complex and irregular fold patterns in the Devonian Shale in southern Floyd County apparently reflect either intersecting structural trends or erosional features or both.

Structure contours in the Devonian in southern Knott and Perry Counties trend east-west, while the Pine Mountain Thrust strikes northeast-southwest. Thrust sheets between right lateral strike-slip faults apparently have differentially pushed the rocks in this section of Knott and Perry Counties to the north, where they were shoved against the southern end Of the Paint Creek Uplift.

Figure 17 is a summary of structures in the study area.

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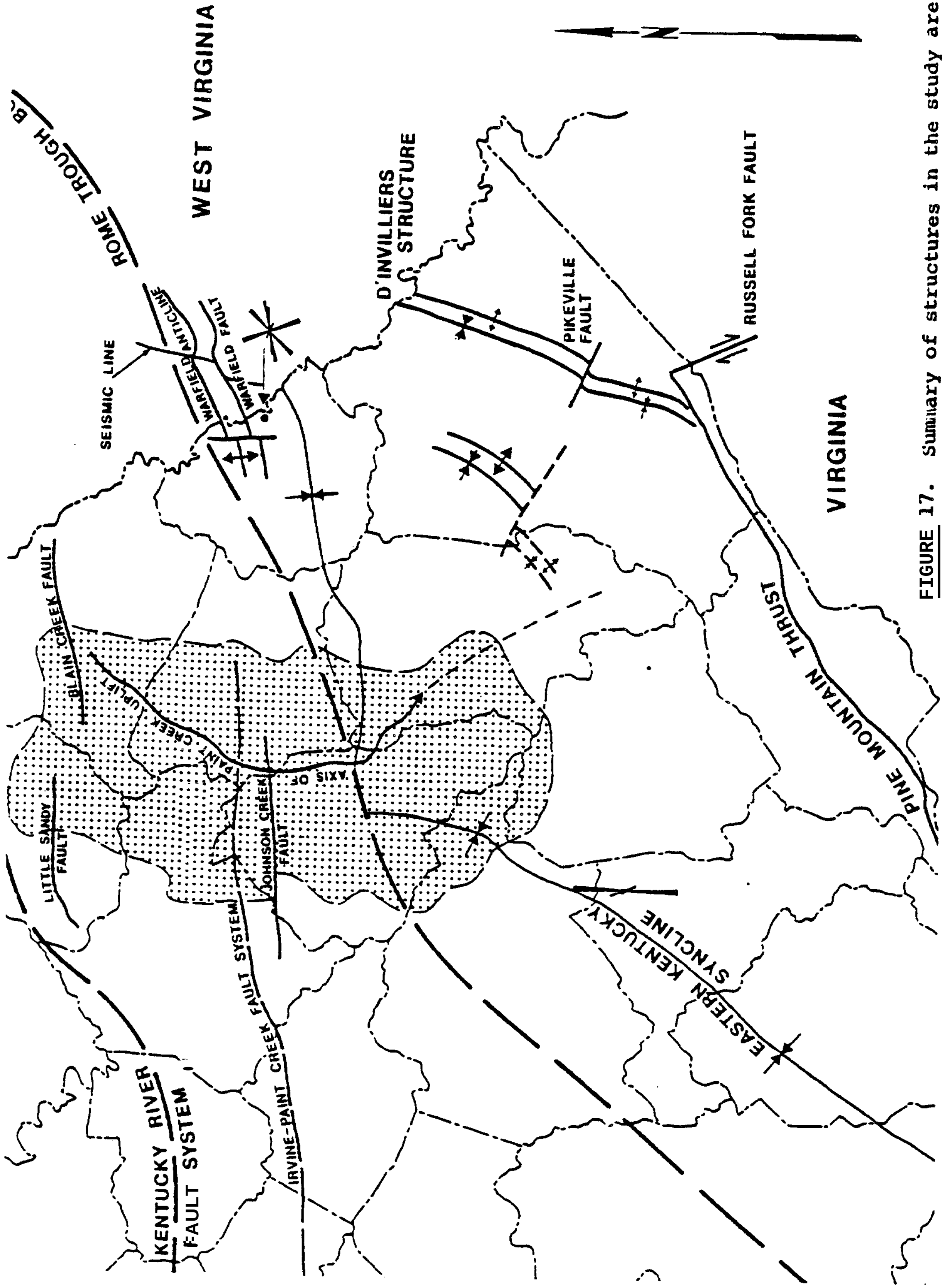

FIGURE 17. Summary of structures in the study area

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SUGGESTIONS FOR FUTURE WORK

The following are suggestions for future work that could greatly add to the understanding of the structure and production of the Eastern Kentucky field:

1) Put the data set from this project on a computer tape for quick data selection and retrieval. Trend Surface Analysis can be run in areas of poor data reliability, and where smaller contour intervals than presented in this study are desired.

2) The structure in Knott, Floyd, and Perry Counties is complex and needs further study. All shale horizons as recorded on the drillers* logs need interpretation so the Big Line is a reliable horizon to model from in that area.

3) Construct a detailed isopach map of the Sunbury Shale, and compare it to isopach maps of the other dark shale facies within the Ohio shale. Its comparison could lead to a better understanding of the depositional environment of the Ohio shale.

4) Construct a detailed isopach map of the Berea Sandstone. This map can be compared to structure maps to help define areas of active structural growth during the Mississippian.

5) The structure of Eastern Kentucky should be integrated with the type and trend of structure in southwestern West Virginia.

6) Construct a structure contour map on the base of

the Newman Limestone. The Newman is often a prolific producer in the Eastern Kentucky field, and it's structure should.be determined.

7) Now that detailed structure of the field has been outlined, the relationship of individual structures to production from the shale should be examined.

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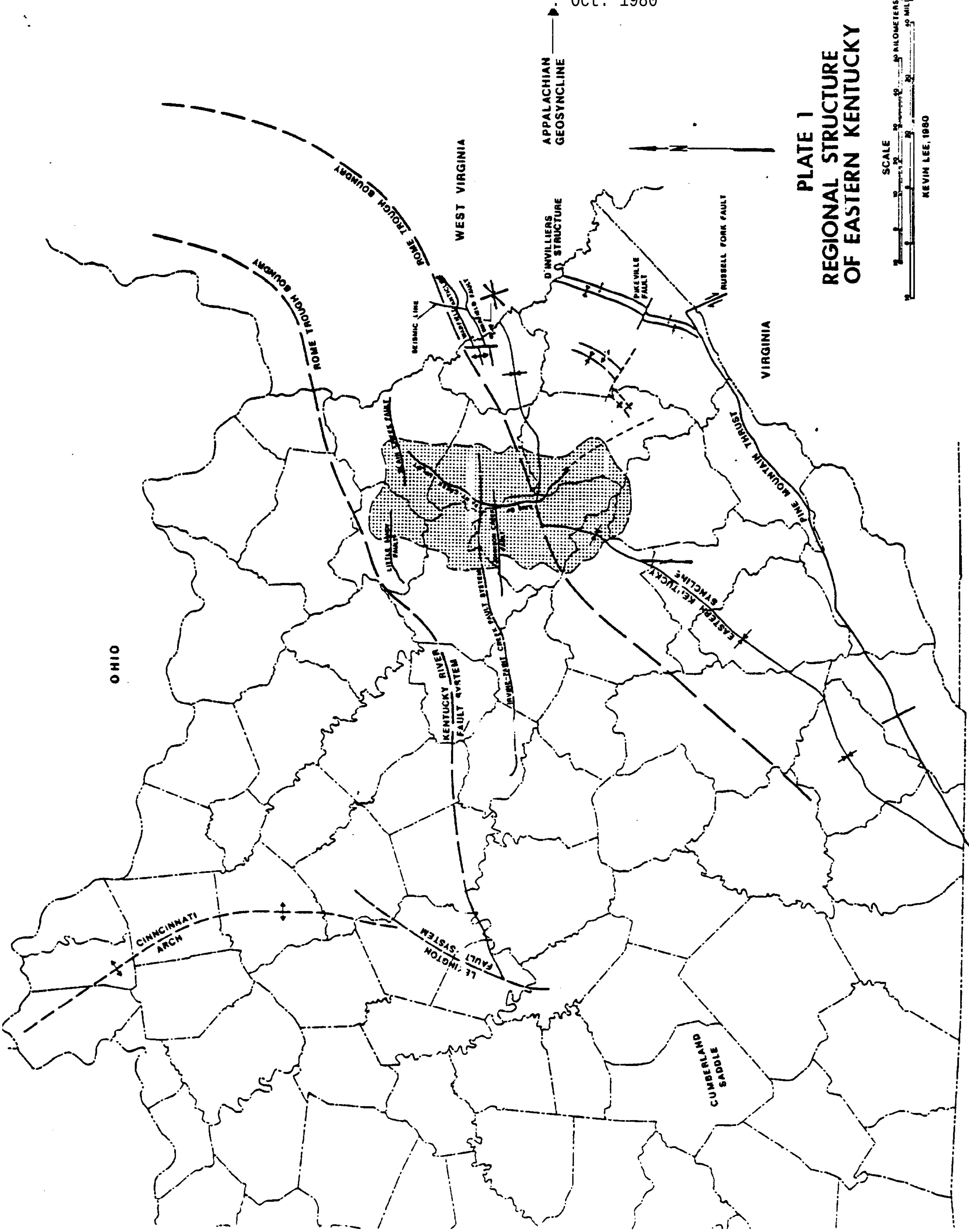

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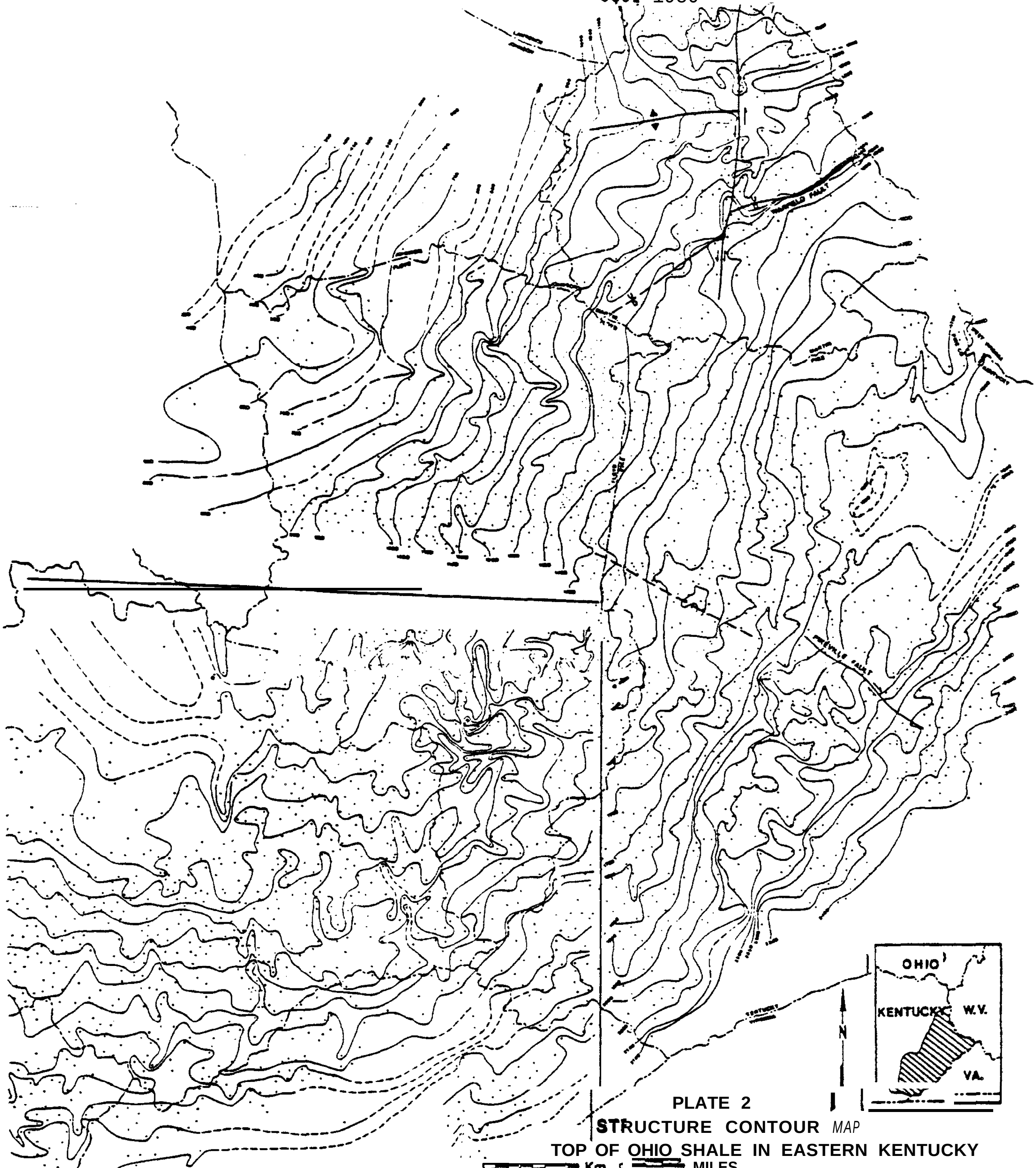

PLATE 2

STRUCTURE CONTOUR MAP

TOP OF OHIO SHALE IN EASTERN KENTUCKY

Km. MILES

K.LEE, 1980

(STRUCTURAL AXIS LOCATIONS PLOTTED FROM BASE OF NEWMAN LIMESTONE, FIGURE 15)

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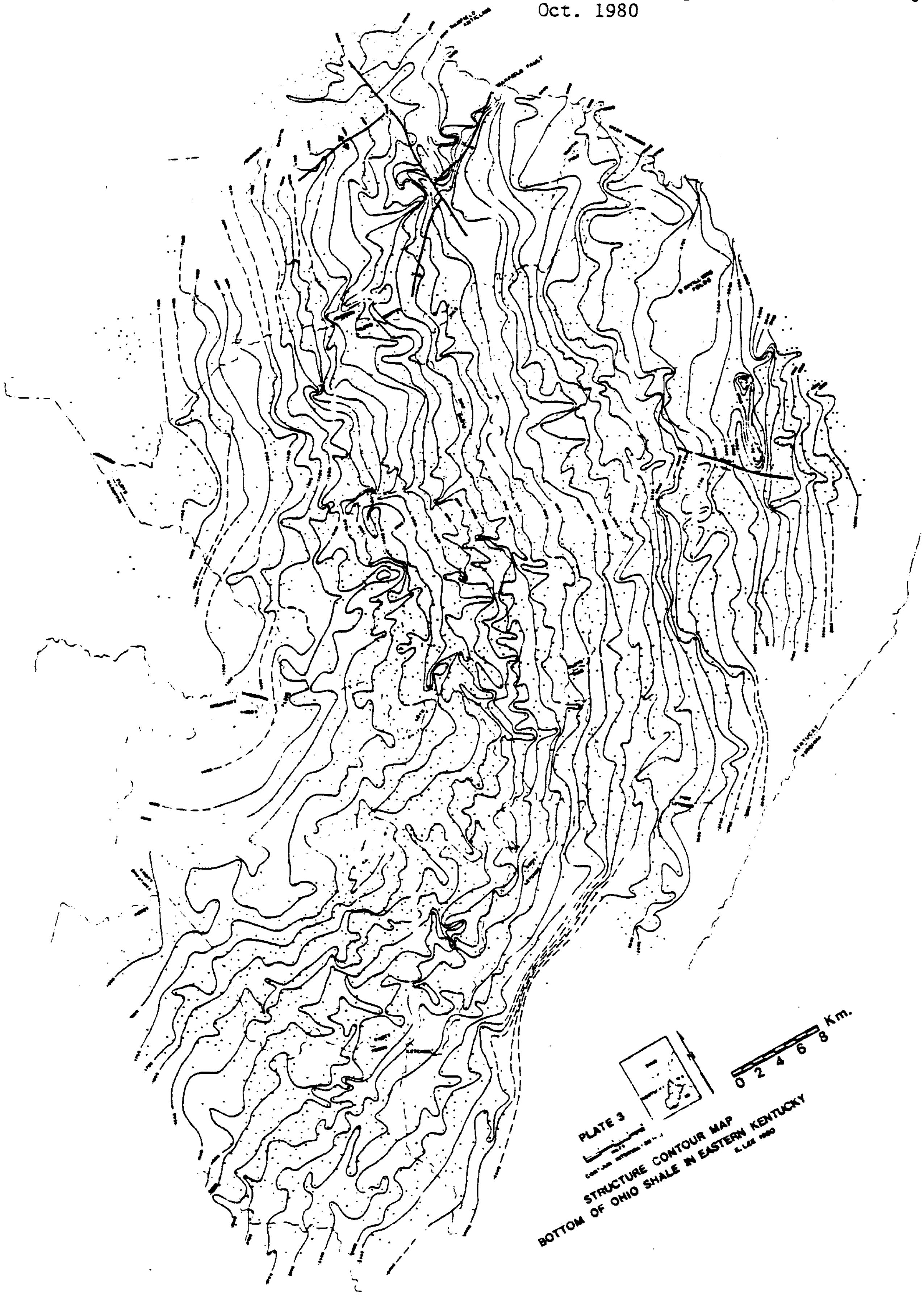

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