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Final Report

GEOLOGIC REMOTE SENSING OF THE MOORMAN SYNCLINE, KENTUCKY, REGION

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DECEMBER, 1980

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16. Abstract

Remote sensing imagery of a region in western Kentucky extending into Indiana, Illinois, and Tennessee was geologically interpreted for eastern shale gas exploration. The region is one Landsat frame enclosing the Moorman syncline, including the Wabash, Rough Creek and Pennyrile fault systems, and many oil and gas fields. Geologists with regional experience found unmapped lineaments in the imagery which were similar to those corresponding to the mapped faults. On the basis of some of these lineaments and other favorable geology, two sites for further exploration were selected. The interpreters concluded that the imagery, particularly the Landsat MSS, showed potential for use in shale gas exploration.

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PREFACE

This investigation was undertaken by ERIM for the Morgantown Energy Technical Center (METC), Department of Energy under Contract DE-AC21-79-MC11687. The test site area for this work is centered on the Moorman Syncline in Western Kentucky; it is the area covered by Landsat frame path 23/row 34 centered approximately on Madisonville, Kentucky. This investigation followed remote sensing work by ERIM by METC on a test site over the Cottageville shale gas field in West Virginia under Department of Energy Contract EF-77-C-05-5524.

To optimally use geological expertise both contractual and voluntary geologic consultants were invited to participate, with preliminary and final interpretative meetings being held. The methodology of the investigation, which turned out to be very successful, was primarily suggested by Claude S. Dean, the initial Technical Project Officer, who also participated in the preliminary geologic interpretation.

The contractual consultants were Robert Shumaker of West Virginia University and Ronald Dilamarter of Western Kentucky University. Robert Shumaker prepared a geologic background study (Appendix A), many useful interpretative overlays, and participated in the interpretation, he played a major role in this study. Ronald Dilamarter prepared a geomorphological study (Appendix B) but did not participate in the interpretation.

The voluntary consultants were John Beard of the Kentucky Geological Survey and Howard Schwalb of the Illinois Geological Survey. Their knowledge and insights were extremely valuable to this investigation. John Beard conducted a field trip, interpreted images, and participated in both the preliminary and final interpretation meetings. Howard Schwalb participated in the preliminary meeting and interpreted imagery.

The final selection of localized areas for further study was made at the final interpreter's meeting by Robert Shumaker, John Beard, and the principal investigator Philip Jackson.*

Many valuable contributions were made by the consultants and the initial Technical Project Officer Claude Dean, and these contributions in terms of direction, insight, and actual interpretative products, were basic to the success of this investigation. However, the results and conclusions are the responsibility and decisions of the principal investigator; he alone is responsible for any errors, omissions or limitations.

We wish to express many thanks to John Beard and Howard Schwalb. Their generosity in contributing to this work, and their unselfish contribution of their professional knowledge and insight were fundamental to this investigation. Thanks is also expressed to Pamela Swonger for her generous support in final report preparation.

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*The Principal Investigator, Philip Jackson, is currently working for the University of Michigan. Work under this program was completed under Subcontract 144000-1, Purchase Order 214179.

TABLE OF CONTENTS

Section Page

1 INTRODUCTION. 1

2 GEOLOGIC TEST SITE. 7

3 INTERPRETATION. 9

3.1 METHOD 9

3.2 RESULTS 13

3.3 AREAS WORTHY OF FURTHER EXPLORATIVE STUDY. . . 17

4 DATA PRODUCTS AND ANALYSIS. 23

5 DISCUSSION. 27

6 CONCLUSIONS AND RECOMMENDATIONS 35

Sections 1-6, BIBLIOGRAPHY. 37

Appendix A: STRUCTURAL GEOLOGY OF THE MOORMAN SYNCLINE AREAS OF WESTERN KENTUCKY . . 39

Appendix B: GEOMORPHOLOGY OF PORTIONS OF WESTERN KENTUCKY AND ADJACENT AREAS. 109

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LIST OF FIGURES

Figure		Page
1	Test Site Locations (Landsat frame path 23/row34). . .	5
2	Landsat Color Composite of Test Site	11
3	Computer-Drawn Display of a Combination of Two Interpreters' Lineaments on Landsat Image.	15
4	Big Bend Area of Green River	18
5	Breckenridge-Hancock Area in NE Portion of Landsat Frame	19

1
INTRODUCTION

The Eastern Gas Shale Program (EGSP) is dedicated to the increase of gas production from the Mississippian-Devonian shales in the eastern United States. Although these shales underlie between 4-600,000 km^2 in several states, forming an enormous source of gas, commercial shale gas fields are few. It is thought that the shale gas fields are related to fracturing of the shale -- the fractures providing conduits and reservoirs for the released gas (Overbey, 1975).

Faults and fractures at depth are sometimes manifested at the surface in subtle ways which cannot be observed by geologic field work, and are often related to regional structures. The exploration for new fields should include every possible means of exploring for these and similar geologic features.

One exploration means capable of discovering faults and fractures is remote sensing. Not only can such features be discovered which are not identifiable on the ground, but modern remote sensing encompasses large areas so that regional interpretation can be simultaneously achieved. Very slight surface anomalies due to soil composition, moisture, or topography and their effect on vegetation produce interpretable variations on remote sensing imagery. In addition, remote sensing is far less expensive than surface geophysical measurements and interpretation.

More briefly, the following simple sequence demonstrates the potential for application to shale gas exploration: shale underlies an enormous region in the vegetated eastern United States. Few fields produce commercial gas from the shale. Geologists suggest that fractures and faults produce the conditions for commercial production. Through remote sensing techniques, fault and fracture systems are discovered and related to regional structure at a cost substantially below other exploration methods. The proper use of remote sensing should aid in Eastern Gas Shale exploration.

In this project remote sensing is considered a reconnaissance exploration method. Without further confirmation, remote sensing lineaments should not be the basis of a substantial investment or a major decision such as drilling a well. The imagery can be used to pick limited areas for more intensive (and more expensive) investigation such as surface geophysics, more intensive geologic surface mapping, or possibly exploratory drilling. However, in many cases it is doubtful whether further surface mapping will be productive because the surface manifestations of subsurface faults and fractures may be diffused and subtle. The remote sensing task is to increase the probability of revealing subsurface conditions by geophysics or other means.

This project bears on the following aspects of such a task: the types of imagery to use, the types of analysis and data processing, the development of interpretative procedures, the picking and justification of promising exploratory areas, and the evaluation of remote sensing for gas shale exploration.

First, for the types of imagery to be used, we attempted to use the available imagery which was similar in scale to Landsat. In addition to Landsat MSS, Landsat RBV, Skylab, NASA high altitude (U-2), and Seasat imagery were used, Categorically the Landsat was most useful, and rendered the other images almost superfluous. During two meetings the interpreters insisted on spending almost all their time on the Landsat MSS.

Second, many data processing procedures were tried. The most fruitful for interpretation was a three-color presentation, at approximately 1:40,000 of Landsat MSS on a color monitor, the data directly taken from a digital tape.

Third, the development of interpretative procedures included the use of geologists experienced in the area and region. An initial interpretative meeting was held early in the project period, and a final near the end. Interpretation emphasized the knowledge of local geology and geophysical data. Background papers were prepared and used on the structural history, sedimentation and geomorphology of the test site region. Eleven separate transparent overlays were prepared showing mapped faults, streams, isopachs, etc. Several interpreters independently interpreted the test site region, marking lineaments which appeared similar to those caused by actual faults.

Fourth, specific, more detailed test sites were picked from the larger site. Three promising exploration areas were chosen after the first interpreters' meeting, and two localized areas were chosen for recommended exploration sites at the last meeting.

Last, the evaluation was made in terms of the interpreters' judgement of the extent and convincingness of the imagery, comparing lineaments corresponding to known faults with lineaments which appear to be similar. An evaluation also was made of the imagery, enhancements, and procedures to be followed. Emphatically, however, no final evaluation can be made until the chosen areas for exploration are tested at least by geophysical methods. Remote sensing, being a reconnaissance tool, cannot confirm itself. The suspected "lineament faults" which do not correspond to known faults, and which may indicate fractured areas for shale (or other) gas production, must remain suspected and unproven until tested. Currently they are only artifacts which seem to convince the eye that interesting geological features may exist.

The test site was chosen so that remote sensing could be used to find the localized areas mentioned above. The Moorman Syncline in Western Kentucky was chosen for this purpose. A Landsat frame (path

23, row 34) centered near Madisonville, Kentucky, latitude 37°30'N, longitude 87°30'E, encompasses the site. Several reasons dictated the choice of this Western Kentucky region: black shale underlies the site at reasonable depths and isopachs, shale gas is produced in the area; known faults run through the site so that they can be used as references when lineaments indicate suspected faults; and the possibility of other faulting exists because of the structural nature of the region (see Figure 1).

Many products were acquired, generated, and transformed for this investigation, in addition to the background geology articles. These products, which have been supplied to DOE, the Kentucky Geological Survey, and Western Virginia University, represent a resource for further work in this area.

According to the three final interpreters, two of whom are geologists with knowledge of the area, the imagery convincingly indicates features which could well be unmapped faults. The two localized areas were picked because of these convincing indications coexisting with known geology concordant with shale gas production. Again, it should be emphasized that geophysical or other confirmation is called for by these conclusions.

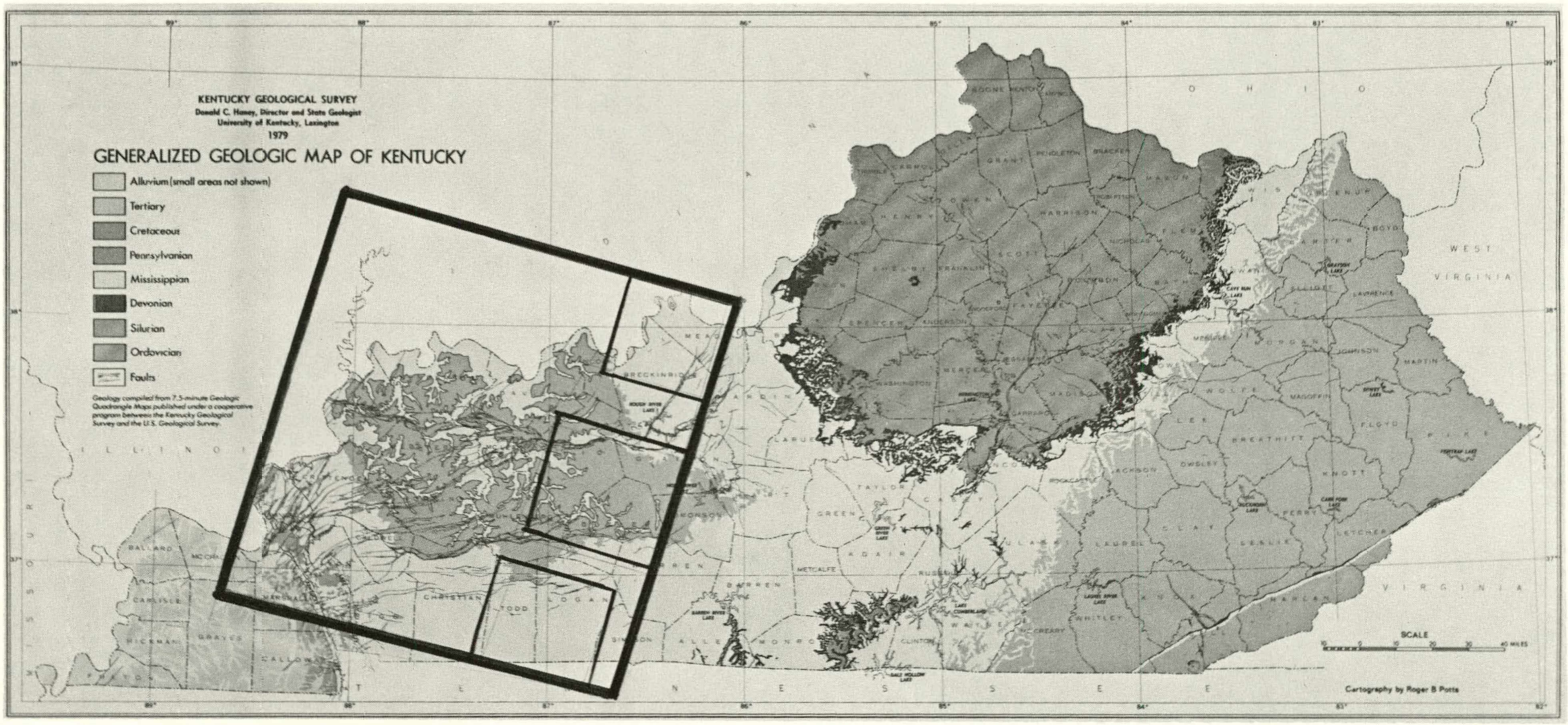

Figure 1. TEST SITE LOCATIONS. LANDSAT FRAME PATH 23 ROW 34 SHOWN ENCLOSED IN HEAVY SOLID BLACK LINES ON GEOLOGIC MAP OF KENTUCKY. THREE LOCALIZED TEST SITES SHOWN IN LIGHTER LINES WITHIN THE LANDSAT FRAME.

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GEOLOGIC TEST SITE

The test site is the area covered by Landsat frame path 23, row 24, centered near Madisonville, Kentucky at 37°20'N latitude and 87°30' E longitude. This area was chosen to investigate remote sensing for shale gas exploration for the following reasons:

1. Known fault systems are within the area, so that comparisons could be made between image lineaments corresponding to known faults and those indicating suspected faults.
2. The area has been structurally active, so that the possibility exists of unmapped faults.
3. The area includes many oil and some gas fields over a wide area, and the isopachs and depth of shale are compatible with commercial gas production.
4. The area is similar in topography and vegetation to other potential shale gas regions of the Eastern United States.

Because lucid geological and geomorphological descriptions are included as appendices, the description here is brief.

The Landsat imagery used in this report covers most of Western Kentucky and some of Southern Illinois, Southern Indiana, and Northern Tennessee. This portion of Kentucky is within the Eastern Interior Basin and is roughly divided east and west by a major tectonic feature, the Rough Creek Fault System. North of this system regional dip is 15-17 m/km from the east toward the west; from the southern flank of the basin the dip is to the north 50 to 150 m/km into the Moorman Syncline where the dip reverses and the rocks rise into the Rough Creek Fault zone.

The Rough Creek Fault zone extends from Southern Illinois, where it is called the Shawnee Fault System, eastward through Kentucky at least to Grayson County, a distance of 200 km. It is a complex series of faults containing rocks that range in age from Devonian to Permian. There are many explanations for this feature ranging from "faulted anticline" to "strike-slip."

The rocks of the Eastern Interior Basin are Pennsylvanian and Mississippian; the Pennsylvanian is a series of sandstones and shales with minor amounts of coal and limestone; the coal is of great economic importance. The upper part of the Mississippian is Chester in age and consists of a series of limestones, shales, and sandstones that are cyclitic in nature. The sandstones produce and have produced significant amounts of oil and gas since 1920. The rocks below the Chester are primarily carbonates but within the top 60 m there are four or more oolitic limestone sections which produce oil in economic quantities.

In addition to the Rough Creek fault system there are two other fault systems of some prominence: the Wabash fault zone, striking approximately N20°E in the NW section of the Landsat frame, and the Pennyrile fault system extending from the Mississippi Embayment (a Cretaceous overlap) in the SW corner of the frame, from where it strikes NE and bends approximately east across the frame.

For more detail on the geology and geomorphology, see Appendices A and B.

3
INTERPRETATION

3.1 METHOD

From the outset, the intent of this project was to keep the geology of the region paramount and to interpret remote sensing in terms of the fullest possible understanding of the geology of the test site. Toward this end geologic consultants with experience in the region were invited to interpret the imagery and advise on the use of remote sensing. In addition background reports were prepared on the geologic history, structure, geomorphology, and recent sedimentation of the region. A field trip was taken early in the project period using preliminary remote sensing imagery to gain close acquaintance with the region.

Both remote sensing data products and geologic maps and reports were first obtained. The first remote sensing data product to be used was the Landsat frame of the area. This frame was printed at a 1:250,000 scale, and to closely relate all phases of geology, same-scale overlays were prepared on transparent plastic of the following items:

1. Oil and gas fields
2. Fault systems
3. New Albany shale isopachs
4. Stream patterns
5. Surface faults
6. New Albany shale structure
7. Soil types in Indiana
8. Near surface structure
9. Center coordinate base map
10. Topographic contours of Nashville quadrangle
11. Topographic contours of Evansville quadrangle

After the early field trip to the Moorman Syncline, interpreters first marked lineaments on overlays at 1:250,000 on the entire Landsat frame. This was done individually. A meeting was then held at ERIM in Ann Arbor to discuss the geology, gain some consensus of the individual perception of "lineaments", attempt to flag the most convincing of the lineaments, search for other features such as arcuate structure, and select smaller areas for more intensive interpretation.

The result of this and a following meeting in Morgantown, was to select three areas on the eastern edge of the Landsat frame for more intensive study. These areas were then printed at a larger scale of 1:100,000, and distributed to the interpreters. These areas are shown in Figure 1. A 1:1,000,000 color composite of the frame is shown in Figure 2.

Several enhancement procedures were then performed on the imagery as described in Section 5. The different data products were then examined and individually reinterpreted, and in some cases evaluated as to their significance.

In a final two-day meeting, the imagery was examined interactively on a color monitor, and two relatively small areas were selected as having the most potential for gas exploration. During the first day of the meeting the Landsat imagery was examined on an interactive color monitor at a scale of approximately 1:40,000. Thirty-five millimeter transparencies of the images on the color monitor were obtained with an associated three-gun CRT and a matrix camera. Projections of these transparencies were then viewed the following day. From these projections, detailed interpretations of the two selected locations were made final. These final interpretations were the result of three interpreters viewing, marking, and discussing the available imagery, and evaluating it in terms of the known geophysical background of the region.

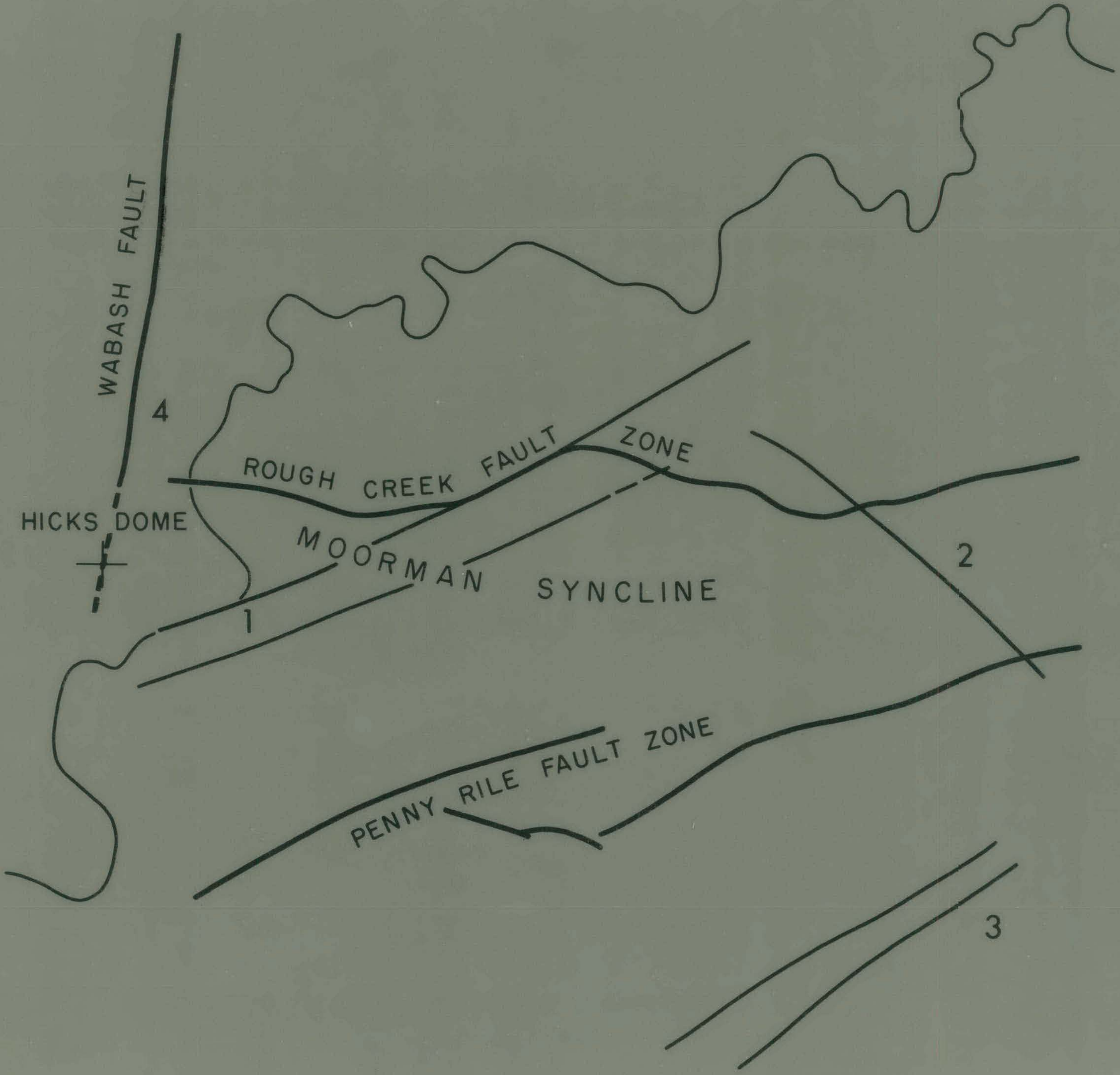

Figure 2. LANDSAT COLOR COMPOSITE OF TEST SITE. OVERLAY IDENTIFIES MAJOR KNOWN AND POSSIBLE FAULTS.

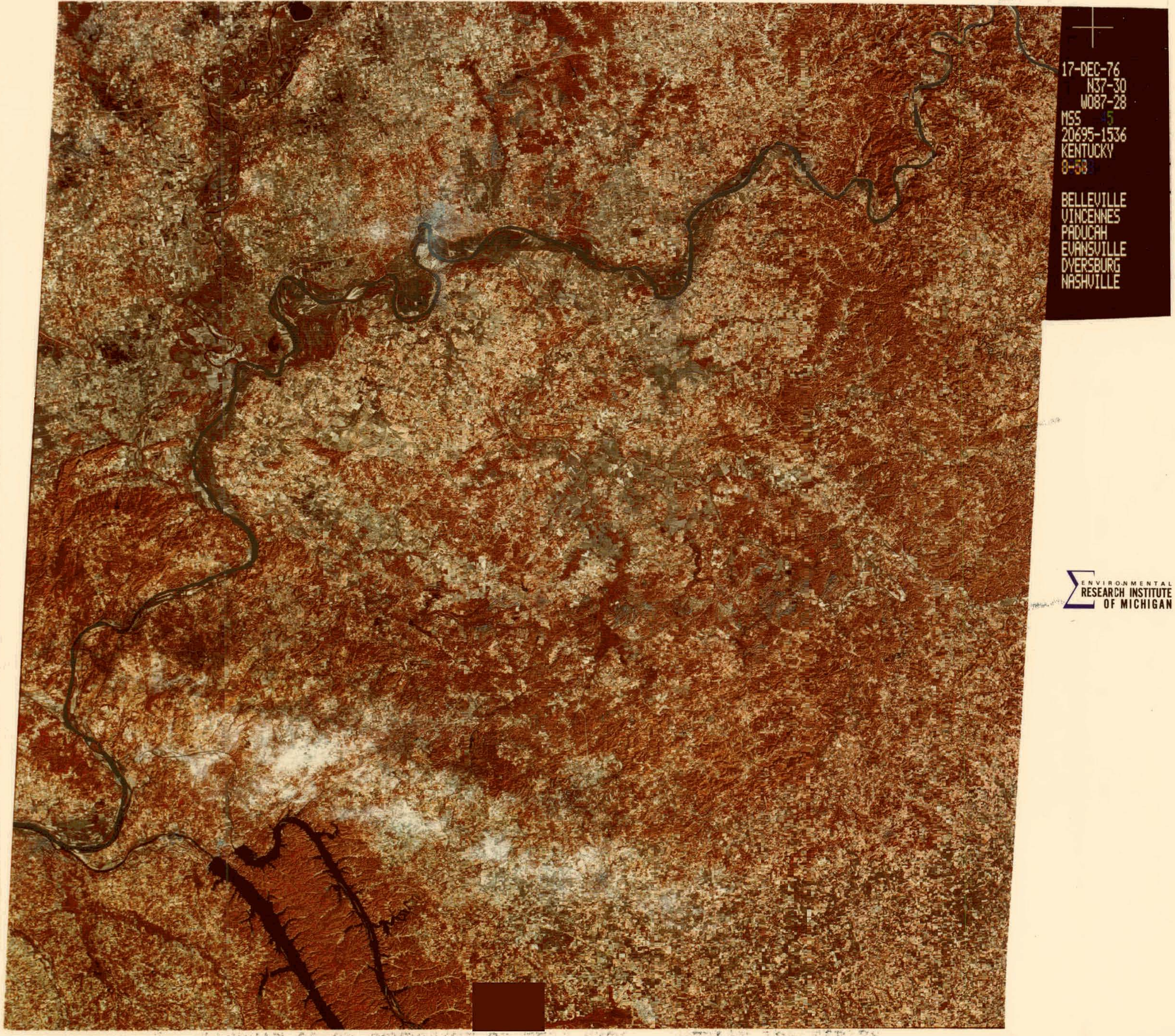

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Figure 3. LANDSAT COLOR COMPOSITE OF TEST SITE. OVERLAY IDENTIFIES MAJOR EDGES AND POSSIBLE FAULTS.

This procedural method, suggested by Claude Dean, is highly recommended. The one change should be that the interpreters should meet more often.

3.2 RESULTS

Landsat frame path 23, row 34 shows many interpretable lineaments. Some are pervasive and long, while some are restricted in length. The similarity between the published tectonic map and the lineaments found on the imagery shows that the imagery is indeed revealing known major faults. When comparing with maps one can see that there are only a few places where established major faults do not correspond with a lineament seen on the imagery. In addition, there are many similar imagery lineaments which do not correspond to mapped faults. Because some of the known faults are only known from well data, not being manifested at the surface, one suspects that the imagery is revealing currently unknown faults.

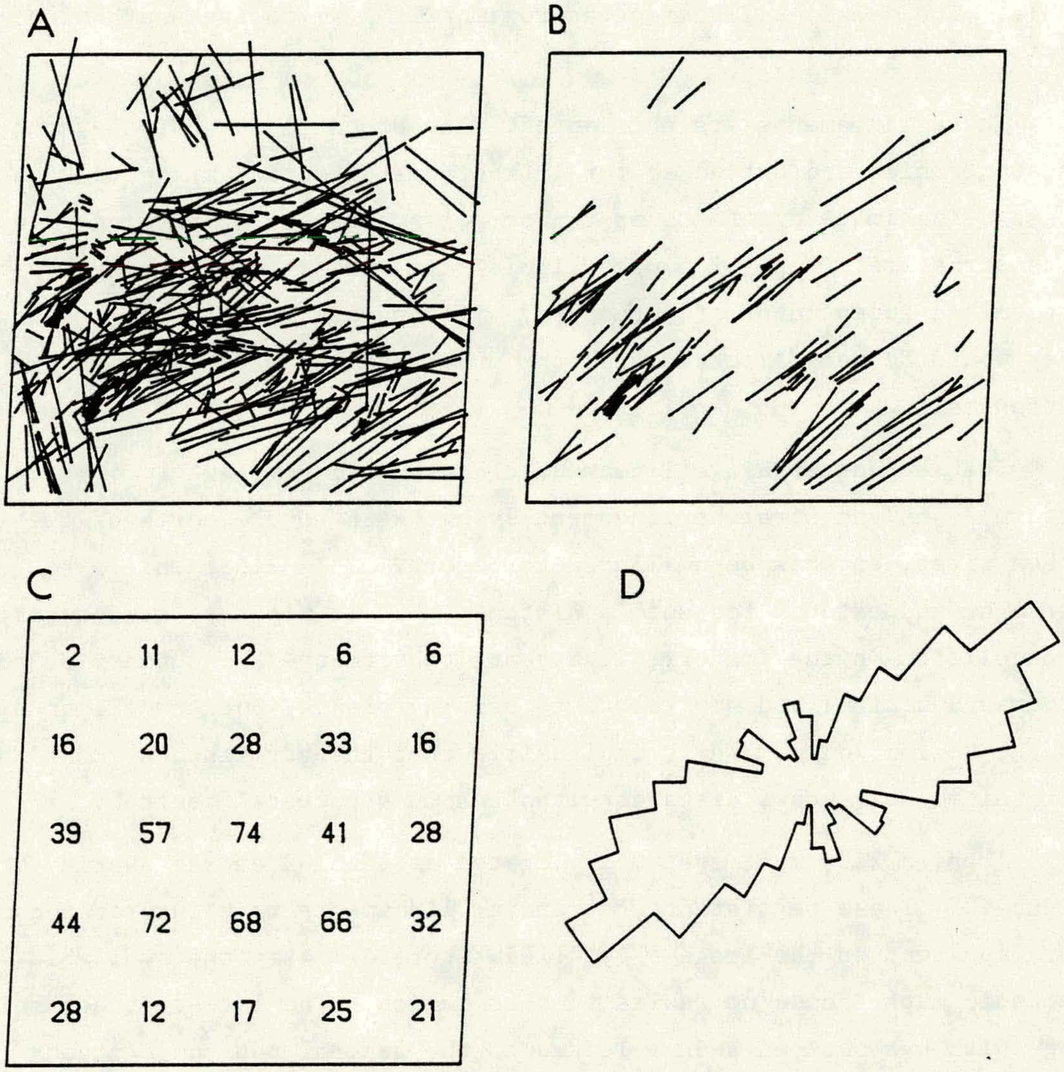
The Landsat imagery appears to be delineating subtle surface changes which are not detectable otherwise. The Landsat zones tend to be broad, whereas the tectonic maps indicate faults by narrow lines or groups of lines. The greater detail in the fault zones shown on the tectonic maps probably is, in part, a matter of scale. Geologists usually talk of fault zones, and then draw a single line on the map to represent that zone. The parallelism and proximity of lineaments to faults probably reflects the zonal nature of the faults, and in that sense, the imagery may be more accurate than the published tectonic maps.

The entire Landsat frame is rich with discernible lineaments for which there is no current geological explanation. These lineaments are most often tonal, and are not related to topography. For example, the shaded relief map prepared by computer using digitized topographic data from Defense Mapping Agency prepared tapes (Bateson and Edwards, 1975) did not show lineaments corresponding to the tonal Landsat.

It is clear when comparing the lineament and tectonic overlays with the images that most faults are expressed on the image. There are, however, many prominent lineaments that are not presently mapped as faults. Many of these lineaments are presumed to be fault zones, and one should be able to construct a more accurate tectonic map based on "reasonable" interpretation of the images. The word "reasonable" is used with interpretation because of the profuseness of the lineaments that could be mapped. Some of the lineaments may not be faults but zones of intense jointing, some may be lithologic contacts, and some may be randomly oriented patterns which appear to line up as valid geologic features.

There are a great many lineaments that could be mapped; too many, in the sense that if all lineaments were marked, the resulting maps would be a mass of confused intersecting lines, so-called "chicken-track" maps. Figure 3 shows the results when all suspected lineaments from two interpretations are mapped. We have, therefore, restrained ourselves to the most prominent lineaments so far as a rationale for selecting potential shale gas well sites.

Two different types of results are evident. The first is the pervasive, long lineaments which may indicate major structures which are presently unknown. The overlay on Figure 2 indicates four of these. The first is the long pair of lineaments marked 1 on the overlay. This lineament is a tonal gradation which is little related to topography, and extends most of the distance across the Landsat frame. Note that the upper lineament of the pair aligns with an almost anomalous straight section of the Ohio River with sharp bends at each end of the section, proceeds through and aligns with an approximately 20 km dogleg of the Rough Creek fault, and continues to extend in the same direction toward the northeast after it leaves the Rough Creek



2	11	12	6	6
16	20	28	33	16
39	57	74	41	28
44	72	68	66	32
28	12	17	25	21

Figure 3. COMPUTER-DRAWN DISPLAY OF A COMBINATION OF TWO INTERPRETERS' LINEAMENTS ON LANDSAT IMAGE

A. Lineaments
B. Lineaments Filtered Between E15°N and E45°N
C. Density of Lineaments within 30 x 30 km areas. Numbers represent lineaments crossing or terminating in area.
D. Rose Diagram with 10° Angular Resolution

fault. The parallel lineament approximately 7 km to the south also extends for a long distance.

These lineaments are not mapped. The probability that they can be so definite and extend so far in the same direction mitigates against these being image artifacts or random alignments having nothing to do with structure. But, of course, it is still possible that they are random and independent of structure. If they are related to structure they would be very important for the understanding of the regional tectonics.

The second pervasive lineament, labeled 2 on the overlay of Figure 2, is the straight lineament lying NW-SE to the north of the Green River, and has been alluded to before. This lineament is so straight and extends for such a distance that it might be structurally controlled. On the imagery, it appears to form the NE boundary of the Moorman Syncline, and may relate to bedding planes, but the slight dip in the region would make it implausible that the straightness could be maintained for such a distance without some structural control.

A third lineament system is located at label 3 on the overlay of Figure 2. These persistent NE trending lineaments were interpreted as very apparent on the imagery by all interpreters when the available tectonic maps showed no faults in this region. The latest structural map which has not yet been released to the general public (Kentucky Geological Survey) shows some faulting in this area.

The fourth example of pervasive lineaments is shown at label 4 of the overlay on Figure 2. Essentially this indicates that the Wabash fault system may be extended through Hicks Dome; this persistence through Hicks Dome is not currently mapped. The viewing of Landsat on the color monitor was very convincing to the three interpreters that a lineament which connected to the Wabash fault system proceeded directly through the dome. Again it should be emphasized that the existence of an interpreted lineament on remote sensing images does not mean that an actual structural feature exists, and no claim is being made that the Wabash fault system does proceed through the dome. The point here is that there is an indication, a plausibility, that such an extension is possible, and such an indication is worthy of further investigation. We do not wish to depart from the viewpoint that remote sensing is used for reconnaissance.

3.3 AREAS WORTHY OF FURTHER EXPLORATIVE STUDY

As a result of the last meeting, two localized areas were chosen which were deemed worthy of further evaluation and exploration as possible test sites for black shale gas wells. The Landsat imagery on the color monitor and subsequent 35 mm projections were examined in detail by three interpreters at the final interpretation meeting. Using the year's experience and comparing with maps of the oil and gas fields, known faults, geophysical features, geologic features, black shale structure, and black shale isopachs, they recommend the two areas shown in Figures 4 and 5.

A great many features which could be interpreted as faults and fault zones were clearly visible on the imagery, but in many cases the faulting had not been mapped. Various geological features were distinguishable by tonal changes -- particularly so along the southern flank of the Illinois Basin and in the Moorman Syncline.

The two locations are in the Big Bend area of the Green River and the Breckenridge-Hancock area. A portion of the Evansville quadrangle USGS map is shown in Figure 4, the Big Bend area suggested for further exploration is shown within the solid circle. The lineaments interpreted on the imagery are marked. Not only the imagery lineaments influenced these selections, but the known geology and geophysics were noted in terms of possible black shale gas production.

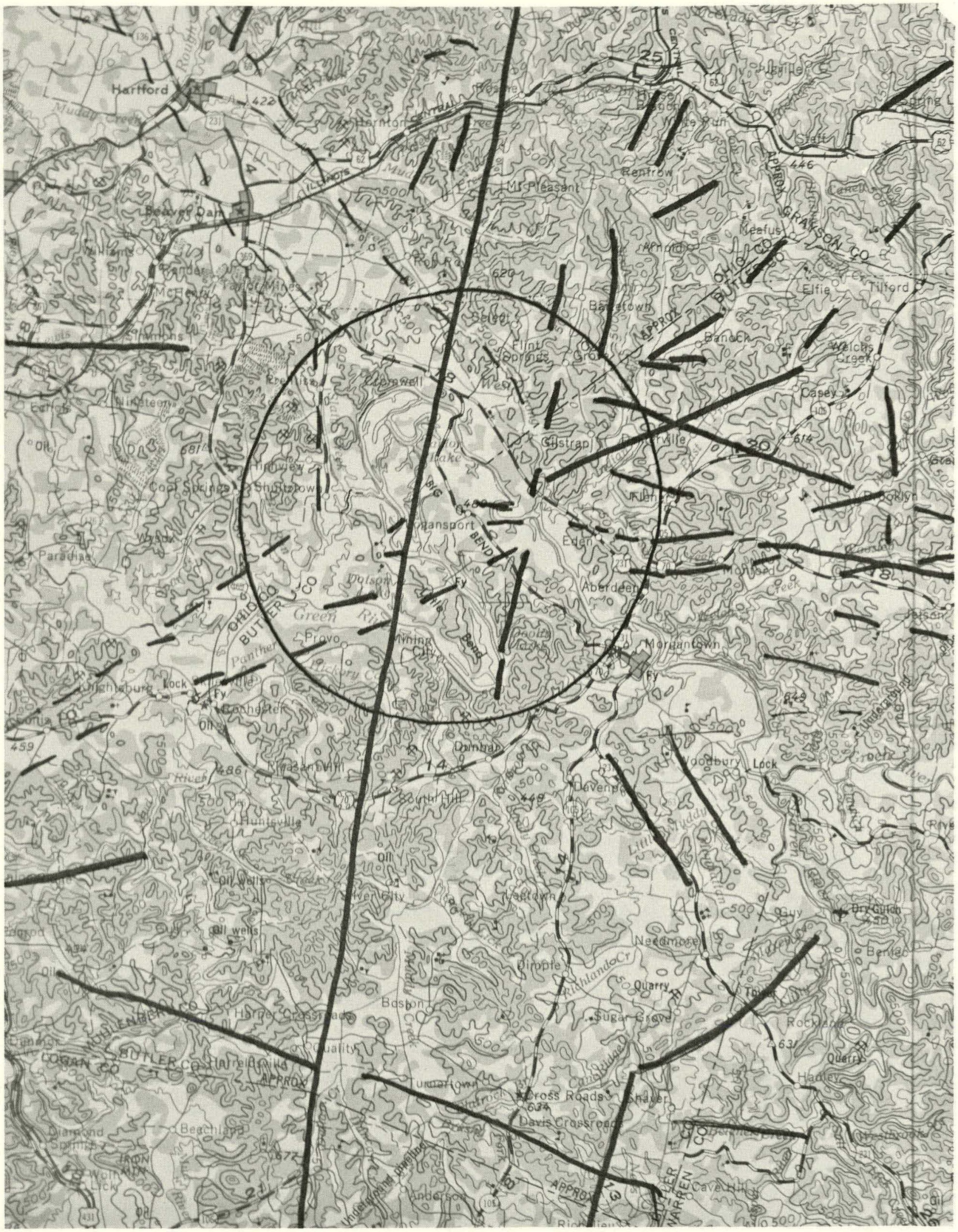


Figure 4. BIG BEND AREA OF GREEN RIVER (ENCLOSED IN LIGHT CIRCLE)

Selected for further exploration for potential gas production. Solid lines are lineaments, dashed lines enclose tonal anomalies. Long vertical lineament extends almost the length of the Landsat frame.

Figure 5. BRECKENRIDGE-HANCOCK AREA IN NE PORTION OF LANDSAT FRAME (P23/R34)

Selected for further exploration for potential gas production. Heavy lines are lineaments. Rectangle encloses potential location.

The reasons for selecting the Big Bend area are as follows:

1. It is the largest drainage anomaly along the Green River.
2. The loop within the drainage anomaly lies within the tonal anomaly and extends NE-SW.
3. There is a topographic anomaly associated with the tonal anomaly; that is, the area along the anomaly is topographically lower than the adjacent area.
4. Cross-lineaments trending NW-SE, EW, and one large lineament trending NS intersect within the area of the anomaly.
5. A major fault lies within the area just to the south and has been mapped to approach the Green River.
6. The floodplain changes in the area associated with the crossing of the EW trending lineaments -- and there are smaller stream habit anomalies, that is, the floodplain bends within the main loop associated with these EW trending lineaments.
7. Recent surface mapping in the area shows a regional flattening of dip suggesting a deeper structure.
8. Gravity and magnetic trends of the area intersect along the anomaly.
9. There is sufficient New Albany shale thickness in the area -- around 60 meters.
10. The New Albany shale is at a reasonable drilling depth -- approximately 760 meters.

The Big Bend area lies well south and north of any production from the shale so that it is truly a wildcat area.

The Breckenridge-Hancock area is shown in Figure 5.

The reasons for selecting the Breckenridge-Hancock anomaly for further evaluation and exploration are as follows:

1. There is a drainage anomaly along the Ohio River.
2. There is an old gas field (abandoned) with reported shows of gas from the New Albany shale in the town of Cloverport.
3. The meander loop of the streams parallels the lineament trends.
4. This is an area of crossing lineaments that are regional and apparent to all three interpreters. These are:
    a) NS lineament of the Big Bend area noted above.
    b) NE trending regional lineament from Hicks Dome crosses just south of the meander loop.
    c) Local NE trending lineaments primarily just to the east of the area, and EW trending lineaments just at the north edge of the anomaly.
5. A well completed in the black shale some seven miles to the NW tested 200,000 cubic feet per day, but was abandoned because of the low price of gas (27¢) at the time of drilling and a presumed high nitrogen content. The nitrogen content is thought to be a function of the method of sampling the gas, and may not be reliable.
6. The shale thickness is 45 meters, sufficient for commercial production.
7. The shale is at a reasonable depth for drilling 460 meters.

The detracting aspects of the Breckenridge-Hancock area are the lack of map structuring in the area and the lack of any associated gravity or magnetic trends intersecting within the area.

To summarize the results of interpretation:

1. Almost all mapped structures show on the Landsat color composite as lineaments. However, faults on maps are drawn with narrow lines, whereas the imagery shows wider tonal zones.

2. Many other lineaments clearly show on the imagery which do not correspond to surface mapped faults. The consensus of the interpreters is that these could indeed be faults or otherwise structurally controlled. So many image lineaments occur that only the more obvious ones can be reasonably investigated.
3. The lineaments tend to follow established trends, and seldom violate the currently inferred structure.
4. The image lineaments are not subservient to the topographic expression, indicating that, if they do represent faults, they could be missed in geologic surface mapping.
5. Some lineaments are pervasive and lengthy. If any of these represent faulting, major structural revision would be indicated. Also, mapped faults appear to be extended, such as the Wabash through Hicks Dome.
6. Areas exist where lineaments come together, and where other geologic features, including the depth and isopachs of the New Albany shale, are favorable for potential gas production. Two such localized areas were chosen. Further exploration of these two areas is strongly recommended.
7. Despite these highly favorable results, we consider remote sensing to be a reconnaissance technique which aids in focusing ground-based investigations such as geophysics. The actuality of faults and favorable structures is a question which must be decided by further ground-based investigations, and not by conjecture, no matter how plausible on the imagery.

4

DATA PRODUCTS AND ANALYSIS

The satellite imagery used for this project was that obtainable over Landsat frame P23 R34; Landsat, Seasat, and Skylab images and tapes were obtained.

Three Landsat MSS tapes were acquired for the following dates:

May 10, 1977 (828 3915 294500)
December 17, 1976 (826 9515 360500)
March 22, 1976 (824 251 5443500).

One frame (four quadrants of Landsat Return Beam Video (RBV) on
June 1, 1978 (830008815480XA, XB, XC, XD).

Seven Skylab images were obtained for the following dates. Because the Skylab images cover only portions of the Landsat frame, the individual images are of different areas.

November 30, 1973 (COL G408090034000)
November 30, 1973 (CIR G40A051062000)
November 30, 1973 (COL G408090033000)
June 10, 1973 (BIR G20A008240000)
June 10, 1973 (BIR G20A007243000)
June 10, 1973 (COL G20A010259000)
June 10, 1973 (B&W G20A012243000)

Both optically and digitally processed Seasat synthetic aperture radar images were obtained:

June 4, 1979 (Revolution 565)
June 25, 1979 (Revolution 766)
June 29, 1979 (Revolution 788)

No NASA high-alitude imagery was found over the three 1:100,000 test sites.

All pertinent maps and literature were obtained from the Kentucky Geological Survey; these included Geologic Quadrangle (GQ's) for the 1:100,000 test sites, gravity, magnetic, structure, New Albany shale isopachs and depths, oil and gas fields, and contour maps of the region. Literature included many reports from NRC on this and adjoining mid-continent region, as well as Kentucky Geological Survey articles.

As stated in the interpretation and discussion section, Landsat color compositing was primarily used for interpretation, although several types of enhancements were performed on the imagery:

1. Color Compositing
   A means of presenting multichannel data in one image, color compositing has become popular for Landsat data. Three channels are commonly used, with each channel represented by a primary (or near primary) color. Landsat MSS bands 4, 5, and 7 were composited, each band represented by a separate color. Band 4 was imaged in blue, band 5 in green, and band 7 in red. Almost all the interpretation was based on Landsat color composites.

2. Ratioing
   Ratioed Landsat MSS bands were color composited. The three ratios were 4/5 (blue), 5/6 (green), and 6/7 (red).

3. Edge-Enhancement
   To attempt to increase contrast, edge-enhanced images were prepared. These are produced by replacing a pixel's value by the difference between its value and the average value of a selected number of pixels surrounding the pixel. This has the effect of high-pass filtering. A color composite was made of edge-enhanced bands 4, 5, and 7, using the average of 9 pixels.

4. Optical Fourier Transforms
   Transparencies were made of Landsat band 5, and placed in a Fraunhofer diffraction optical system, as described by

Jackson (1979). The purpose was to determine directional trends in the imagery. Sixteen overlapping sections, each representing approximately 50 km^2, were Fourier transformed in a Fraunhofer diffraction setup. The transforms were observed, and photographs made with variation of exposure levels. The diffraction was isotropic except on one transparency. This transparency, centered on Union County, caused diffraction weighted in the N 40°W direction, which would indicate lineal trends in the E 40°N direction.

5. Level and Color Slicing

Essentially these are performed when preparing color composites or viewing on the color monitor. A histogram of image intensity levels is prepared, and assignment of intensity levels is made for its three bands. In color slicing, the balance between the three colors is adjusted for relative intensities to enhance desired features.

6. Shaded Relief Images

Using digitized topographic data, shaded relief maps were prepared using the method of Bateson et al (1975). The digitized data can be used in computing the shadows that would be produced by the sun at a selected azimuth, elevation and viewing angle. A shaded relief map was made for the Nashville quadrangle with the "sun" placed at 30° elevation in the NW.

7. Density, Filtering and Rose Diagram of Interpreted Lineaments

After interpreters have drawn lineaments on overlays, the lineaments are entered into a computer memory. From these data, lineaments maps, lineament maps filtered for both direction and length, density of lineaments, and a rose diagram are drawn, as shown in Figure 3. The density "boxes" shown are 30 km x 30 km, and the numbers indicate the number of lineaments crossing or terminating within the box.

8. Gradient Filtering

A directional method of filtering (Jackson and Wagner, 1979) was applied to Landsat band 5 to attempt to enhance the image of suspected lineaments. Essentially the direction of the gradient (orthogonal to a lineament direction) is found, and only pixels whose gradient is within a selected angular width are retained in the image. Greymaps were made of these images, as well as directional histograms (rose diagrams).

9. Automatic Selection of Lineaments by Digital Computer

Late in the project time period we learned of an automatic lineament detection program of an industrial concern which had leased the algorithm to a major oil company for exploration purposes. Test site 3 was chosen and an automatized lineament map purchased. It is dissimilar to the geologists' interpretation.

To summarize, many, but not all available images were obtained, and several, but not all types of enhancement and analysis were attempted. For example, during this period a new type of image at a very small scale became available - heat capacity mapping. Our awareness of this availability came too late to obtain this imagery. Also, recently ERIM has obtained new algorithms for destriping, edge-enhancing out to 100 pixels in each direction, and merging edge-enhanced with non-edge-enhanced images -- too late for inclusion in this work.

These latter are mentioned to emphasize that new products and techniques are continually being developed, and may add greatly to the quality of interpretation in the future.

As stated in the interpretation section, color composite data was almost exclusively used. The other enhancements contributed negligibly to the interpretation. The products, enhancements, and analyses are archived at ERIM for possible future or more intensive study.

5

DISCUSSION

The conclusion of the three final interpreters is that the remote sensing imagery has shown the possibility of geologic structural features which have not yet been mapped. These possible structures occur in areas where other characteristics are favorable for shale gas production. Particularly the depth and thickness of the New Albany shale are favorable. In addition persistent, long lineaments on the imagery might indicate faulting or fracturing which would require revision of the structural description of the region. In this sense the results of this investigation were favorable. However, to be useful as well as favorable requires geophysical validation of these features on the imagery.

The reconnaissance nature of remote sensing should again be emphasized. It is the economical first step in exploratory studies, and should be used to more efficiently employ expensive ground-based techniques. The geologic and vegetational characteristics of the region appear to make it suitable for effective remote sensing investigation.

Although the interpreters finished on an optimistic, favorable note, caution is still advised. Interpreting images is a qualitative, subjective operation. In addition, the images only reveal the surface, where the interpretation is applied to characteristics at depth. Lineaments are controversial, not only in the very existence of individual lineaments, but in their interpretation. An interpreter can discover and identify subtle lineaments which current pattern recognition technology cannot discern or even identify when they have been discerned visually. This fact often makes image lineaments subjective, and reflects the inclination, habits, and visual pathology of the interpreter. Subtle, marginal lineaments are often important, for the obvious lineaments are more likely to be caused by known fractures which have already been mapped on the surface, require no confirmation, and therefore do not add to geologic understanding.

The Glossary of Geology of the AGI describes lineaments as follows:

> Lineament: Straight or gently curved, lengthy features of the earth's surface, frequently expressed topographically as depressions; these are prominent on relief models, high altitude air photographs, and radar imagery. Their meaning has been much debated; some certainly express valid structural features, such as faults, aligned volcanoes, and zones of intense jointing with little displacement, but the meaning of others is obscure, and their origins may be diverse, or purely accidental. Colloquial synonym: "linear".

Another aspect is that different interpreters, no matter how experienced, often perceive different lineaments on the same imagery, and sometimes fail to perceive one another's. A striking example of perception of different lineaments by different individuals in several groups is given by Podwysocki et al (1975).

With these caveats out of the way, we can mention the positive aspects of this investigation:

1. The interpreters agreed that most known structures were imaged.
2. There were other features on the imagery which were similar in appearance to the characteristics of the known structure, but for which no mapped structures are known. The interpreters agreed on the convincingness of these features, to the extent that we recommend further geophysical exploration for confirmation.
3. Two of the interpreters had spent much of their professional lives studying the area. One has extensive experience in exploration photogeology in this region, and one has extensive remote sensing experience. All agree that potential structure was found.

It is most interesting that the lineament trends, for any one area, are very consistent. In addition there are many more lines on the imagery than on the published tectonic maps. The similarity in trend between the maps suggests that lines on the imagery reflect actual structural features, faults, which geologists mapping the area were either unable to detect through lack of exposure or through lack of sufficient stratigraphic offset.

Some of the imagery lineaments may reflect bedding trends. This is probably true of the broadly arcuate trends in the center of the image from Hicks Dome on the west along the axial trend of the Moorman Syncline to the east. The edge of the Moorman Syncline just northeast of the Green River is very straight on the imagery, and appears as a possible fault. This is lineament 2 shown on the overlay of Figure 2. This very straight, long bedding plane exposure may well be related to subsurface faulting. However, the general low dip of the surface rocks mitigates against straight linear trends being much other than fracture trends or cultural features. Fortunately cultural features can be eliminated from map inspection, and usually have a character that is perceptually different from natural features.

Mapped faults which show on the imagery sometimes appear to be extended from the limits shown on the map. A case in point is the extension of the Wabash fault system down through Hicks Dome. This extension is perceptible on the 1:250,000 color composite print of Landsat, barely palpable on the 1:1,000,000, but was very clear and definitely seen when viewing the color monitor and on the 35 mm slides prepared from the monitor image.

The imagery of this area shows apparent lineaments, so that controversial, subtle lineaments were not required for interpretation. This implies that remote sensing could hold potential benefit for similar areas in the midcontinent. Both regional and localized features were discerned.

Many image features are independent of topography, tonal in nature, and, therefore, were probably due to slight compositional changes occurring diffusely over a swath, and reflecting some subsurface characteristics. This phenomenon would be difficult or impossible to detect on the ground, so that an actual fault having been previously undetected is probable.

The method of using remote sensing, primarily suggested by Claude Dean, proved to be effective. The knowledge of the geology was emphasized. Geologists with extensive experience in the test site region were invited to participate in the interpretation. The method, described in the interpretation section, proved to be very effective. Discussions between the interpreters were especially profitable, and at least doubling the number of meetings would be worthwhile. The background reports were valuable, and can serve any future investigations. For future investigations, a product base has been built up with imagery at METC, ERIM, Kentucky Geological Survey, Illinois Geological Survey, and West Virginia University.

One surprising result is that only one image product, unenhanced at that, was essentially accepted by the interpreter. This was the three-color representation of Landsat MSS. During the first meeting an edge-enhanced, 1:250,000 scale, three-color composite of a winter scene was primarily used. After this an unenhanced version was made. The interpreters preferred this latter version. The most useful image was that on a color monitor. The clarity and number of lineaments was maximized on this presentation. Projections of 35 mm slides made from an associated matrix camera were also useful.

In similar work we would recommend a 1:250,000 color composite print and 35 mm slides (approximately 1:500,000 on the slide) taken with the matrix camera. The slides can be projected to whatever scale is desired. The small-scale print can be used for regional and synoptic purposes, the projected slides for detail and more contrast. The projection has much more dynamic range than the print, enabling better delineation of features. These two data products are the basis for most interpretation.

Although other images were obtained and studied, they were not found to aid interpretation. In some cases lineaments were confirmed, in most cases not. No significant features were found on the other imagery which were not evident (and usually clearer) on the Landsat.

The Seasat SAR images were gathered specifically for this project. Both optically and digitally processed images were obtained of most of the area of the test site. The principal investigator (who has had extensive experience with SAR images) was particularly interested in these Seasat SAR images, favored their use on this project, and had expectations for their interpretive capabilities. They were useful, often playing a supporting role to Landsat. As mentioned elsewhere, the interpreters preferred to pay attention to the color composites. The tonal anomalies found on the Landsat often were not apparent on the Seasat, and known features were difficult to delineate on the Seasat SAR imagery -- the Green River, for example. Possibly the high depression angle of the Seasat radar combined with subtle topographic features worked against delineation of features. Also the many tonal features on the Landsat imagery may have been compositional, often subtle and diffuse, and possibly not detectable by single-channel radar.

Many types of image enhancements have been and are being developed. These are both geometric, and compositional. In the geometric, the directionality or the tonal variability of the image are enhanced, as sometimes achieved by directional filtering and edge enhancement. In the compositional, broader areas are differentiated, as sometimes achieved by ratioing or by techniques such as maximum likelihood. The compositional requires more than one channel of data.

None of the enhancements or computational procedures significantly aided the interpreters. The consensus of the interpreters was that one unehanced (from a geometric standpoint) data product was sufficient to interpret. This imagery was enhanced in the sense that level slicing and color slicing were performed to achieve contrast.

Why, when all these enhancement procedures are available, did the interpreters essentially use only one unenhanced image? Probably for two reasons: the characteristics of the image in terms of what we were searching for, and the fact that, given a good, clear, image, the human eye is extremely skillful in selecting patterns.

As mentioned in the interpretation section one aspect was the profuse number of lineaments, from obvious to subtle, that were found on the imagery from direct observation. The problem encountered was one of lineament quantity and quality. There are a great many lineaments that could be mapped; too many, because if all lineaments were marked the resulting maps would be a mass of confusingly intersecting lines, so-called "chicken-track" maps. Under such conditions one stops searching for less obtrusive lineaments when the number of newly discovered lineaments appears adequate. Under such conditions enhancements become superfluous. The interpreter is already seeing all that he needs to see, and possibly more. "Sharpening up" what is already fully perceived does not aid the viewer.

Our experience in this particular area should in no way be taken that enhancements and image analyses are not worthwhile. They are extremely valuable when subtle, overlooked features are sought for in an image. Also, with multichannel data, one can analyze for composition better than visual means. We are only reporting our experience on this project, not evaluating or downgrading the value of enhancements in other remote sensing work.

Despite the positive results in finding potential unmapped faults and localized areas in Western Kentucky for further exploration, work cannot be evaluated until it is shown whether image-indicated structure is actual structure. Without geophysical or other surface confirmation, remote sensing work is futile and cannot be evaluated.

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CONCLUSIONS AND RECOMMENDATIONS

1. Remote sensing shows potential for aiding in shale gas exploration in the Moorman Syncline area.
2. Most known fault systems were apparent as lineaments on the imagery, and similarly appearing lineaments appeared elsewhere on the imagery, indicating the possibility of further faulting or fracturing.
3. In some areas interesting lineaments, surface features and geologic knowledge combined to such an extent that the possibility of gas production was concluded. Two areas were particularly promising. These are recommended for further exploration.
4. Landsat MSS color composites without enhancements were found to be of prime value in image interpretation.
5. The participation of geologists experienced in the regions was essential. Such participation is highly recommended.
6. Two meetings and other interactions of the interpreters were highly beneficial. More frequent meetings are recommended.
7. Geologic background papers aided considerably in the interpretations, particularly when the author can then participate in the interpretation. Such papers are recommended for similar studies.
8. Despite the encouraging results of this study, remote sensing should be treated as a reconnaissance method only: a very economical technique which can aid in proper placement and use of surface geophysical and geologic interpretation.

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SECTIONS 1-6
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APPENDIX A

STRUCTURAL GEOLOGY OF THE MOORMAN SYNCLINE AREA OF WESTERN KENTUCKY

by

Robert C. Shumaker

A.1 PURPOSE

The intent of this report is to establish a geologic background preparatory to undertaking a remote sensing study of Western Kentucky. The specific purpose of the remote sensing study is to evaluate the utility of enhanced imagery in mapping geologically significant lineaments that can then be used to site wells for exploration of natural gas from the Devonian shale.

This report serves a dual purpose, and therefore it is organized into two parts: the first part (Section A.2) set the geological stage for the interpreter and geologist who is unfamiliar with the study area; the second part (Section A.3) presents the structural style of the fault zones that may be selected for testing with the drill.

A.1.1 AREA OF INVESTIGATION

The study area is defined by Landsat image frame path 23/row 24 (Figure A-1) in Western Kentucky. It includes a variety of geologic and geomorphic provinces, including portions of the Mississippi Embayment on the southwest, the Southern Shelf on the south, the west flank of the Cincinnati Arch on the east (Figure A-2) and the Illinois Basin on the north and northwest. The study area centers on the Moorman Syncline (Figure A-1). Some geologists have divided this larger synclinorium into several subdivisions, and they have restricted the use of Moorman to the southernmost structural low (Figure A-3). The author prefers to apply a broader usage (Figure A-4) where the fault zones bordering the Moorman Syncline are the Rough Creek faults on the north, faults of the Embayment-Illinois Fluorspar

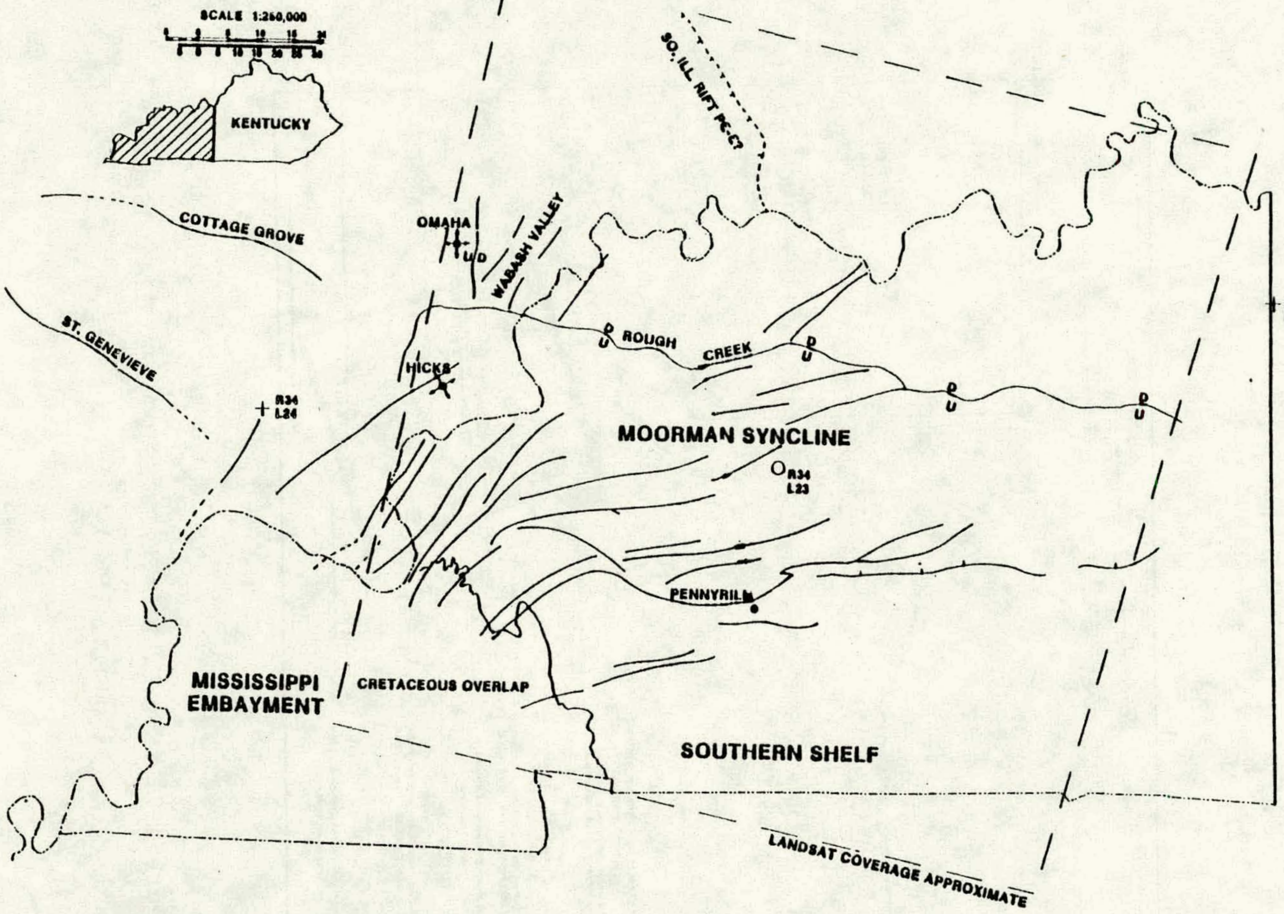


Figure A-1. LANDSAT FRAME PATH 23/ROW 34 AREA, WESTERN KENTUCKY WITH INCLUDED REGIONAL GEOLOGIC FEATURES

(Generalized from Schwalb and Potter, 1978)

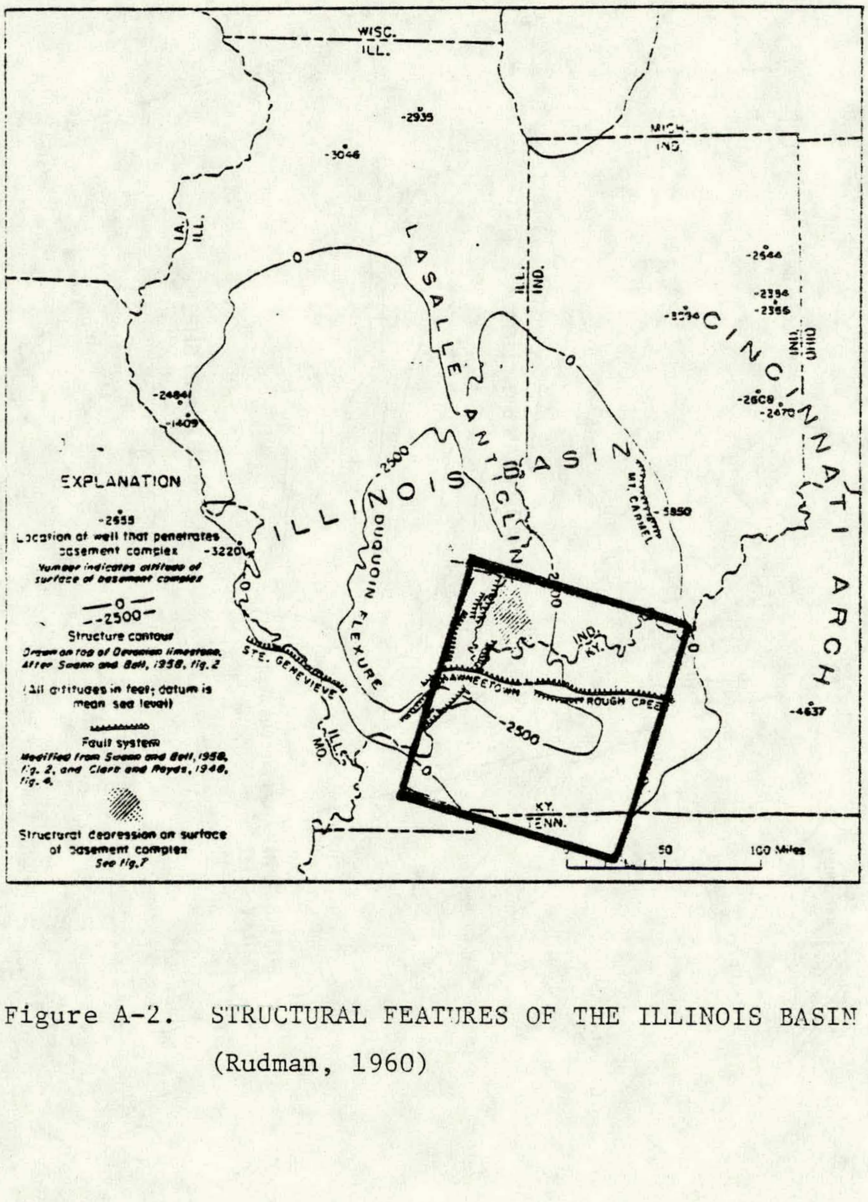


Figure A-2. STRUCTURAL FEATURES OF THE ILLINOIS BASIN
(Rudman, 1960)

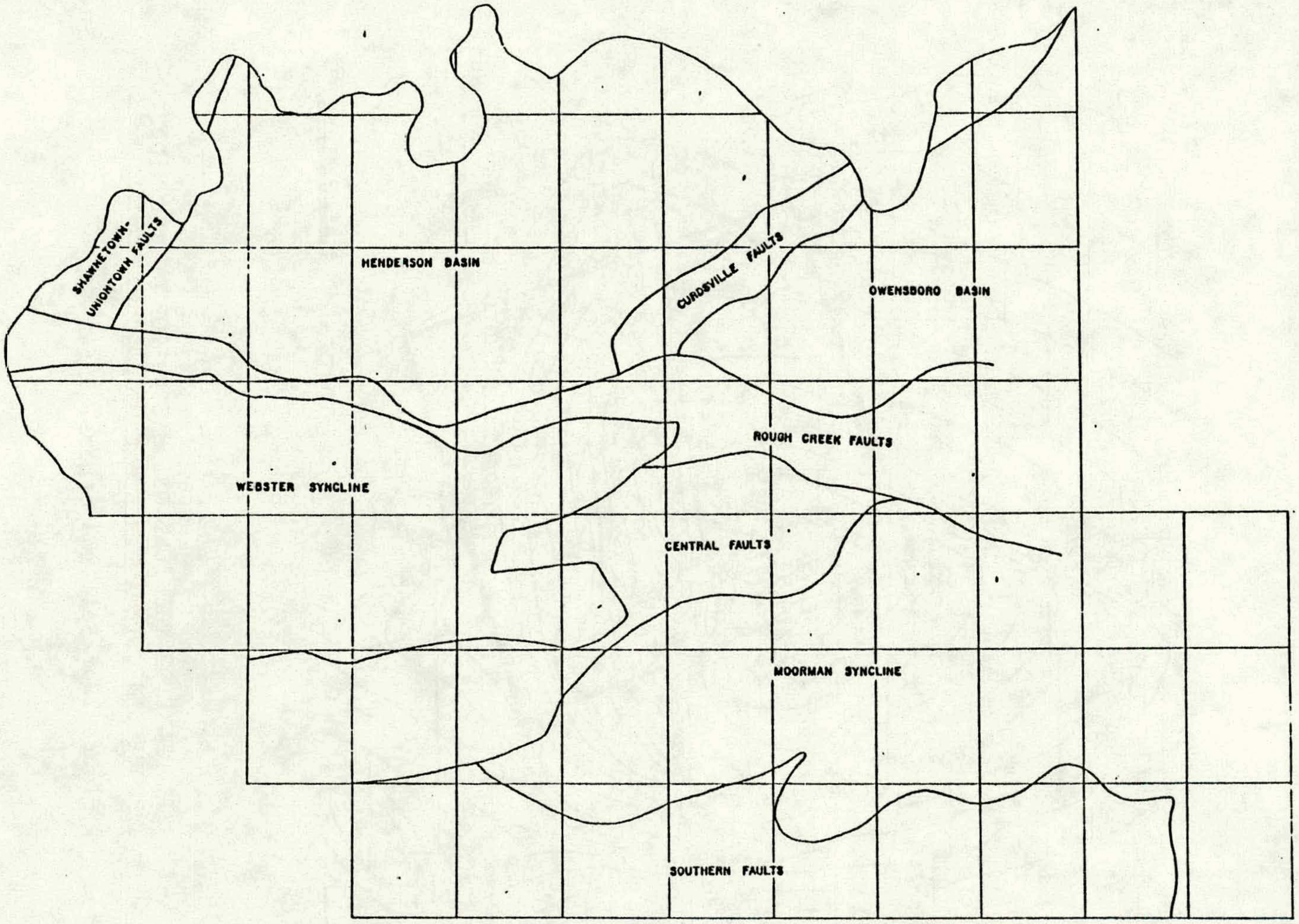


Figure A-3. STRUCTURAL DIVISIONS OF WESTERN KENTUCKY
(Mullins, 1968)

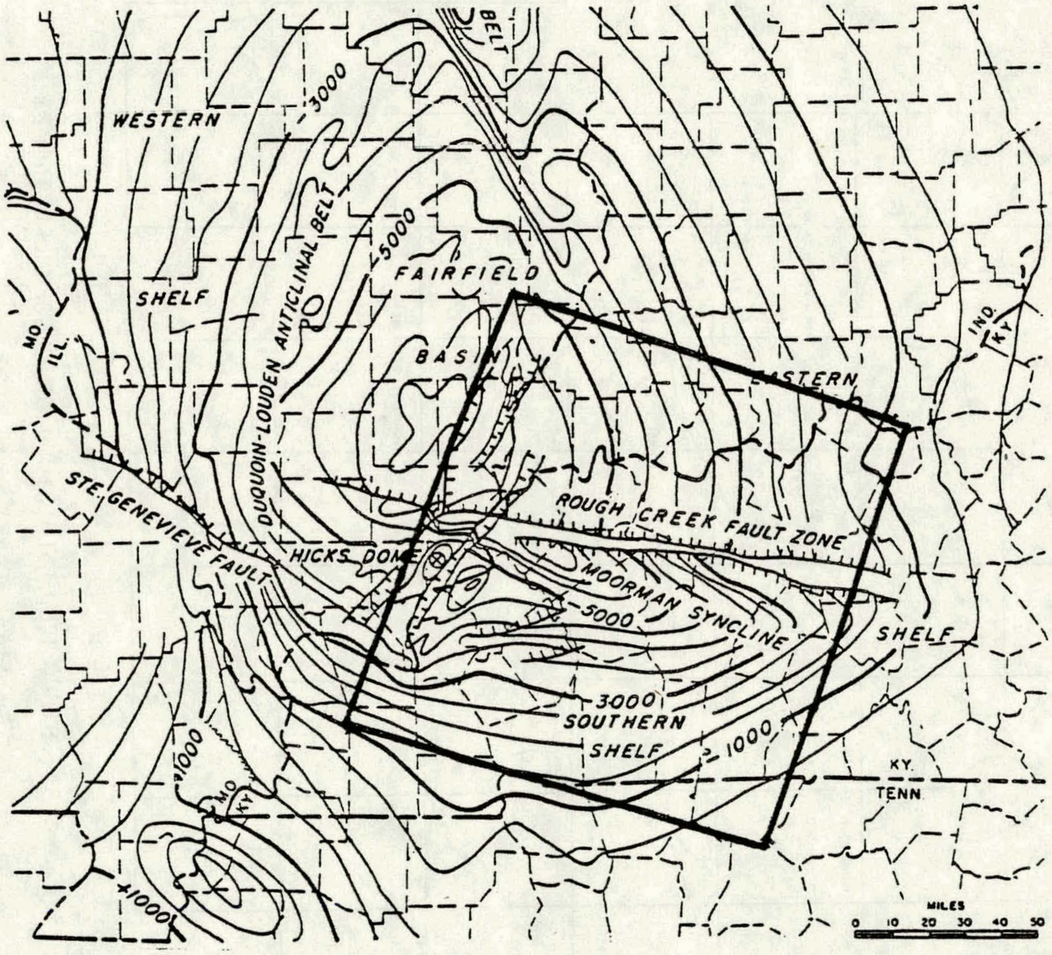


Figure A-4. STRUCTURE OF THE ILLINOIS BASIN, TOP OF THE MIDDLE ORDOVICIAN OTTAWA LIMESTONE MEGAGROUP

(Figure 2 of Bell and others, 1964)

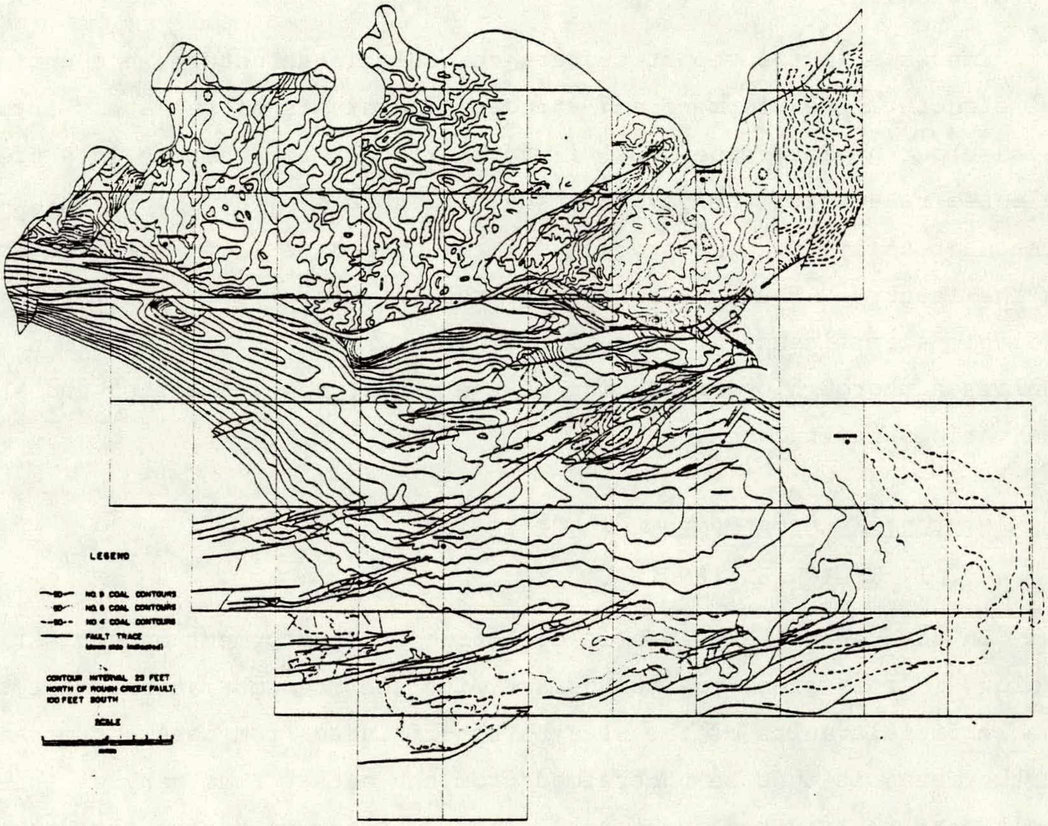


Figure A-4a. PENNSYLVANIAN COAL STRUCTURE OF WESTERN KENTUCKY
(Mullins, 1968)

district on the west, and the faults along the Southern Shelf on the south. An emphasis will be placed here on describing and understanding the Rough Creek fault and the Southern Shelf fault zones. This is a pragmatic judgement dictated by the likelihood that these fault zones contain the fracturing most likely to be prospective for Devonian shale gas production.

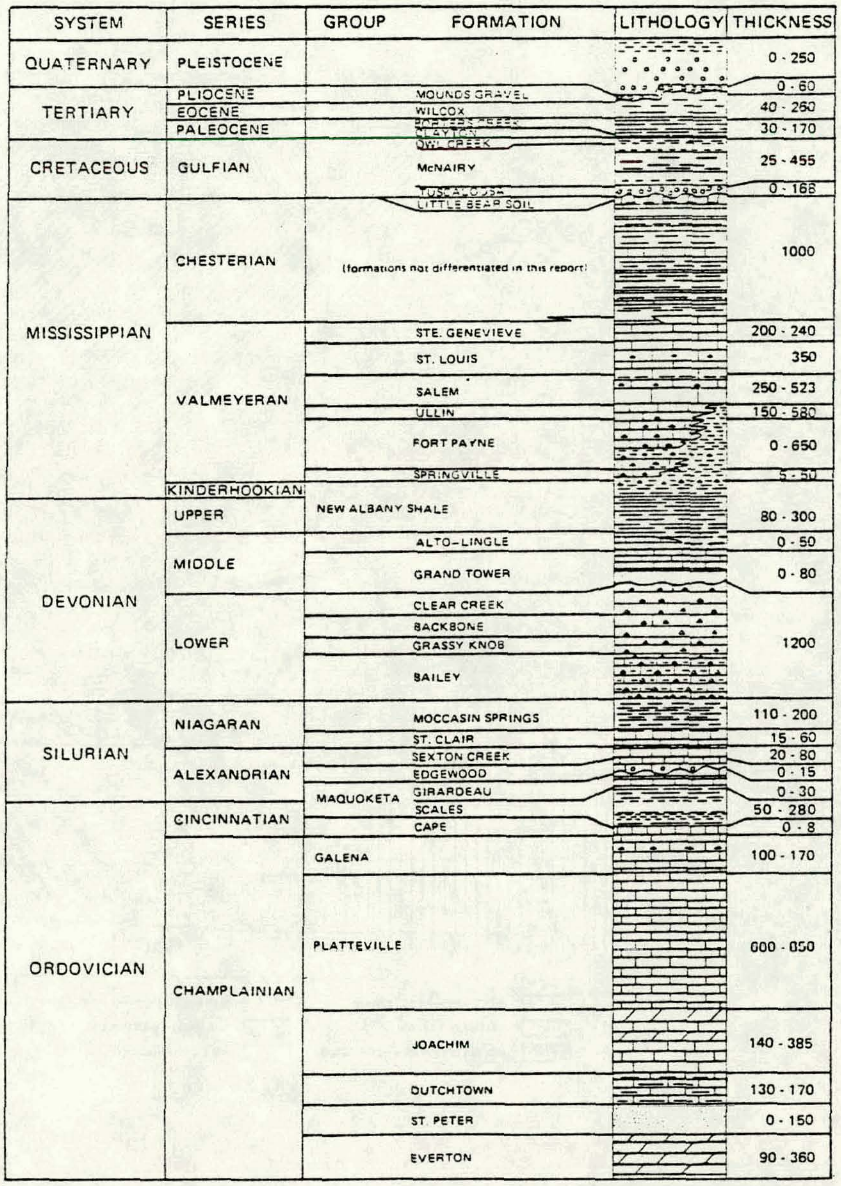
Emphasis in the report centers on geologic structure, presenting the structural development and structural analysis of the study area because our predetermined goal is to seek zones of fracture in a preselected reservoir, the Devonian shale (Figure A-5) by a structural-lineament analysis. The project's first objective is to make lineaments on the imagery. Then the difficult problem arises of evaluating the geologic significance of these lineaments. An accurate evaluation implies a thorough understanding of the structural evaluation and style of the various fault zones.

A.2 HISTORICAL DEVELOPMENT OF THE REGION

A.2.1 REGIONAL STRUCTURE

In discussing the historic evolution or development of the surficial geology in this area, one must start with the Precambrian basement for the surficial faults of the study area originate from basement movement. Furthermore, it must be understood from the outset that many of these faults are reactivated structural zones that formed during the Precambrian.

The area under consideration is a part of the stable North American craton which is generally envisioned to be an area of domes, arches and broad basins. More specifically, the area lies at the southern end of one of these broad basins, the lower and middle Paleozoic Eastern Interior Basin (Figure A-6). It is directly south



SYSTEM	SERIES	GROUP	FORMATION	LITHOLOGY	THICKNESS
QUATERNARY	PLEISTOCENE				0 - 250
TERTIARY	PLIOCENE		MOUNDS GRAVEL		0 - 60
	EOCENE		WILCOX		40 - 260
	PALEOCENE		PORTERS CREEK CLAYTON		30 - 170
CRETACEOUS	GULFIAN		OWL CREEK McNAIRY		25 - 455
			TUSCALOOSA		0 - 168
			LITTLE BEAR SOIL		
MISSISSIPPIAN	CHESTERIAN	(formations not differentiated in this report)			1000
	VALMEYERAN		STE. GENEVIEVE		200 - 240
			ST. LOUIS		350
			SALEM		250 - 523
			ULLIN		150 - 580
			FORT PAYNE		0 - 650
			SPRINGVILLE		5 - 50
	KINDERHOOKIAN	NEW ALBANY SHALE			80 - 300
DEVONIAN	UPPER				
	MIDDLE		ALTO-LINGLE		0 - 50
			GRAND TOWER		0 - 80
	LOWER		CLEAR CREEK		1200
			BACKBONE		
			GRASSY KNOB		
			BAILEY		
SILURIAN	NIAGARAN		MOCCASIN SPRINGS		110 - 200
			ST. CLAIR		15 - 60
	ALEXANDRIAN		SEXTON CREEK		20 - 80
			EDGEWOOD		0 - 15
ORDOVICIAN	CINCINNATIAN	MAQUOKETA	GIRARDEAU		0 - 30
			SCALES		50 - 280
			CAPE		0 - 8
	CHAMPLAINIAN	GALENA			100 - 170
		PLATTEVILLE			600 - 650
			JOACHIM		140 - 385
			DUTCHTOWN		130 - 170
			ST PETER		0 - 150
			EVERTON		90 - 360

Figure A-5. STRATIGRAPHIC COLUMN
(Kolata in Buschbach, 1978)

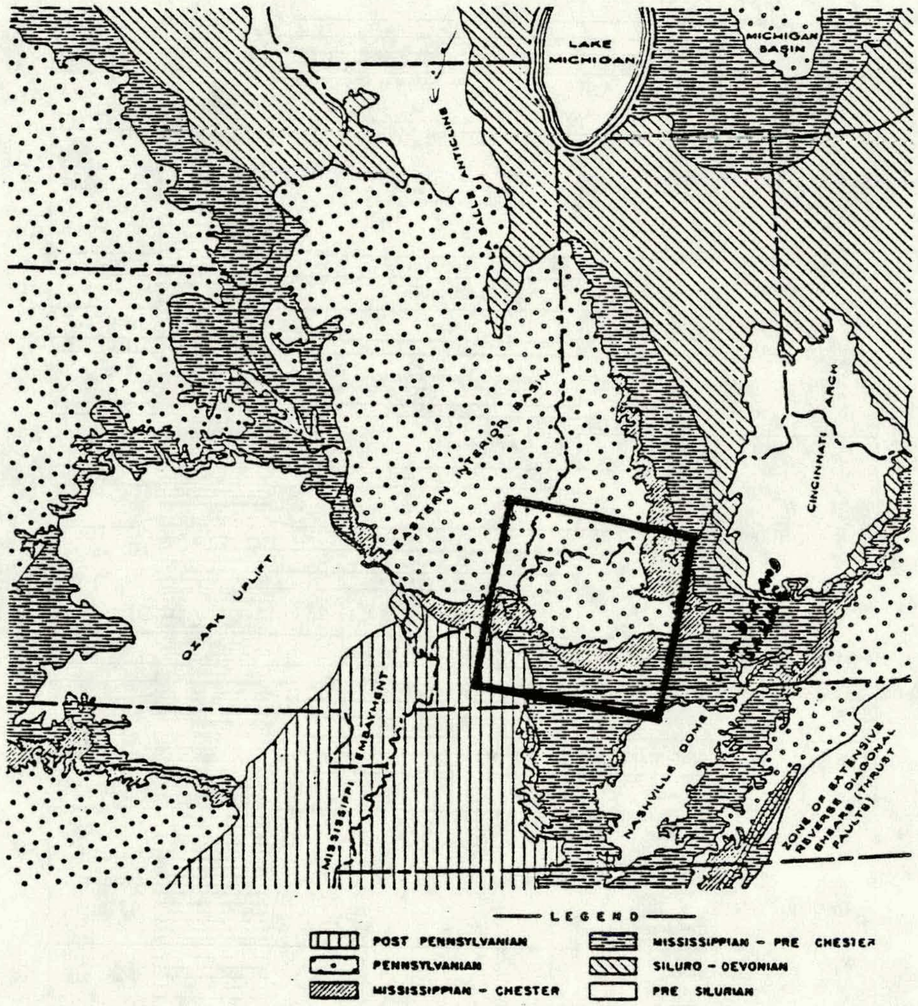


Figure A-6. AREAL GEOLOGY - EASTERN INTERIOR BASIN AND SURROUNDING AREAS

(Clark and Royds, 1948)

of the more smaller restricted Illinois Basin (Figure A-2). The surface structure generally can be thought of as a broad expanse of flat-lying or low-dipping sediments that are broken by an occasional fault or fault zones. Deformation associated with the faulting is quite minor, being restricted to the fault zone proper. Offsets along the faults are usually less than a few hundred feet as seen at the surface. The structural patterns generally assume a horst and graben style occurring in long (tens of miles) narrow (a few miles) fault zones (Figure A-4). The structures are downthrown or dip such as to develop an east-west synclinorium, the Moorman Syncline, in the central part of the study area. The age of deformation as seen at the surface is generally considered to be "Alleghenian" (Permo-Pennsylvanian) in age as the faults cut through the erosional remnants of the Pennsylvanian coal measures which are preserved in the Moorman Syncline. Because of the economic importance of these coal measures this synclinorium is often called the "Western Kentucky Coal Basin."

Regional geologic and tectonic maps, at a scale which show the central United States (Figures A-2 and A-4) generally show only the Rough Creek fault zone presumably because it separates the east-west trending Moorman Syncline from the north-south trending Illinois Basin. Showing this separation seems geologically appropriate based on the regional surface structure. The Moorman Syncline area is quite complexly faulted along dominant east-west trends whereas the Illinois Basin is structurally simpler, with a few surface flexures, and it is characterized by more northerly trends. This contrast in deformation intensity, style, and trend is clearly seen on Figures A-4 and A-4a.

Faults at the head of the Mississippi Embayment within the southern Illinois flourspar district border the study area on the west and the intensity of deformation probably reflects the intersection of the Illinois Basin and Moorman Syncline trends. Igneous intrusives found at the surface and the mineralization along faults of that area may also be a result of a deep crustal flaw at this intersection. Clearly the Illinois, northerly trends, dominate in this area, but the style is complex faulting. These commercially important faults are often shown on the regional maps whereas the Southern Shelf faults may not be. As the maps decrease in scale the southern faults and structural complexity of the syncline become more apparent (Figures A-4 and A-4a).

A.2.2 PRE-CAMBRIAN HISTORY

Over the past decade an understanding of the structure has evolved for this area which suggests that it has had a long and complex geologic history dating back to Precambrian times. What one sees at the surface is only the "tip of the geological iceberg" of a complex deeper structure. A major part of this history involves resurgent tectonics along faults that presumably formed during crustal deformation in Precambrian time.

Unfortunately, very little is directly known of the details of the earliest history as only one well has reached the basement in the study area. However, geophysical data and our knowledge of the Paleozoic sediments are sufficent to suggest the importance of the Precambrian tectonic pattern and to suggest the presence of deep structural complexity. The one deep well of the area was drilled near the complex surface structure in the center of the study area. It penetrated rocks of basic mineralogy (Figure A-7) and the occurrence of basic igneous rock suggests that early rift faulting is important. Recent interpretations of magnetic and gravity maps of the area (Hinze, 1977) suggest that at least one ancient rift traverses the area (Figure A-8). Several distinct linear anomalies on total magnetic intensity maps of the area correspond with the trends along the flanks with the syncline (Figure A-9). One of these lineaments roughly coincides with the Rough Creek fault zone, and another corresponds

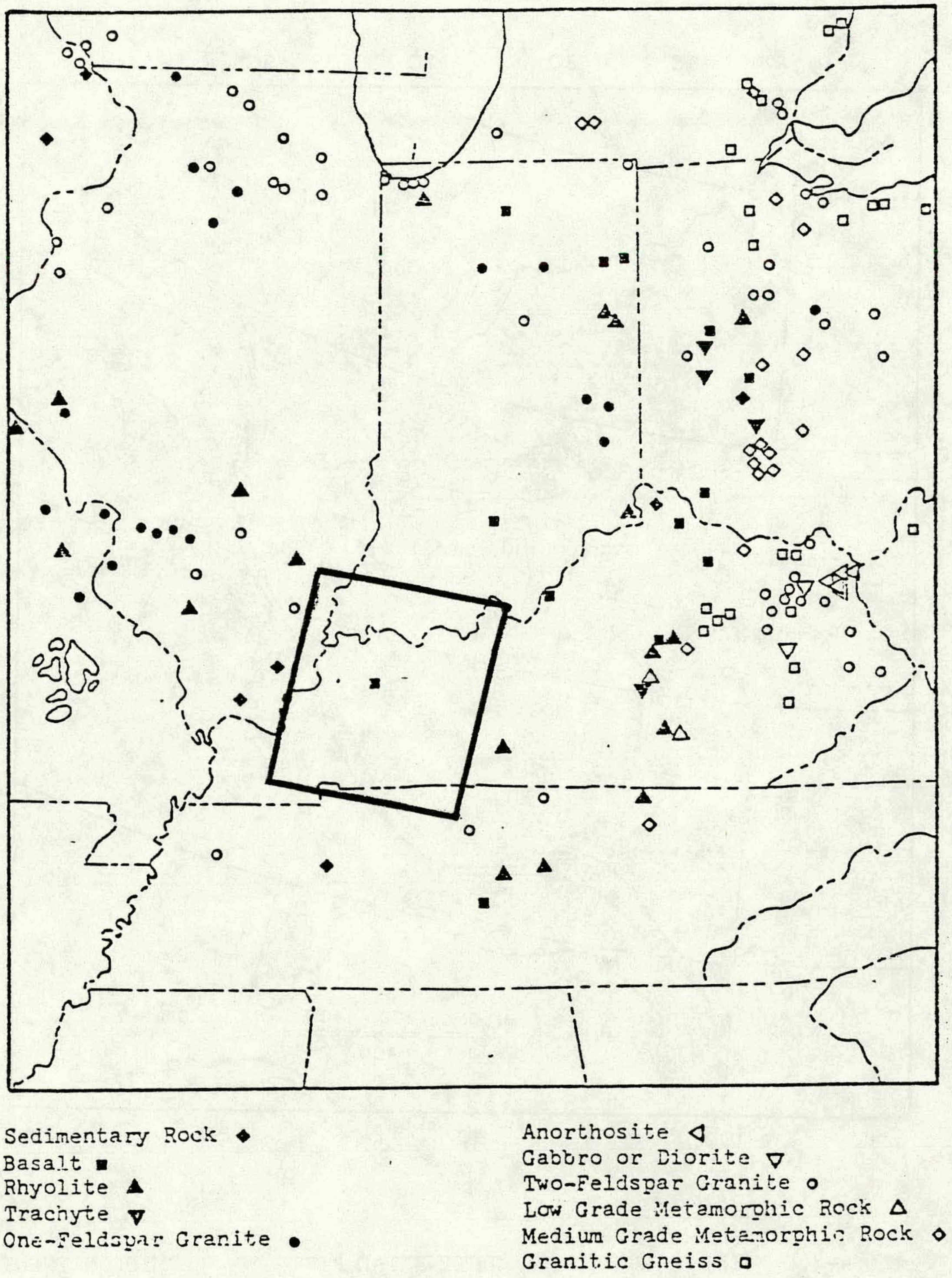


Figure A-7. DISTRIBUTION OF WELLS TO BASEMENT AND BASEMENT ROCK TYPE, EAST CENTRAL UNITED STATES

(Buschbach, 1978)

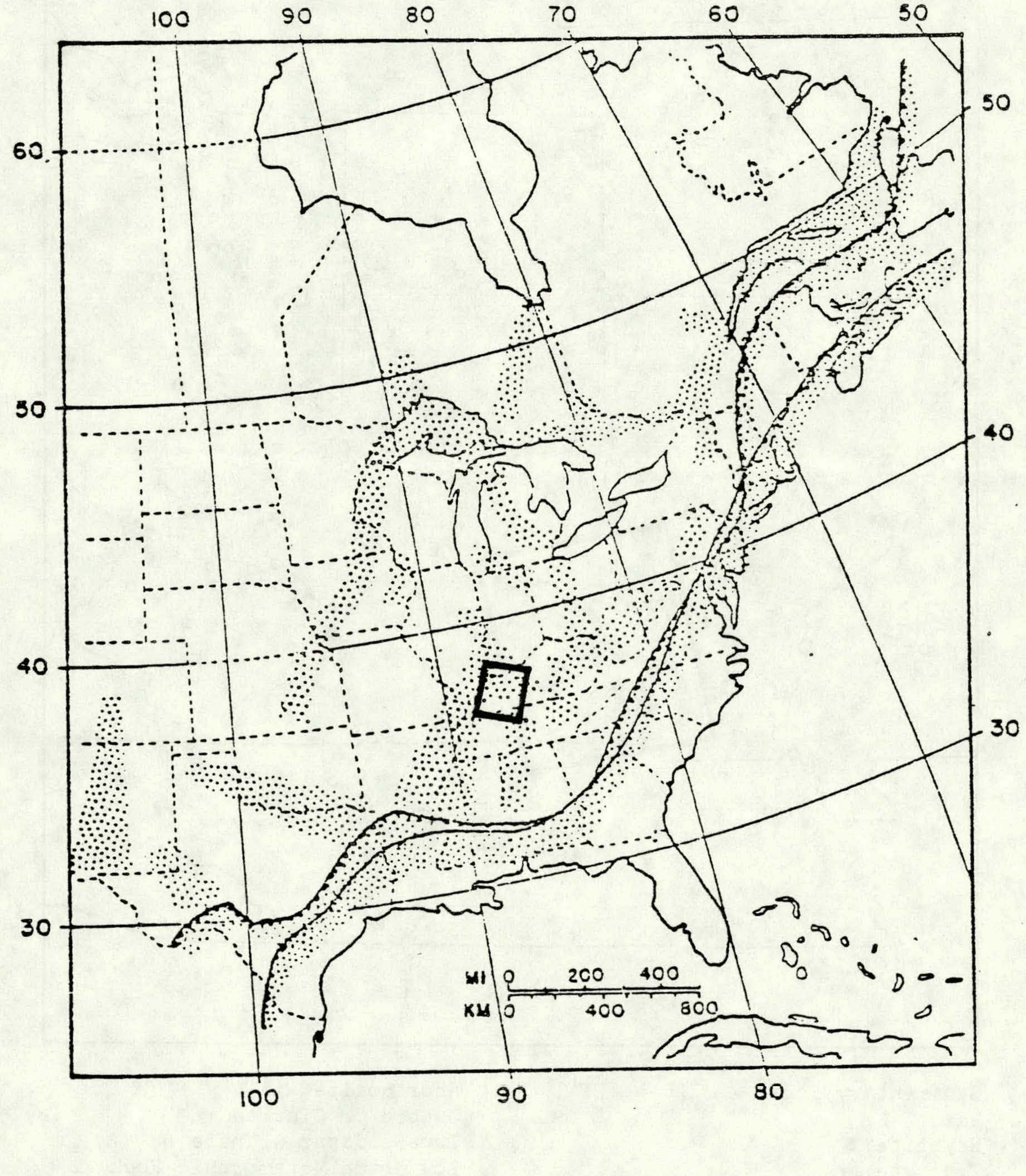


Figure A-8. PRELIMINARY MAP OF CONTINENTAL RIFTS OF THE MIDCONTINENT (Buschbach, 1978)

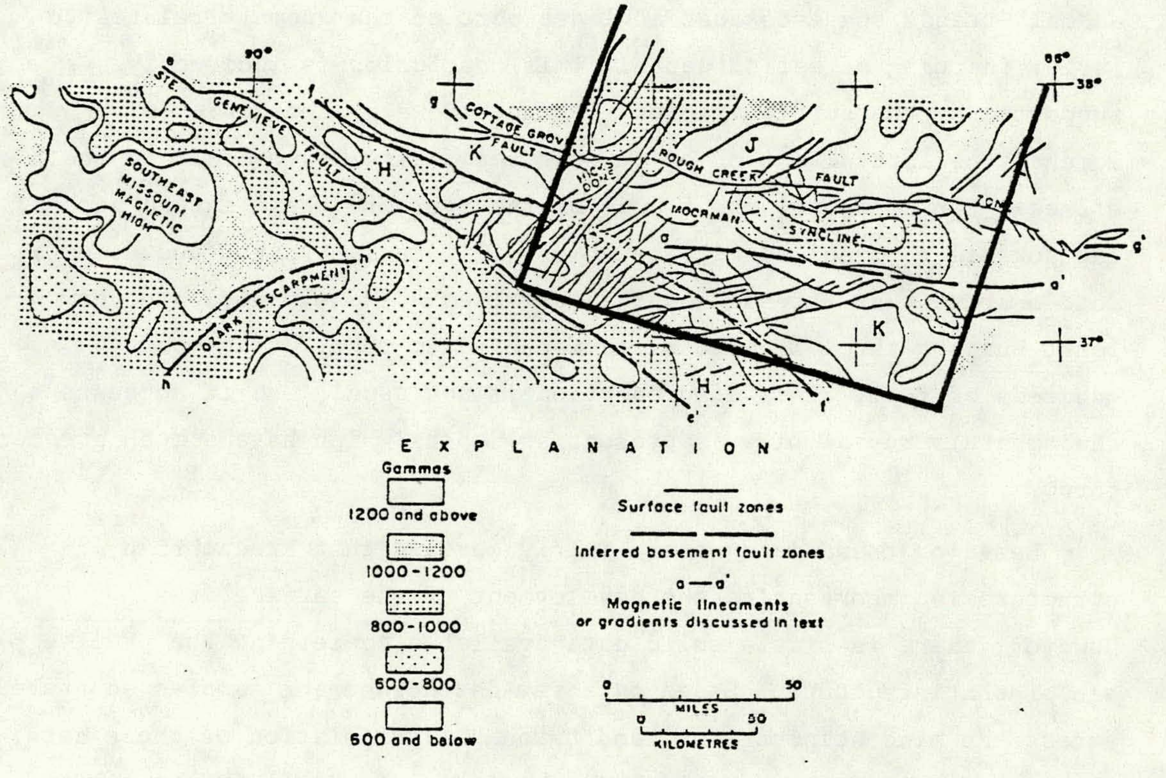


Figure A-9. RELATION OF MAGNETIC ANOMALIES AND LINEAMENTS TO SURFACE AND BASEMENT FAULT ZONES IN WESTERN KENTUCKY, SOUTHERN ILLINOIS AND SOUTHEASTERN MISSOURI

(Modified from Lidiak and Zietz, 1976, in Hinze and Braile, 1977) to the northward terminus of the Southern Shelf faults. These lineaments are steep linear gradients of magnetic intensity, that is magnetic anomalies, which are far greater than those that can be explained by the offset measured across the surface faults. This observation indicates that either a major change in basement lithology occurs across the lineament or that there is a far greater offset of the faults at the basement level. The presence of faulting along the anomaly trends suggests that at least part of the anomaly relates to larger faulting offset at depth. This conclusion is indirectly supported by the surface geology in another way. Consider, for a moment, the lateral extent of the surface faults as compared to their offset. For instance, the faults of the Southern Shelf extend across the surface for tens of miles, and we will see later that they tie into a trend that extends hundreds of miles. These faults are very long, but the throw is most often measured in tens, or at most, hundreds of feet. This disproportion is not usual, and it suggests a fundamental crustal flaw is present at depths which have a much greater throw.

Based on these data we are fairly certain that Precambrian structure is important to the development of the surface area. However, there is little solid data available concerning the precise age of that structure. Based on a few dated basement samples scattered across the midcontinent area, and through extrapolation of these data, the basement in Western Kentucky is estimated to be ±1.4BY in age. The rifts, or shear zones, suggested by magnetic trends and the basement lithology sampled from the one well presumably post-date that 1.4BY age of the basement. We are aware of three Precambrian events that are of a magnitude to create such large linear magnetic anomalies: the event that created the Kansas-Lake Superior-Michigan rift system of Keweenawan age (1-1.4BY), the deformation associated with the Grenville (1.0-.8BY) orogenic event, or the post-Grenville rifting associated with Catoctin (.7-.8BY) volcanism found within core area of the Appalachian orogenic belt.

A.2.3 PALEOZOIC HISTORY-ECOCAMBRIAN

Much more is known about the earliest Cambrian history of the study area than that of Precambrian age. Rudman (1960) published an interpretation of seismic data which clearly shows a pre-Ordovician rift, here called the Southern Illinois Rift (Figures A-1 and A-10). It contains what are interpreted to be bedded sediments lying on crystalline (1.4BY) basement. The sediments have a structural and stratigraphic configuration nearly identical to that found in the Rome Trough (Shumaker, 1975) of Eastern Kentucky and West Virginia. The age of the Rome Trough is Lower to Middle Cambrian, and by this association, the Illinois graben may have developed during the Cambrian. However, the precise age of this particular rift is not known as the pre-Knox sediments have not been penetrated by the drill.

Direct evidence is now being published that the Moorman Syncline lies above an early Cambrian (Rome equivalent) rift (Figure A-11, Schwalb, 1977). Structures associated with the Rome Trough of Eastern Kentucky and West Virginia can be traced through the Cumberland Saddle, (Figure A-6) across the Cincinnati Arch, into the Moorman Syncline (Gardner, 1915) along the Southern Shelf trend (Shumaker, 1975) (Figure A-12). The magnitude of the Rough Creek rift is reflected in an overthickened stratigraphic section, perhaps 1000 meters of pre-Knox sand, silt, and shale, of Middle Cambrian age-Conasauga (personal communication, H.R. Schwalb). This thickening is also clearly shown by comparison of the Basement Structure and Knox Structure maps (Figures A-13 and A-14). This is the same divergence seen in the Southern Illinois rift between the basement and St. Peter Sand (Figure A-10). The isopach of the Everton-Knox carbonates (Figure A-15) reflect structural growth. Note how the trend of the thickening corresponds to

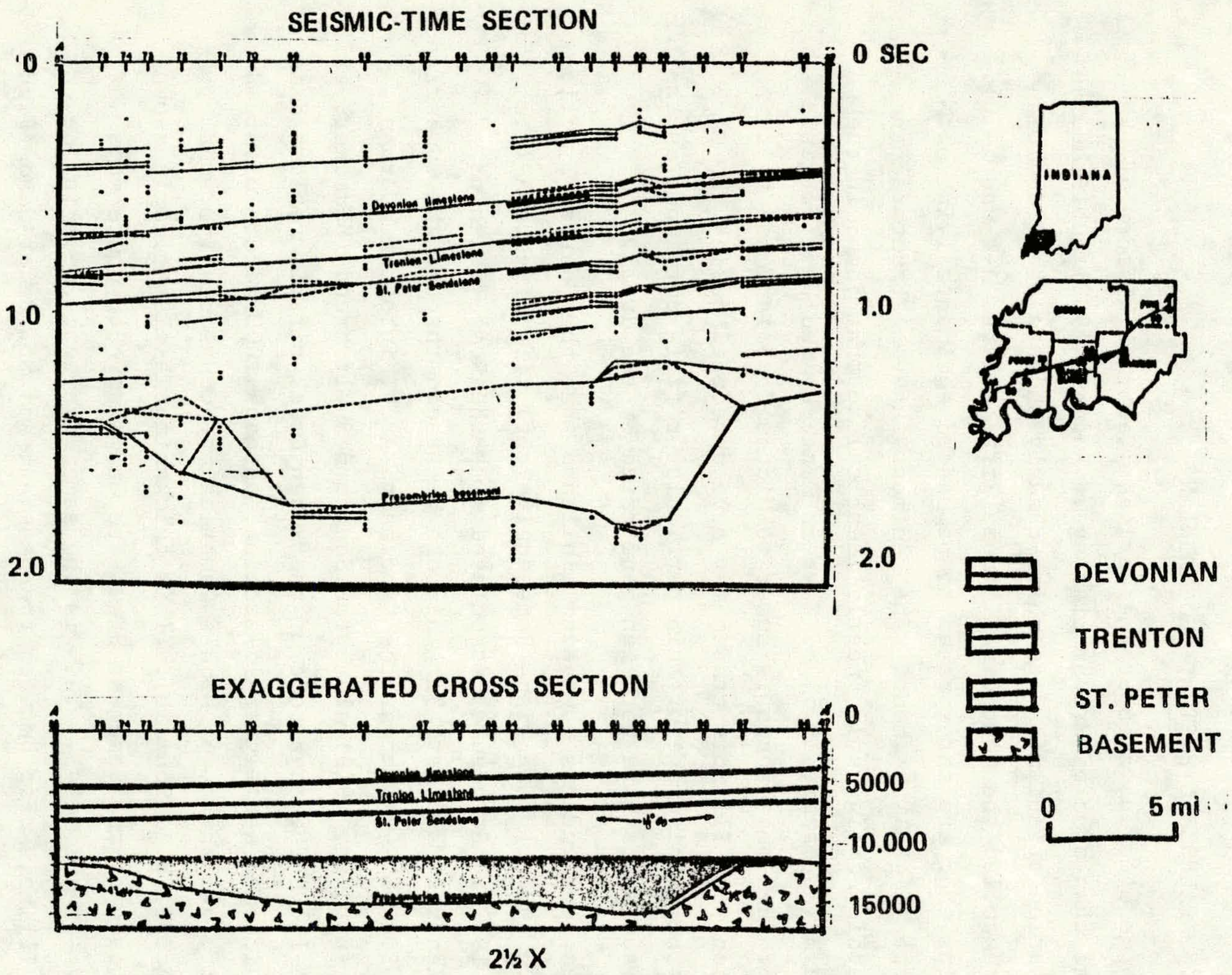


Figure A-10. SOUTHERN ILLINOIS RIFT

(Rudman, 1960)

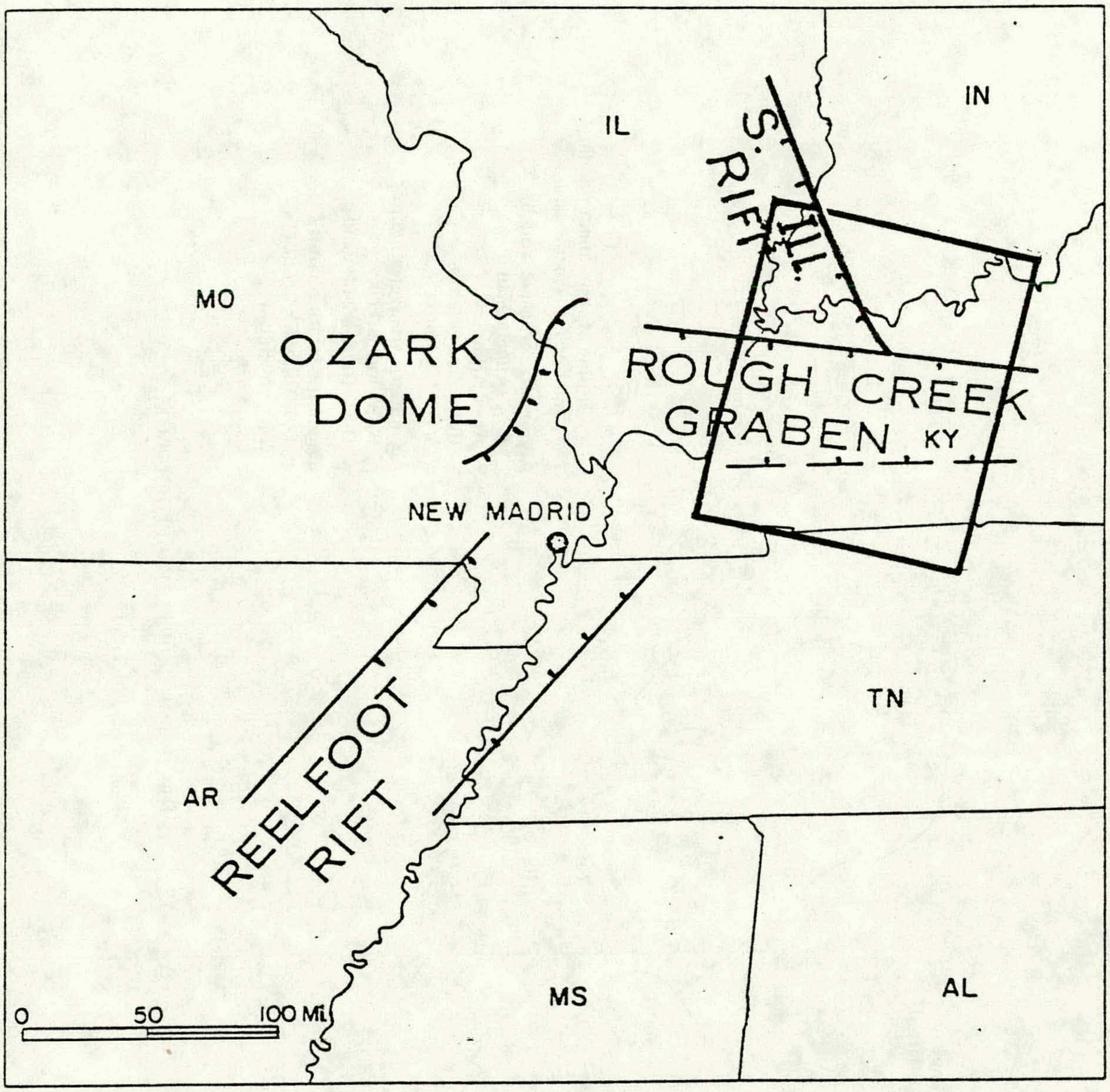


Figure A-11. REGIONAL TECTONIC FEATURES ACTIVE IN LATE PRECAMBRIAN AND CAMBRIAN TIME

(Modified from Buschbach, 1978)

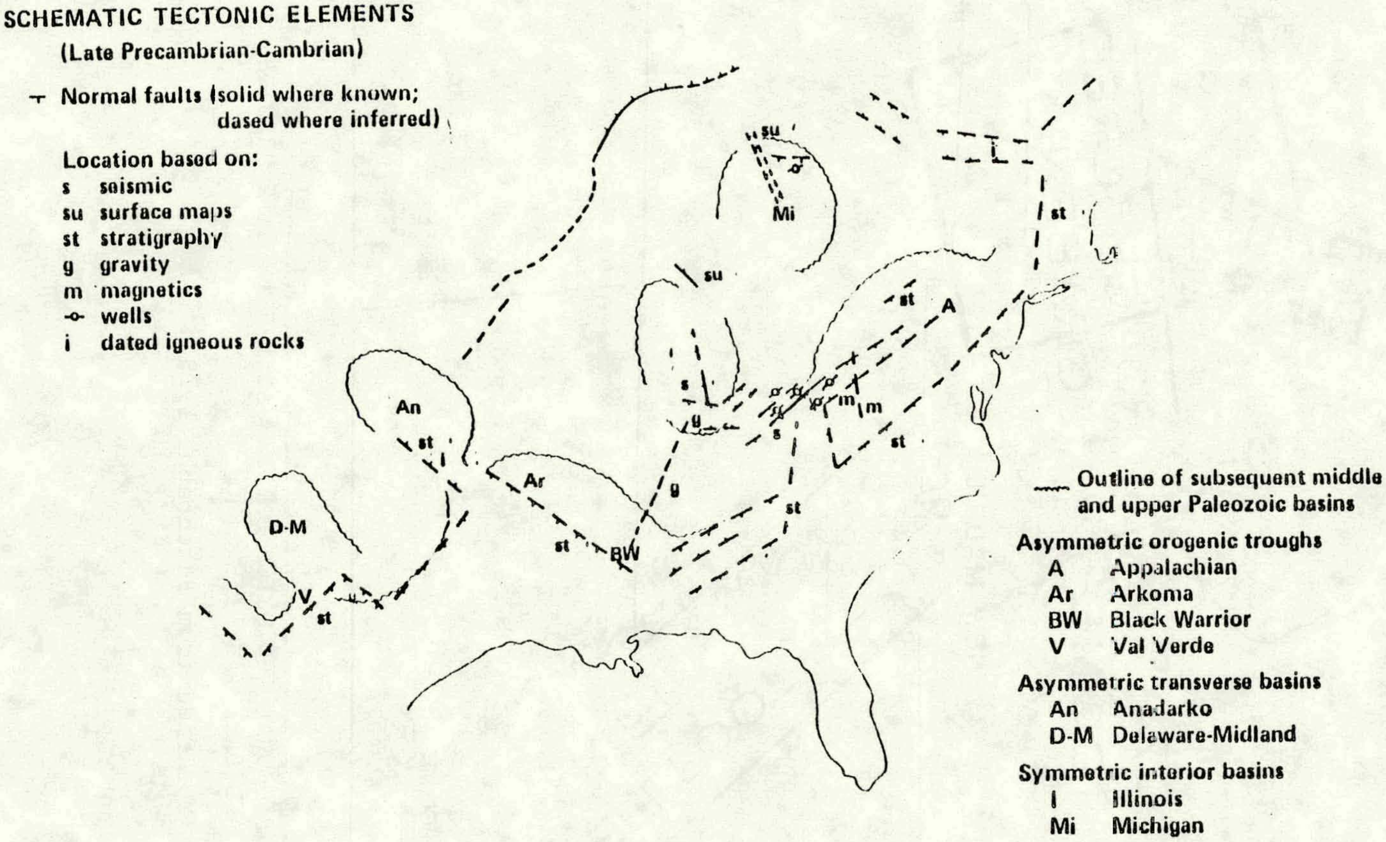


Figure A-12. CAMBRIAN DISRUPTIVE DEFORMATION

(Shumaker, 1975)

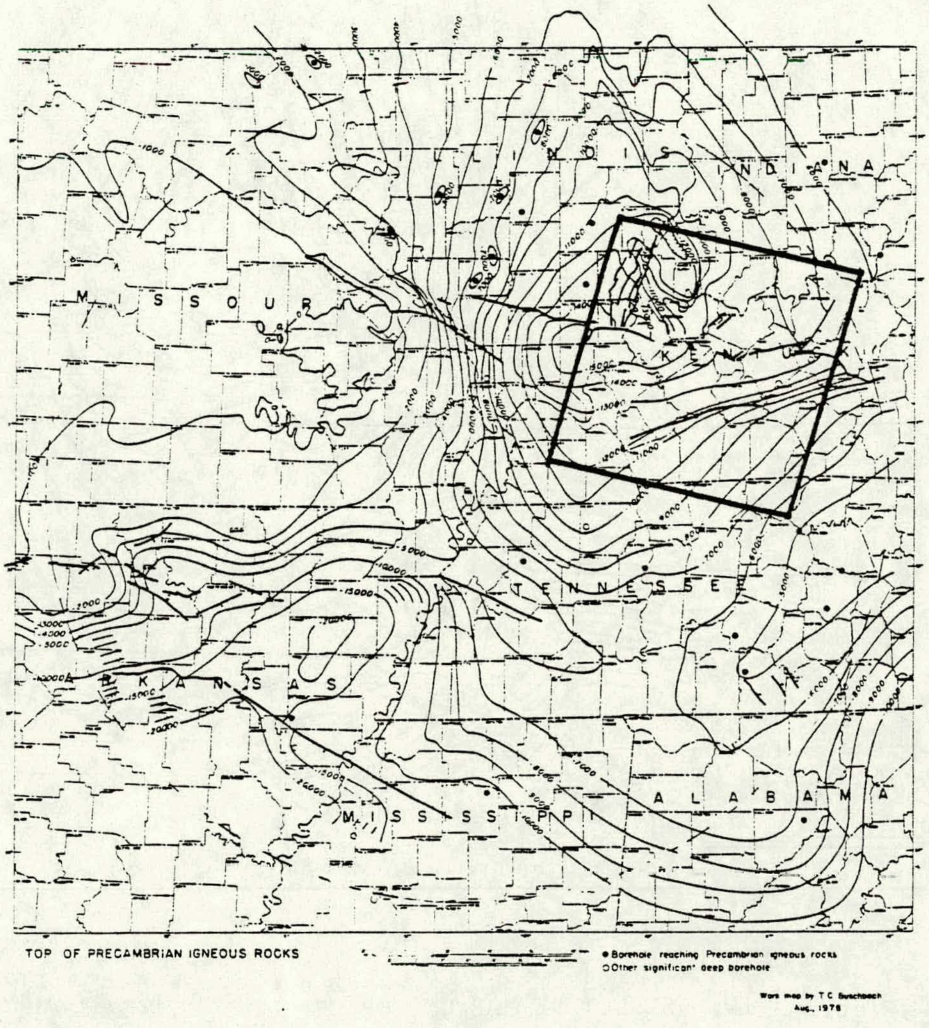


Figure A-13. STRUCTURE ON TOP OF PRECAMBRIAN IGNEOUS ROCKS (Buschbach, 1977)

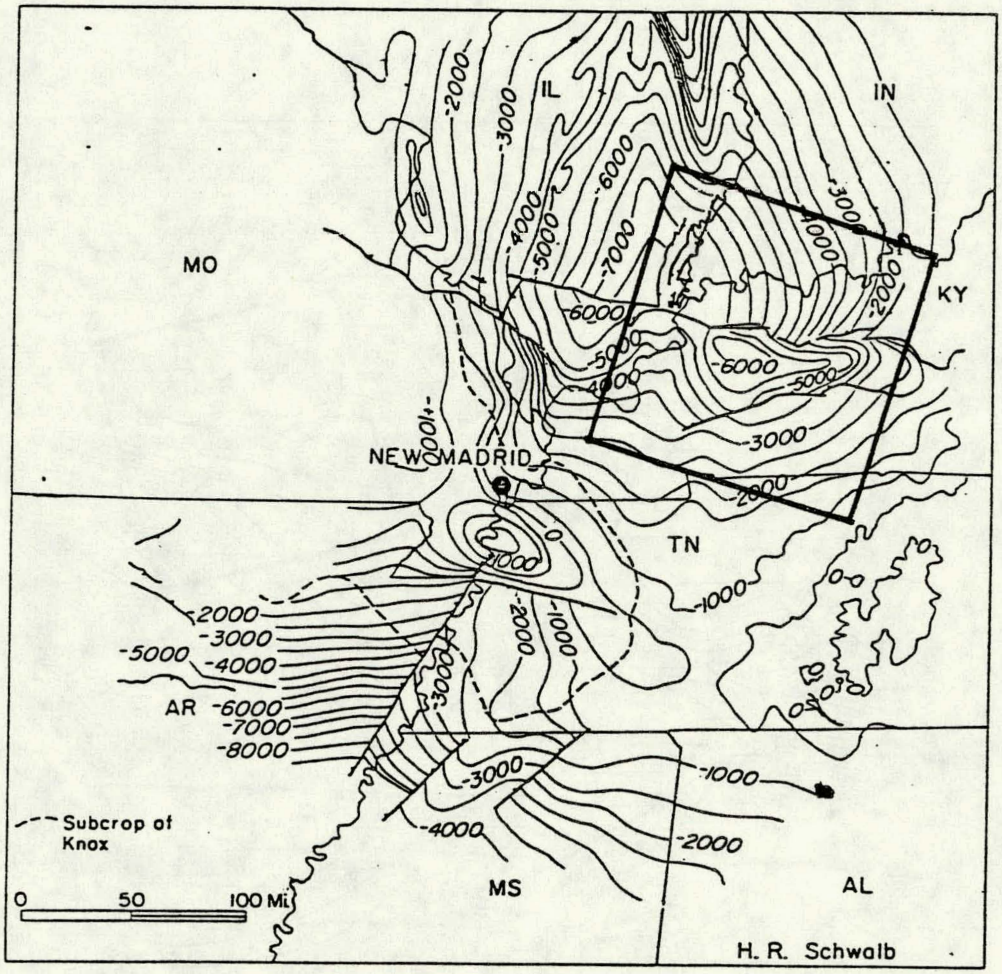


Figure A-14. STRUCTURE MAP ON TOP OF THE KNOX MEGAGROUP (Buschbach, 1977)

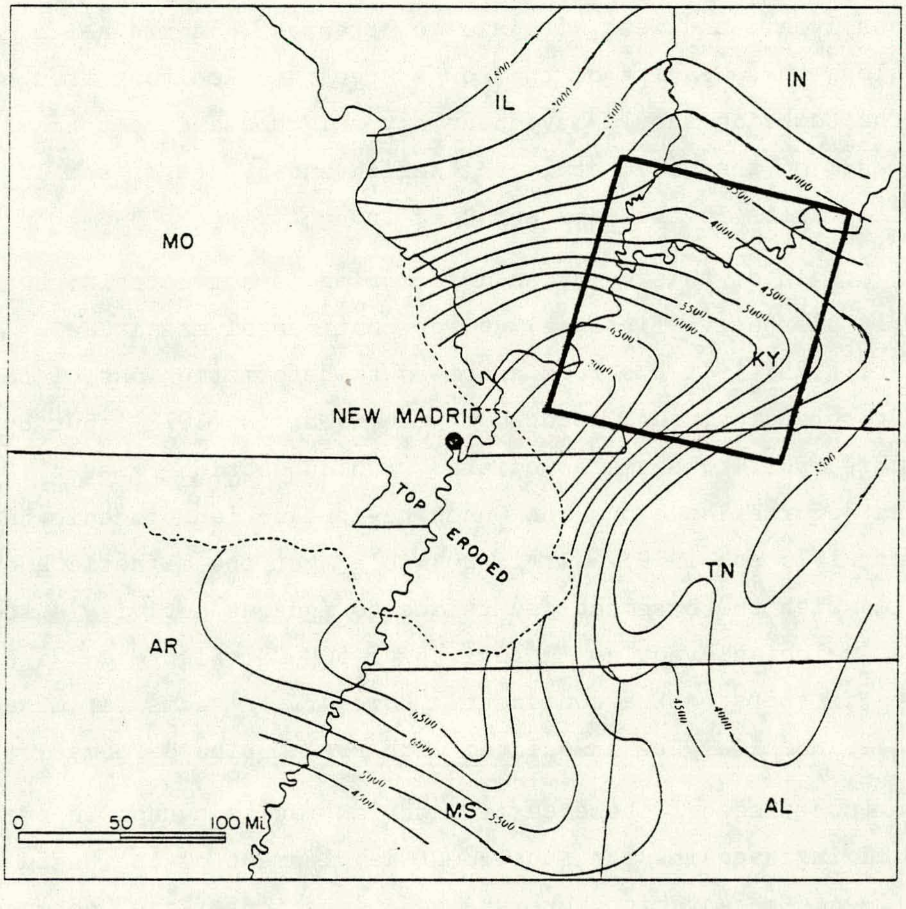


Figure A-15. THICKNESS OF THE EVERTON-KNOX CARBONATES, CAMBRIAN-ORDOVICIAN AGE

(H.R. Schwalb in Buschbach, 1978)

the present east-west trending Moorman Syncline, and that the axis of thickening turns south into what is now called the Mississippi Embayment. As mentioned, this thickening reflects Cambrian rifting that can now be documented to extend across the continental interior from Pennsylvania and West Virginia to Arkansas (Figures A-12, A-16). Offset along these faults of the Rough Creek and Reelfoot Troughs during the Cambrian should have been several thousand feet based on what we know of the sedimentary thickening and by the offset of associated faults in the adjacent Rome Trough.

The origin of this Cambrian deformation is not certain; but it is clearly disruptive (intense) and of continental magnitude (Shumaker, 1975). It has been ascribed to deformation associated with sea floor spreading, an aulocogen by many (Harris, 1978), but by timing this faulting seems associated with subduction-related Avalonian deformation along the Ouachita-Appalachian orogenic belt (Shumaker, 1975 and 1979). It is possible that the magnetic anomalies associated with the basement may relate to igneous activity associated with the Avalonian event as intrusives of 560 MY (Figure A-12) are found elsewhere in rifts on the continent. However, it seems far more likely that those anomalies are associated with Precambrian deformation.

The importance of these early Cambrian faults cannot be overemphasized in assessing the subsequent development of the basin as they influence the architecture and sedimentation of the Moorman Syncline throughout the Paleozoic. In several instances where similar Ecocambrian faults have been studied in detail elsewhere (Schaefer, 1979 and Shumaker, et al., 1978, 1979) they have been found to be middle and upper Paleozoic growth structures, and in certain areas, such as in the Mississippi Embayment, their importance is felt up to recent time. An isopachous map and cross-section of the study area (Figures A-17, A-18) show growth during the deposition of the New Albany. In the study, where the preselected reservoir is the

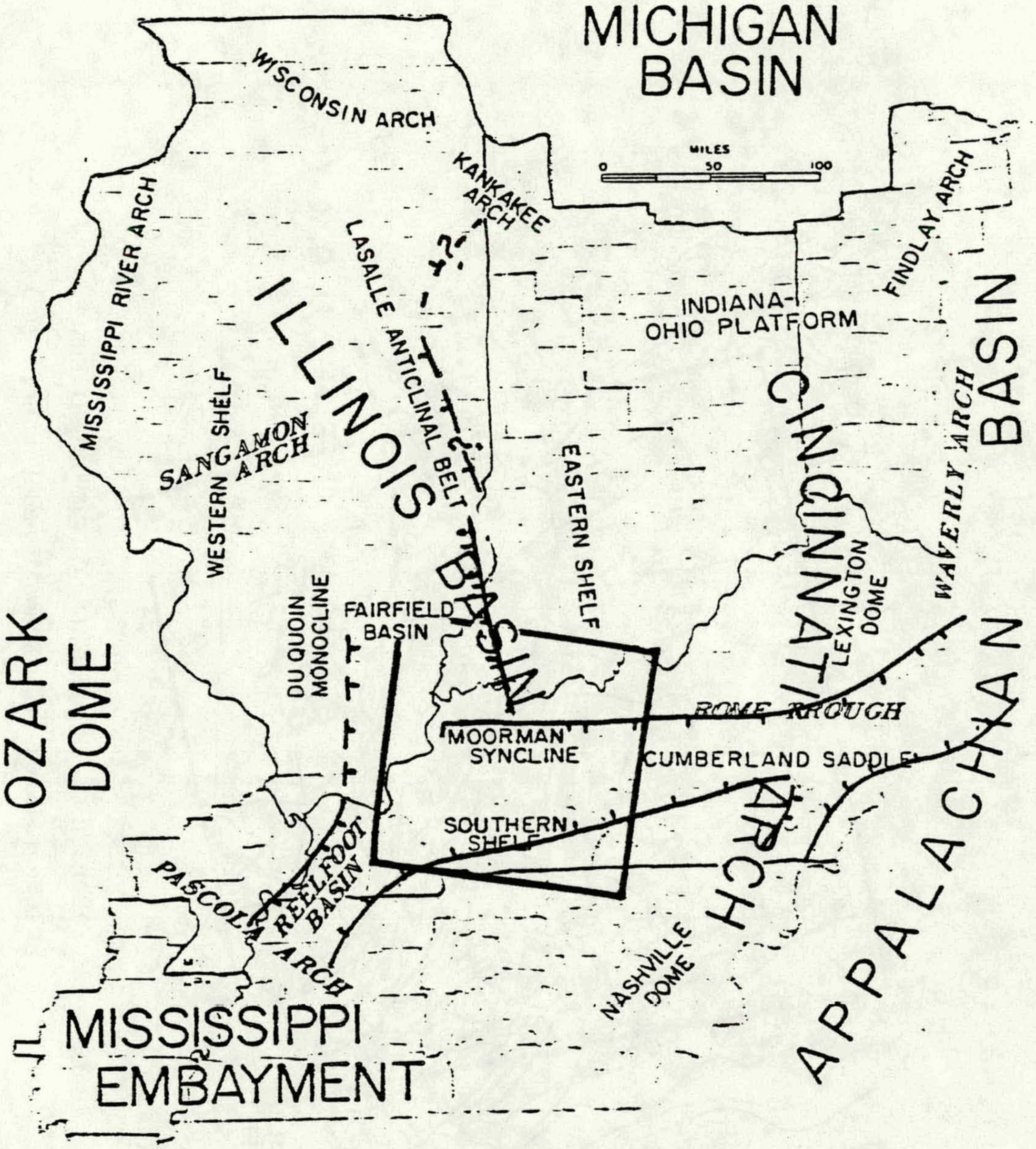


Figure A-16. EO-CAMBRIAN DISRUPTIVE FEATURES - AVALONIAN?
(Base from Bristol and Buschbach, 1971)

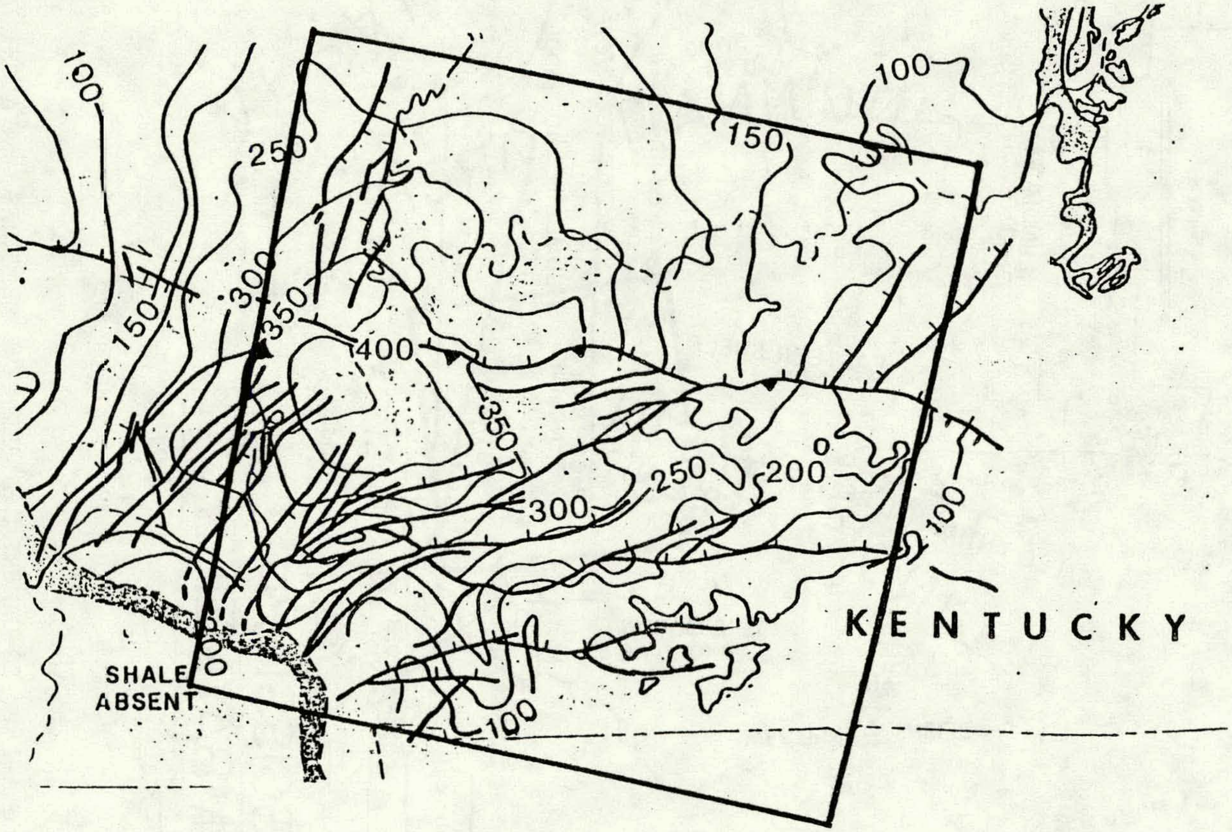


Figure A-17. ISOPACH OF THE NEW ALBANY (DEVONIAN) SHALE
(Generalized from Schwalb and Potter, 1978)

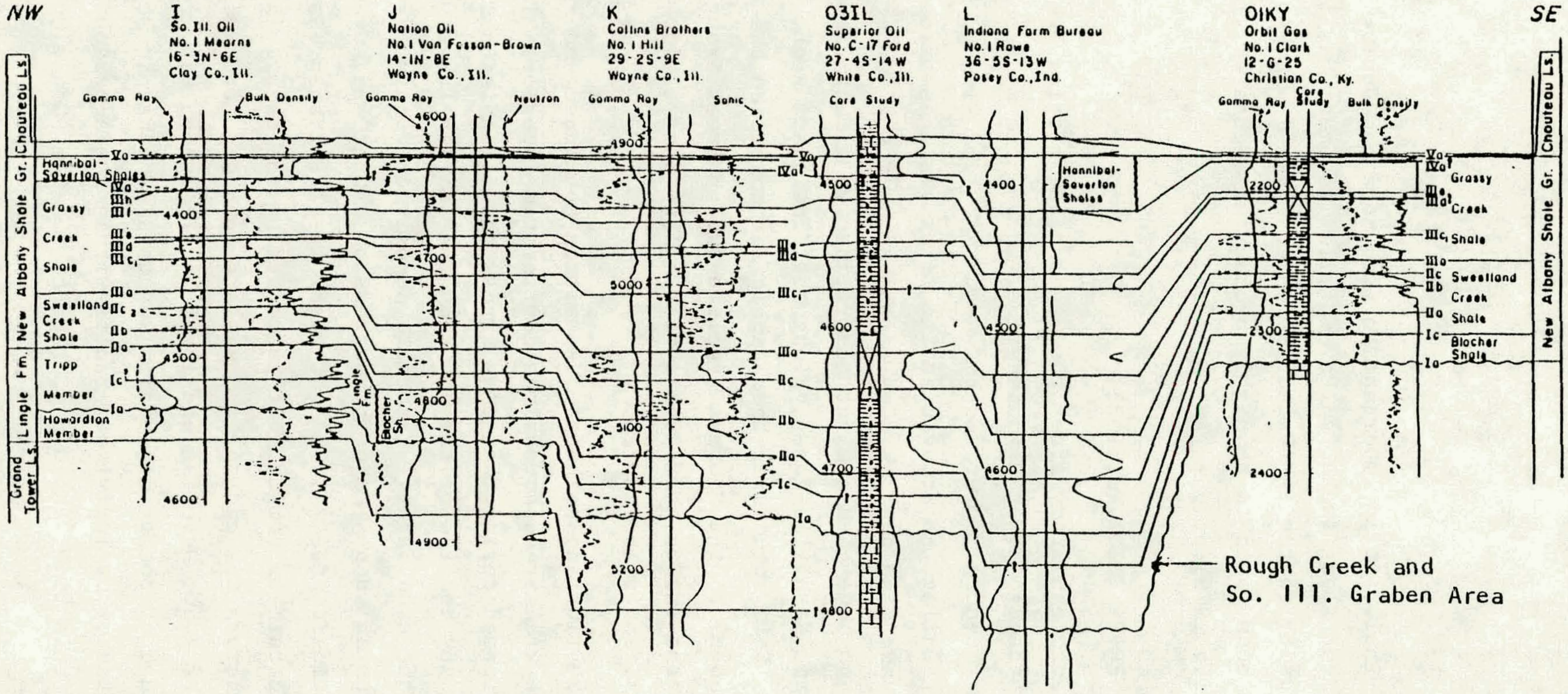


Figure A-18. NORTHWEST-SOUTHEST CROSS-SECTION 1-01KY, USING GEOPHYSICAL LOGS AND CORE STUDIES (U.S. DOE - 111. Contract E(40-1)5203, Annual Report 9/30/79)

New (Devonian) Shale, it is important to also note the Upper Paleozoic movement along these faults. Similar movement has imparted a fracture porosity to the equivalent Devonian Shale in the Appalachian Basin that has been found to be highly productive (Schaefer, 1979 and Shumaker, et al., 1979) of gas.

A.2.4 LOWER PALEOZOIC HISTORY

Lower Paleozoic history after the "Avalonian" rifting event, from Upper Cambrian through Lower Devonian time, across the mid-continent, appears to have been characterized by epeirogony and slow epicontinental sedimentation. During the Ordovician the first vestiges of the Ozark Dome, Kankakee and Cincinnati Arches were seen, but the Cumberland Saddle appears to have been present separating two structural highs, the Lexington and Nashville domes, along the Cincinnati Arch (Figure A-19). This structural-topographic low connected the Appalachian Basin (Rome Trough) to the Moorman Syncline (Rough Creek Trough). The craton was distant enough from Appalachian uplift that shallow water carbonate deposition predominated.

During the Silurian, carbonate deposition continued and reefs (Niagaran) were widespread across the continental interior. The Sangamon Arch formed during that time across the Illinois Basin (Figure A-20). By the end of the Silurian the sea was largely restricted to the study area. Carbonate deposition continued through the middle Devonian when a major transgression of the sea covered the entire mid-continent area. It is not clear if this transgression is eustatic or tectonic in origin. It is marked by the change in sedimentation across the central and eastern continent from carbonate to black muds of upper Devonian and lower Mississippian age. The widespread nature of the transgression suggests a change in sea level was most important, but individual faults within the Appalachian Basin were active at this time, and a precursor of the Ste. Genevieve fault

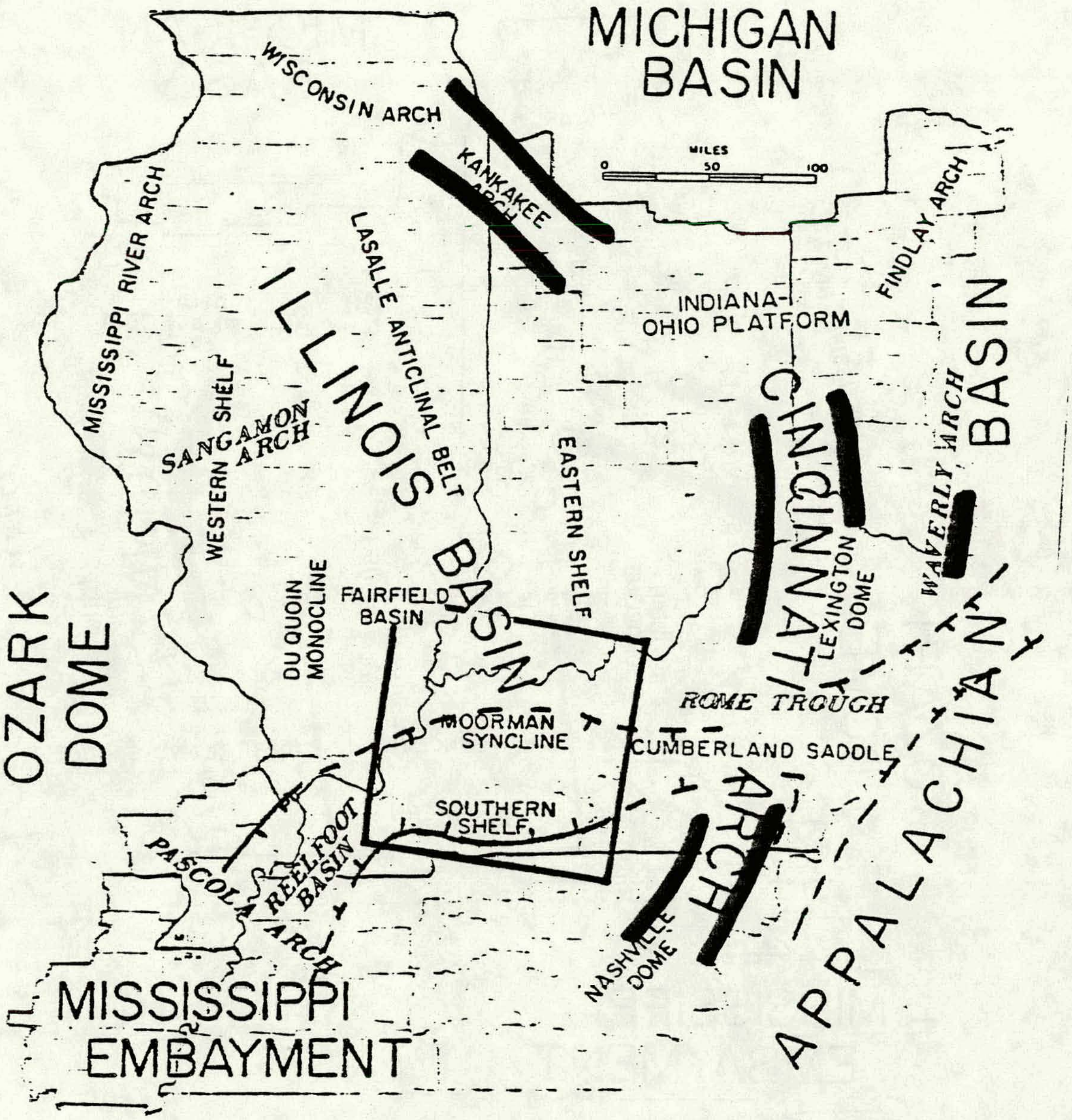


Figure A-19. UPPER CAMBRIAN THROUGH ORDOVICIAN - EPEIROGENIC FEATURES (Base from Bristol and Buschbach, 1971)

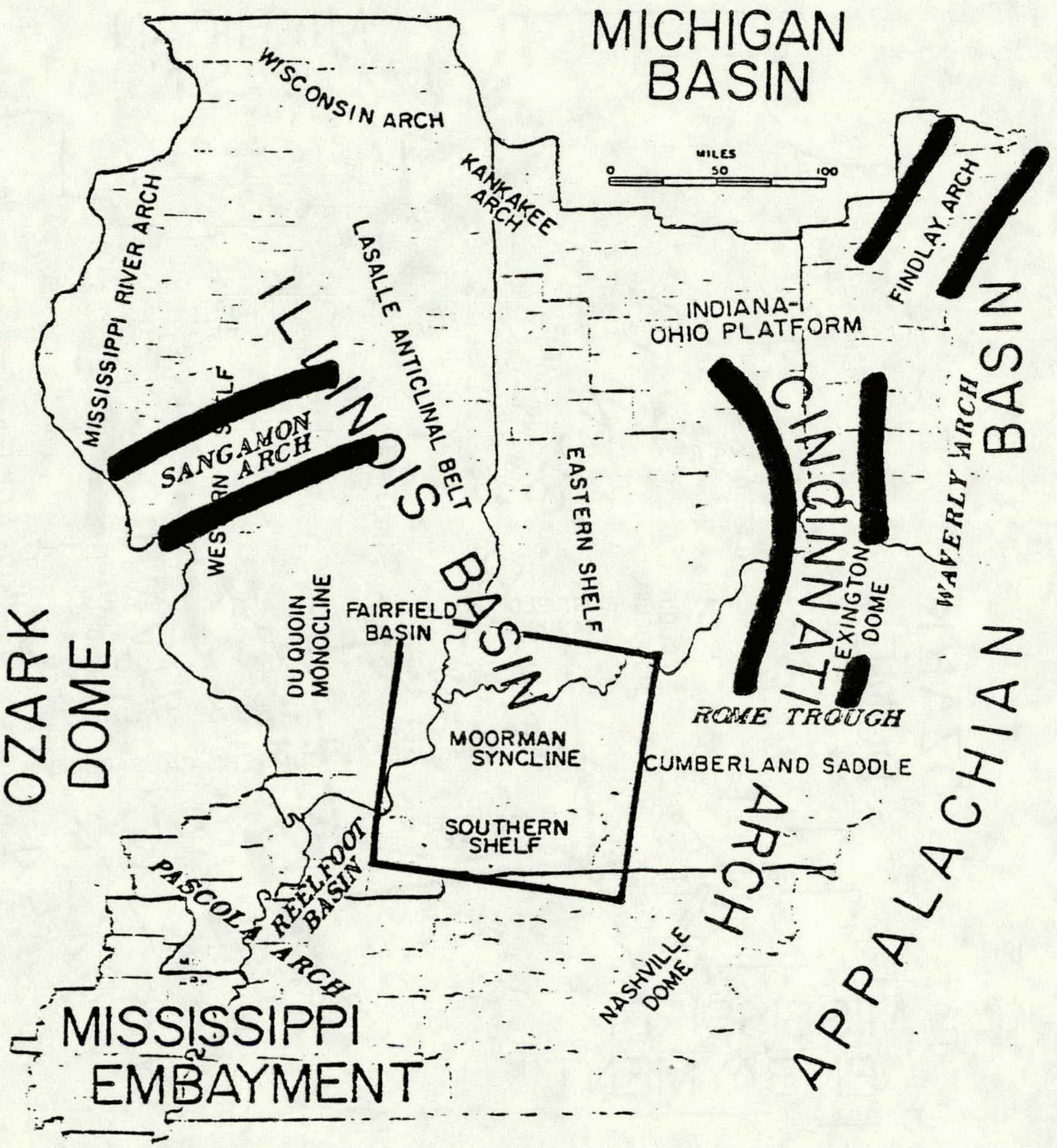


Figure A-20. SILURIAN - EPEIROGENIC FEATURES
(Base from Bristol and Buschbach, 1979)

along the northeastern margin of the Ozarks was also active (Figure A-21). As noted above, the isopachous map and cross section across the syncline suggest local subsidence along ancient rifts of the Rough Creek graben. Progradation of the Devonian Delta from the Appalachian core area suggest tectonism or accelerated uplift. It is the author's guess that most basement faults of the craton were active during this time interval, but that the movement was not nearly of a magnitude comparable to that of the early Cambrian event. It is tempting to suggest that this transgression and tectonic activity found within the craton ties to the Acadian-Caldonian deformation within the Appalachian orogen, but this is not demonstrable.

A.2.5 UPPER PALEOZOIC HISTORY

During Mississippian time, carbonate deposition returned to the continental interior, and the Southern Shelf was established along the southern margin of the Moorman Syncline area. However, during this time interval there was an ever increasing influence of detrital sands entering the Illinois Basin and Moorman Syncline from the north and east (Figure A-22). By the end of Mississippian, the effects of the second major Paleozoic disruptive deformation were being felt across the mid-continent area (Figure A-23). This deformation probably continued through early Permian time (Figures A-24, A-25). It is marked by basic intrusives, dated 290 million years before present (Figure A-26) at the western end of the syncline near the intersection of north-south and east-west basement trends. Similar intrusives are found to the east along the trend of the Rome Trough. The timing of deformation events is similar to that documented for the Ouachita portion of the orogenic belt; thus by association in time and by a noted increase in the intensity of deformation toward the Ouachitas, one can tie this cratonic tectonism found to the Ouachita orogeny (Shumaker, 1975 and 1979). Cratonic structures formed by this

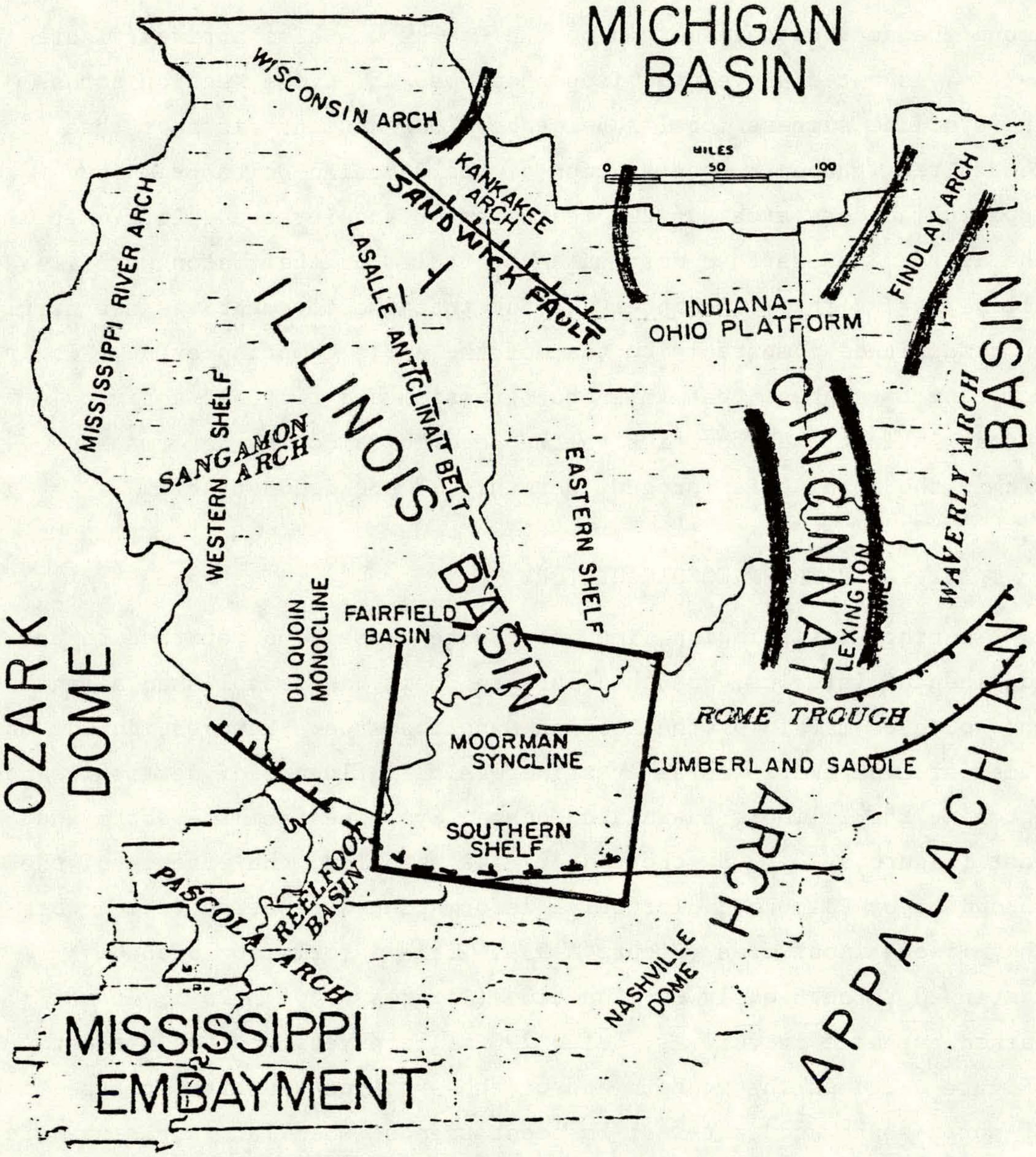


Figure A-21. DEVONIAN - EPEIROGENIC FEATURES
(Base from Bristol and Buschbach, 1971)

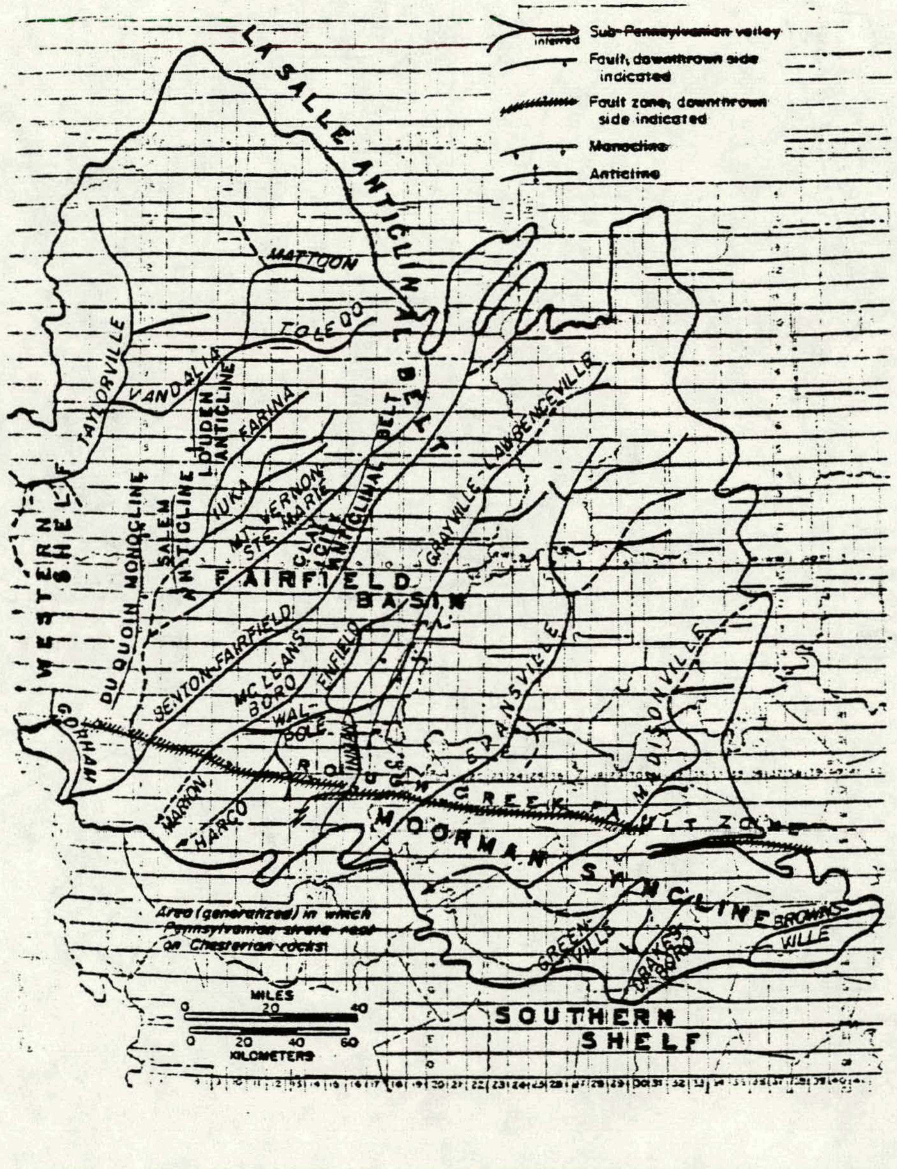


Figure A-22. RELATIONSHIP OF SUB-PENNSYLVANIAN VALLEYS TO TECTONIC FEATURES OF THE ILLINOIS BASIN

(author unknown)

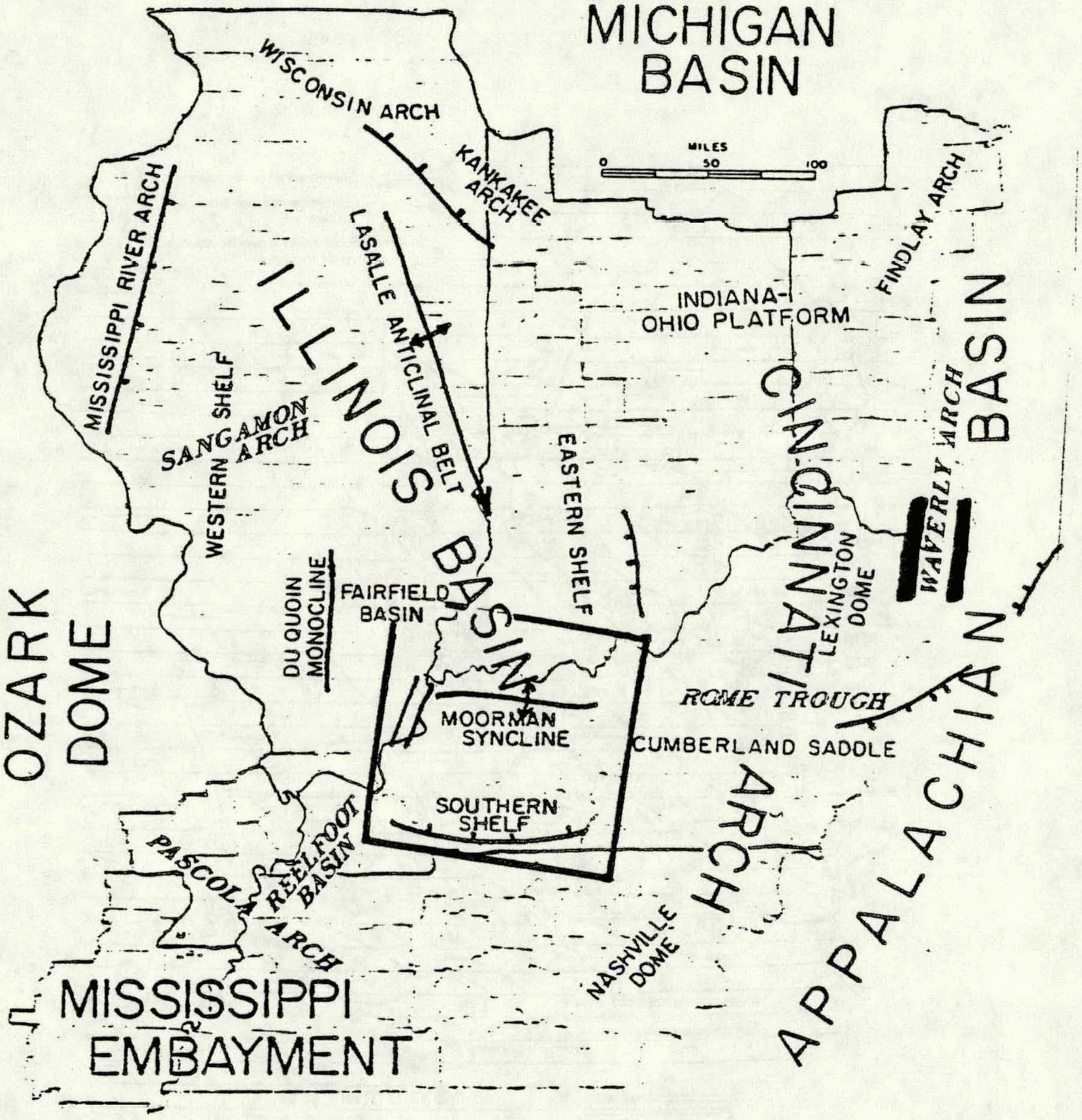


Figure A-23. MISSISSIPPIAN INCIPIENT DISRUPTIVE FEATURES
Base from Bristol and Buschbach, 1971)

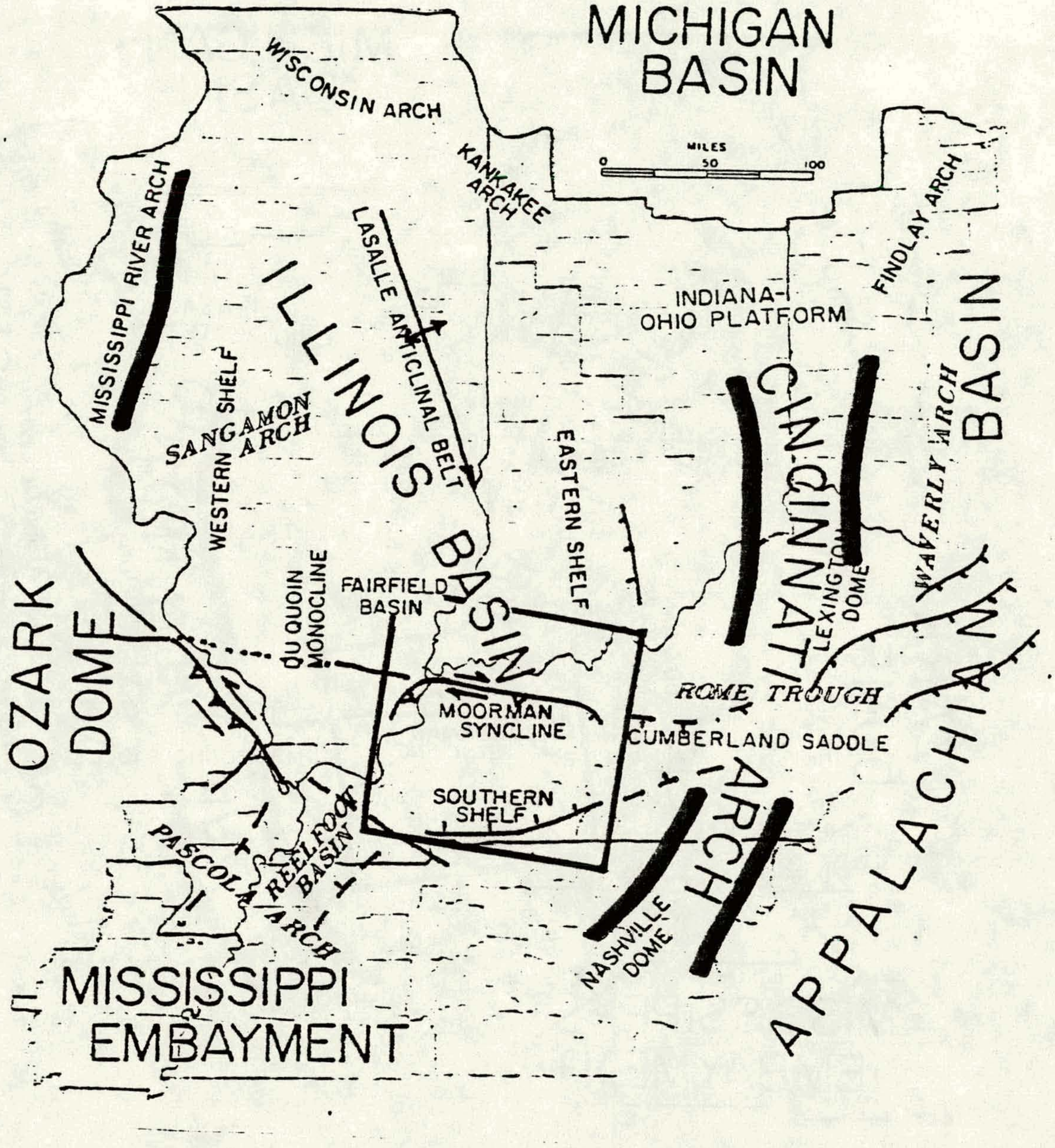


Figure A-24. PENNSYLVANIAN DISRUPTIVE FEATURES
(Base from Bristol and Buschbach, 1971)

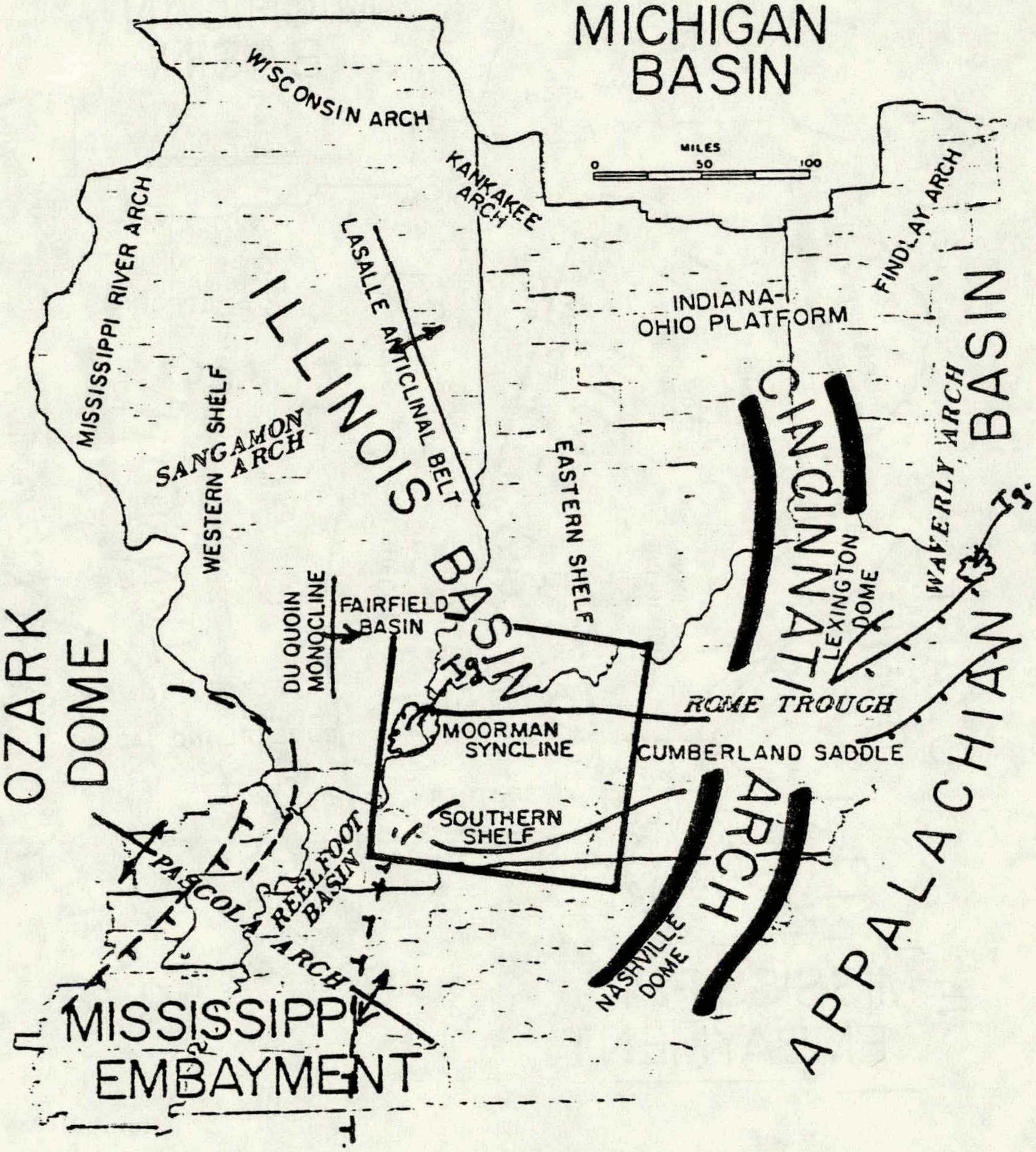


Figure A-25. POST PENNSYLVANIAN STRUCTURAL FEATURES
(Base from Bristol and Buschbach, 1971)

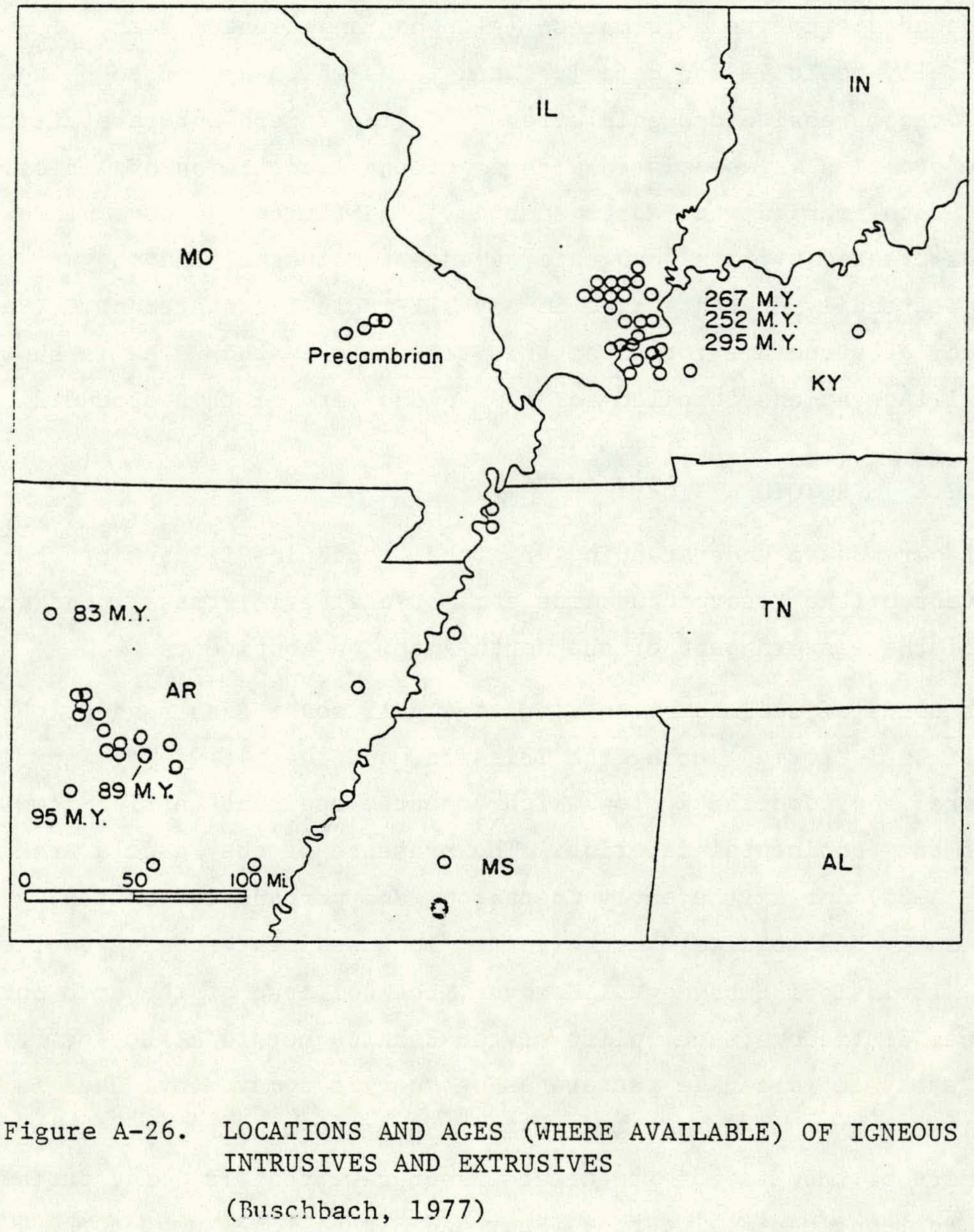


Figure A-26. LOCATIONS AND AGES (WHERE AVAILABLE) OF IGNEOUS INTRUSIVES AND EXTRUSIVES
(Buschbach, 1977)

deformation are those visible at the surface on geologic maps of the study area. This is the second disruptive (intense) Paleozoic deformation, but it is clearly different from the earlier disruptive event. The first disruptive deformation of Cambrian (Avalonian) age, formed structurally negative features characterized by rifts. This second disruptive deformation (Alleghenian) created both structurally positive and negative structures which appear to be the result of compressive orogenic stress. In the modern interpretation, this deformation is associated with continental collision of Africa and/or South America with North America. The faults and tectonic features created by this "orogenic" event are diverse, and they cannot be readily characterized in any all-inclusive statement. The diversity of structure formed at this time in the study area is shown in the illustrations compiled for the second part of this appendix.

A.2.6 MESOZOIC HISTORY

If our modern understanding of global tectonics is correct then the advent of the Mesozoic heralds a major change in stress found in rocks of the eastern part of the North American continents.

Patterns of sedimentation along the gulf coast area suggest that the Gulf Basin formed during the Triassic, and that it was a significant structural and topographic low which accepted sediment carried from most of the continental interior. The presence of the Pascola Arch (Figure A-25) during the early Cretaceous and perhaps during the entire early Mesozoic may have diverted much sediment from accumulating in the Mississippi Embayment. However, the collapse of the arch during the Upper Cretaceous, and uplift of the Rockies heralded the formation of the embayment drainage pattern as we know it today. Evidence is accumulating that stress of sufficient magnitude was present during the early part of the Mesozoic to create fractures, that is joint patterns, across the continental interior (Spar and Sykes). We know of the mapped intrusions and mineralization within the embayment south of the study area of ±90 MY (Figure A-26). The complex fault swarm in the Fluorspar district of Southern Illinois shows that the intensity of deformation within the embayment was quite high. Surely this tectonic activity affected the synclinal study area, but the extent of this involvement is not known.

In studying faults of the Southern Shelf one is struck by the increase in their numbers, complexity, and throw as they approach the Mississippi Embayment. This suggests renewed activity of early formed faults during the Mesozoic and Tertiary time. Mineralization of faults is restricted to the westernmost faults of the study area, and igneous intrusions "along the boundaries of the Rough Creek Rift -- have been dated -- about 90 MY" (Buschbach, 1977).

The Rough Creek Fault zone, the northern boundary of the syncline, was probably active during Mesozoic and Tertiary time. This fault is at the center of the 38th parallel lineament fault trend (Heyl, 1972). The western end of the fault is marked by mineralization of Mesozoic(?) age, and the eastern end includes igneous activity as young as 40-50 MY (Buschbach, 1977). Like faults of the Southern Shelf, the intensity of the deformation increases to the west end where it swings into the embayment precisely where it intersects the ancient Illinois-Reelfoot trend (Figures A-1 and A-11). The apex of this activity is found at Hicks Dome (Figure A-1), a crypto-explosion structure, that marks the intersection of these ancient yet modern structural trends. Clearly, resurgent tectonics has played a key role in the structural development of this area, and it continues today as witnessed by the earthquake activity of this region (Figure A-27). In this remote sensing study we expect to identify these fault systems, and it will be most interesting to see if age of the fault movement will be reflected in the clarity of lineament-fault expression.

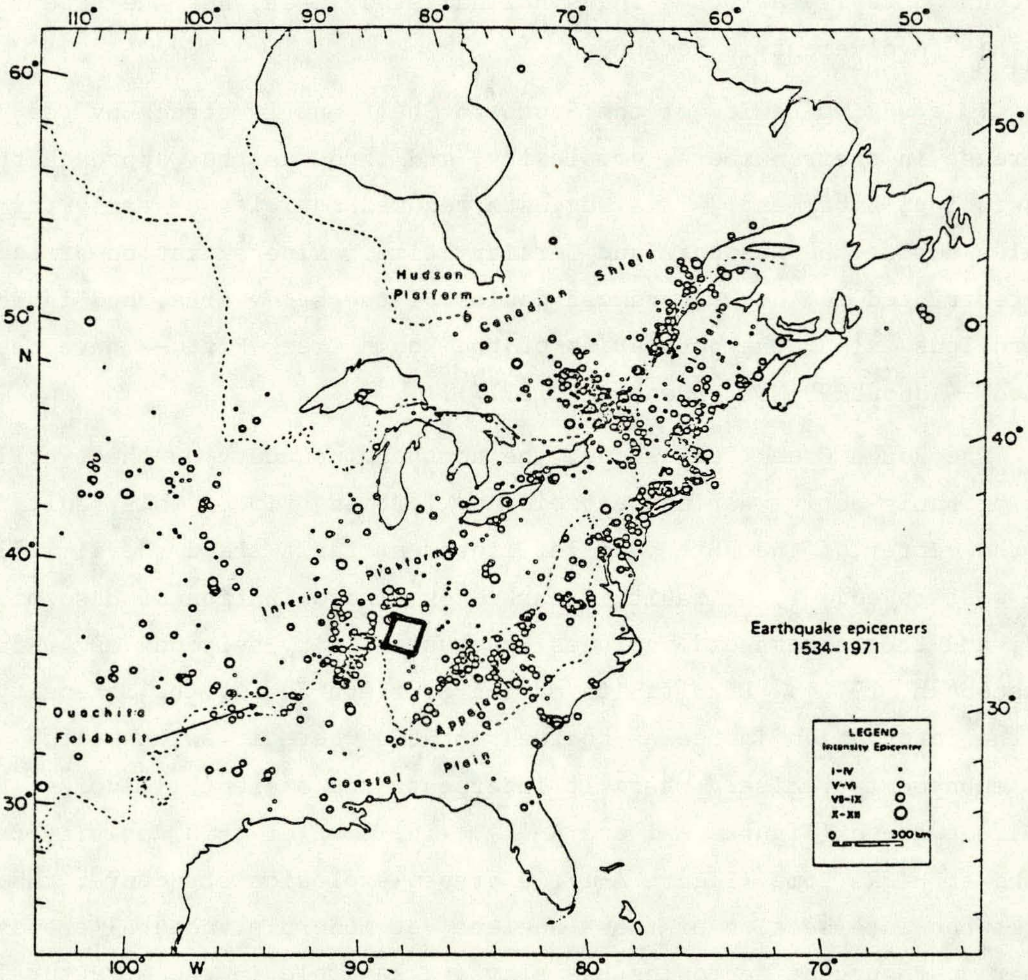


Figure A-27. DISTRIBUTION OF REPORTED EARTHQUAKES (1534-1971) IN EASTERN NORTH AMERICA FROM HISTORICAL AND INSTRUMENTAL DATA

(From York and Oliver, 1976, in Hinze and Braile, 1977)

A.3 STRUCTURAL STYLES OF SPECIFIC FAULT ZONES

There are five named structural zones within the study area, and all are characterized by faulting. Three of these zones will probably not be selected from our preliminary analysis for further detailed interpretation. However, some of the faults within these three zones should be expressed as lineaments on imagery of the study area, and therefore, understanding of these structural zones is also important if we are to identify the geologic significance and interrelationship of all the lineaments on the imagery.

The five structural zones include:

1. The Southern Illinois Rift
2. The Wabash Faults
3. Faults of the Mississippi Embayment
4. Rough Creek Fault Zone
5. Faults of the Southern Shelf

As discussed in the previous section, all of the fault system trends are probably related to deformational trends of Pre-Cambrian age. At any one time in geologic history these faults may have, and indeed are interpreted to have, included movement and deformation much different from that visible at the surface today. It is often difficult to decipher and interpret the effects of the latest deformation as seen at the surface because critical style elements may be inherited from deeper structure that formed at an earlier time under other stress conditions. It is, therefore, hazardous to estimate the stress direction creating the structures within a particular deformed basement block because pre-existing flaws will surely affect both stress conditions within the block and the resulting structural patterns.

A.3.1 SOUTHERN ILLINOIS RIFT

The Southern Illinois Rift is one of the few structures within the study area that has not undergone extensive deformation since its inception (Figure A-28). Indeed we know very little about the structure because it has not undergone the second, that is the Upper Paleozoic, disruptive deformation which left its imprint on the surface sediments in the other structural zones. The surface in this area is covered by glacial drift, and where bedrock is exposed it is gently dipping southwestward toward the center of the Illinois Basin (Figures A-2 and A-4). The Southern Illinois Rift is buried under these gently dipping sediments much as the Rome Trough is buried under the Appalachian Basin. Although speculative, Shumaker (1975) suggested that the La Salle anticline which formed during the second disruptive deformation in late Paleozoic is a reactivated northward extension of the fault bordering the eastern margin of the rift. The seismic line (Figure A-29) shows the rifted nature of the structure, and the isopach map and thermal maturity analysis of the New Albany Shale suggests that the rift did play a role in affecting the distribution and maturation of the shale. The origin of the rift is uncertain; but barring any solid data, the author prefers an Avalonian age related to the onset of subduction at the continental margin.

A.3.2 WABASH VALLEY FAULT SYSTEM

The Wabash Valley Faults (Figure A-30) appear to be structurally simple, dip-slip normal faults that probably formed by crustal tension during the late Paleozoic. The surface of the area is generally covered by glacial drift including loess and alluvian of Pleistocene age that is up to one hundred feet in thickness. The surface expression of these faults may be masked by these sediments. Sullivan and Ault (in Buschbach, 1977) indicate that the fault dips vary from nearly vertical to 45°, and that short north-west south-east striking cross faults (Figures A-31 through A-34) show minor strike slip movement. There appears to be no consistent sense of movement along these cross faults. The major faults assume a relay style (Figure A-35). According to Bristol and Treworgy (in Buschbach, 1977) beds of Pennsylvanian age are cleanly sheared along

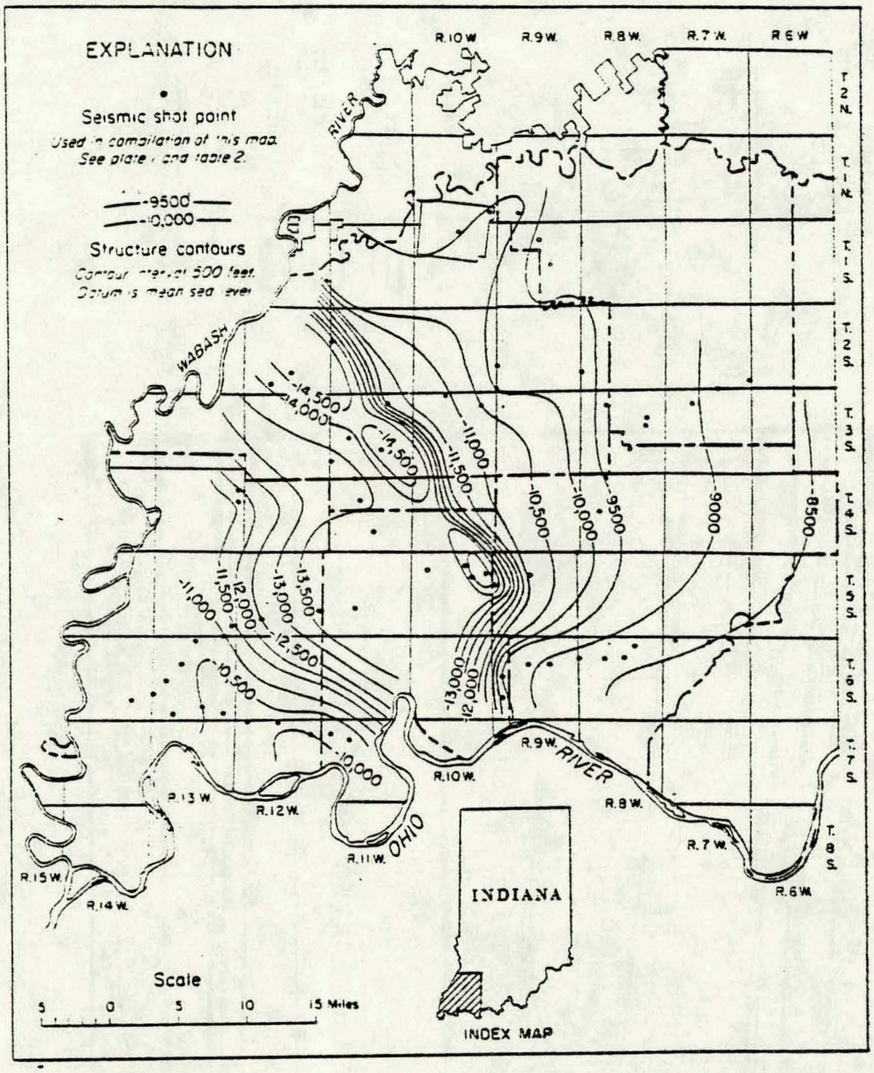


Figure A-28. MAP OF PART OF SOUTHWESTERN INDIANA SHOWING STRUCTURE ON TOP OF THE BASEMENT COMPLEX

(Rudman, 1960)

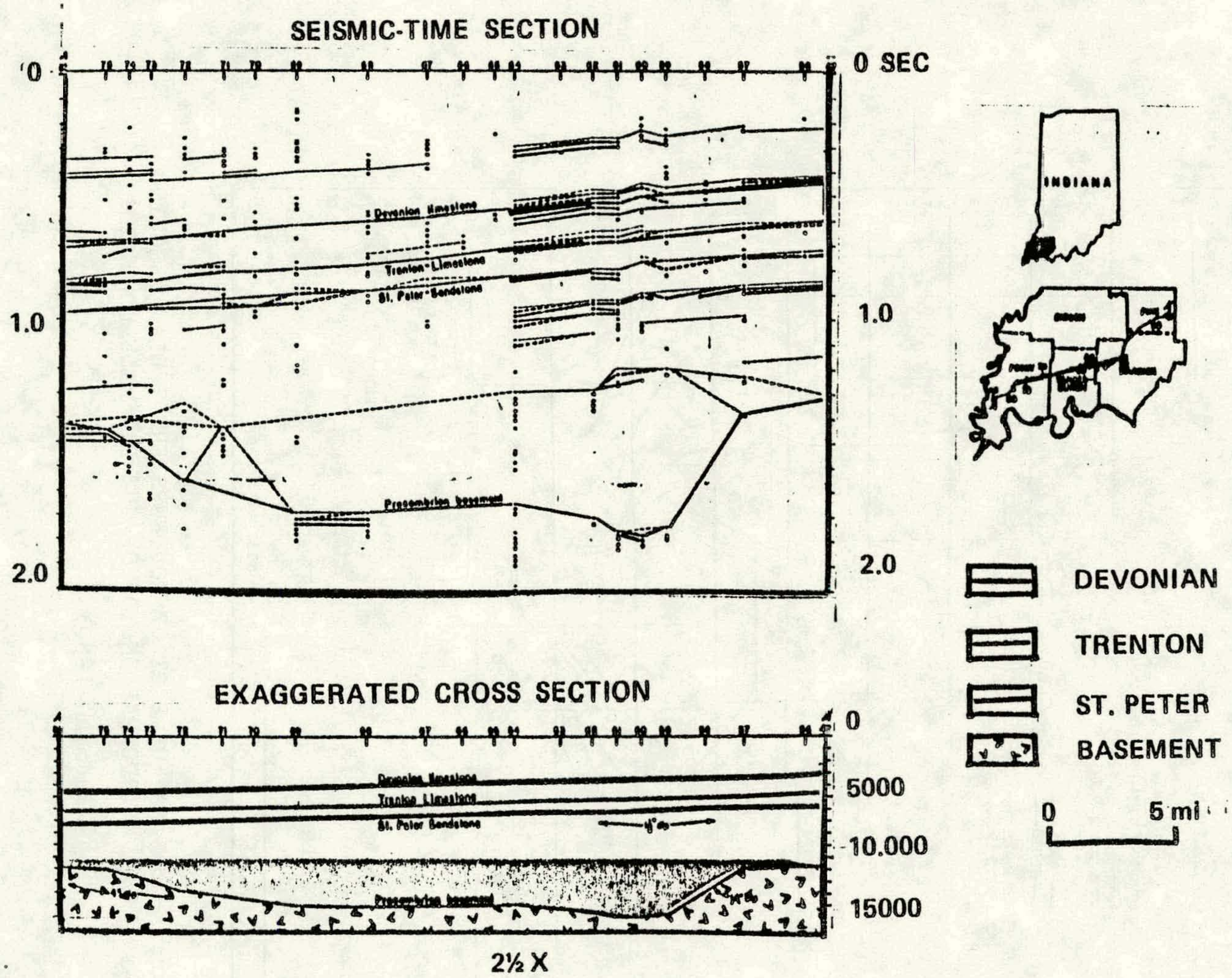


Figure A-29. SOUTHERN ILLINOIS RIFT

(Rudman, 1960)

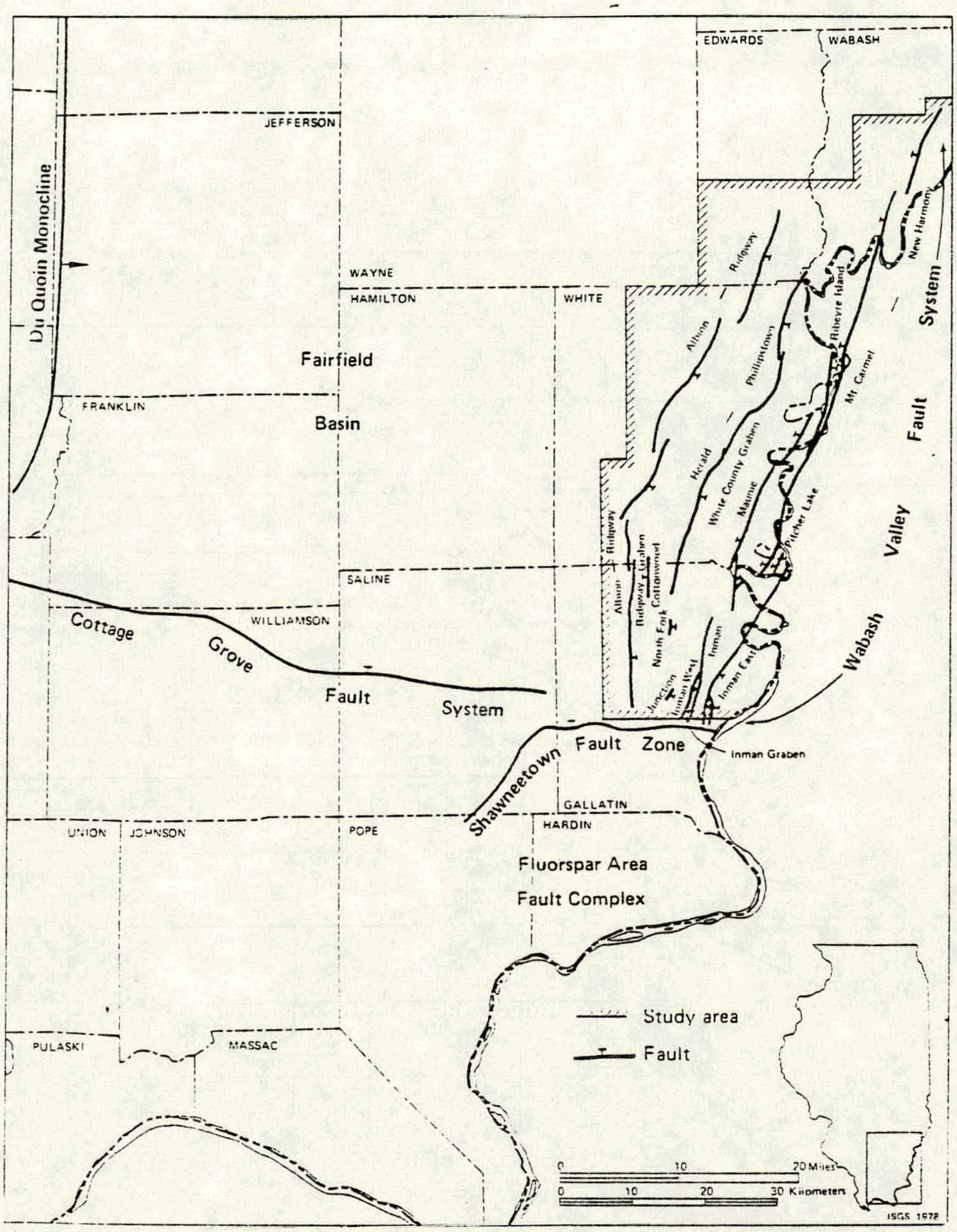


Figure A-30. PROMINENT STRUCTURAL FEATURES AND AREA OF STUDY IN SOUTHERN ILLINOIS

(Bristol and Treworgy in Buschbach, 1978)

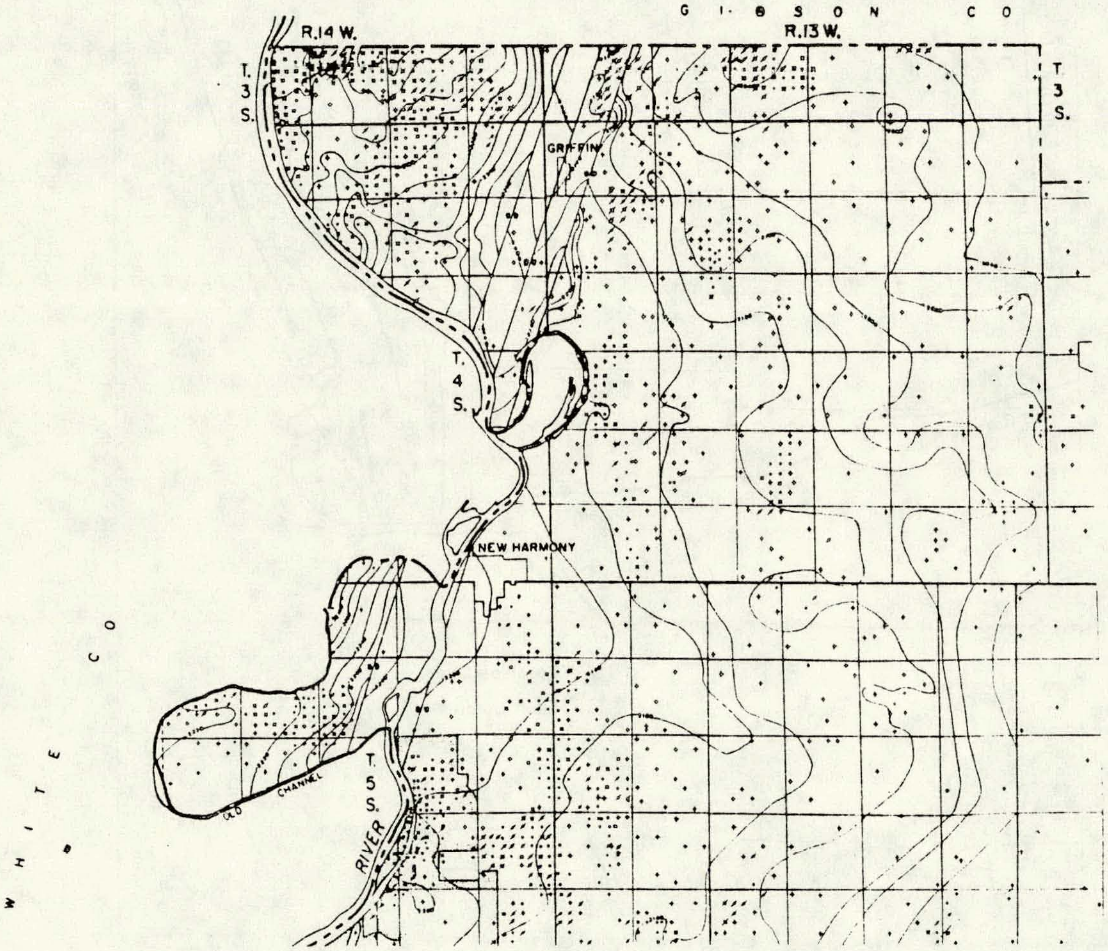


Figure A-31. STRUCTURE ON TOP OF CYPRESS FM.
(Sullivan and Ault in Buschbach, 1978)

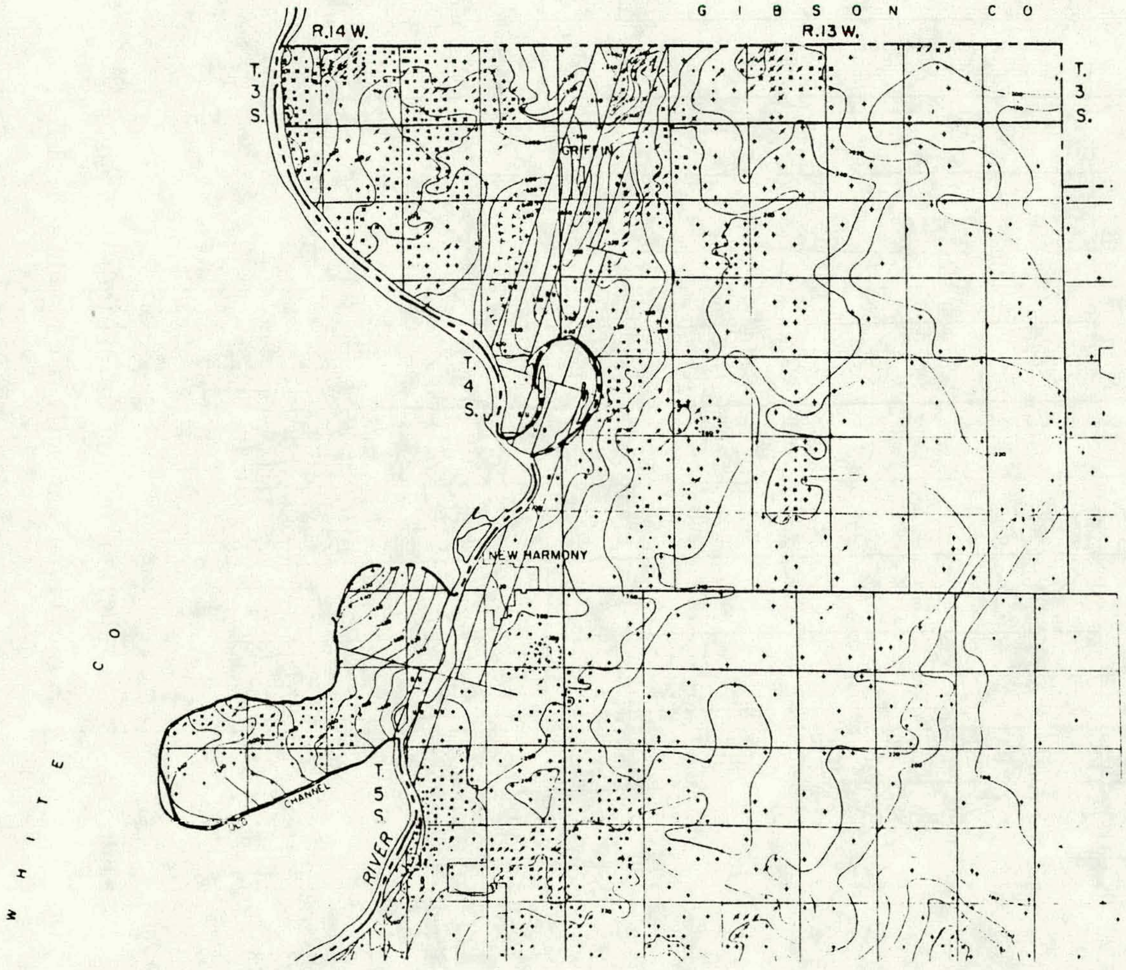


Figure A-32. STRUCTURE ON TOP OF SPRINGFIELD COAL MBR. (V) PETERSBURG FM.

(Sullivan and Ault in Buschbach, 1978)

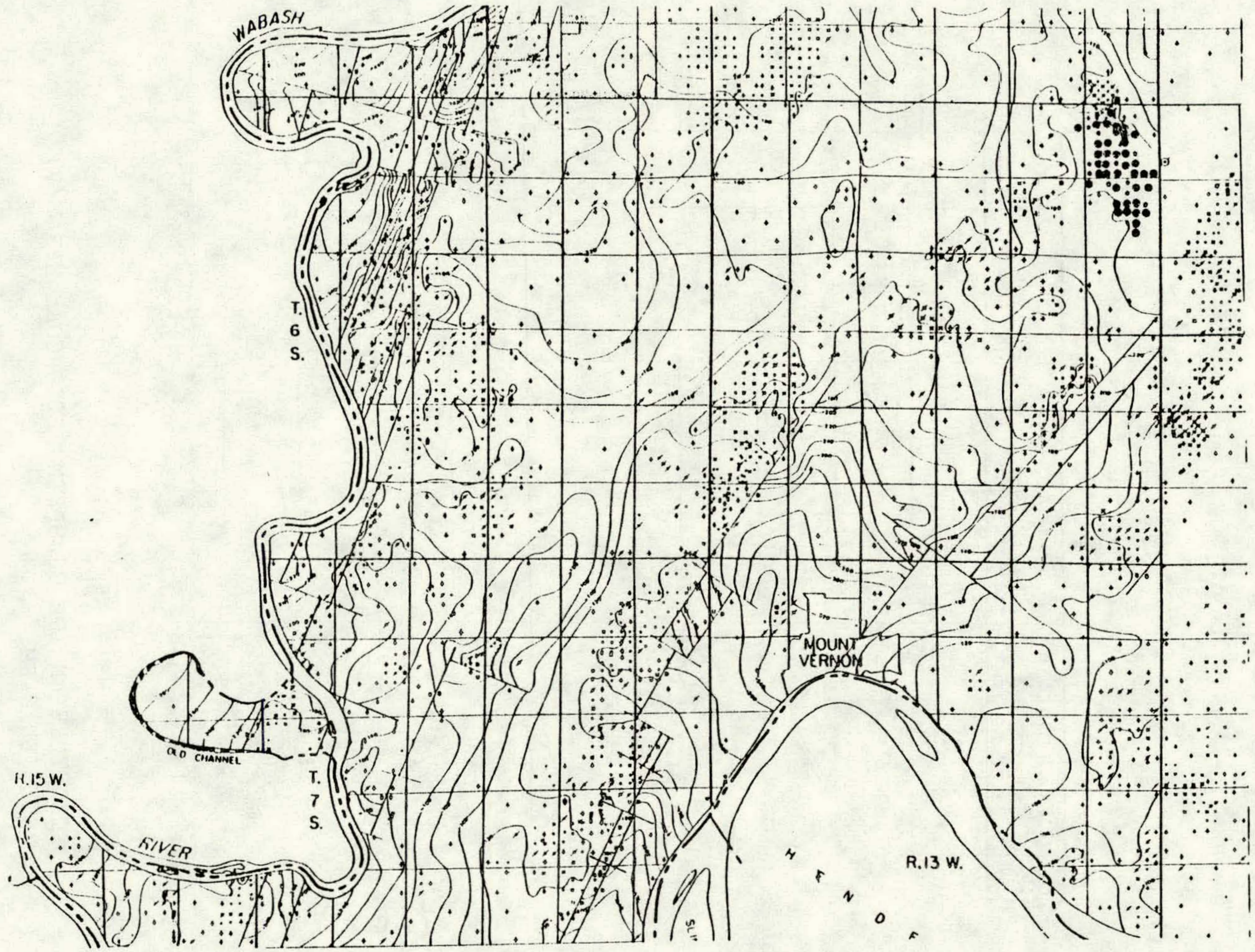


Figure A-33. STRUCTURE ON TOP OF SPRINGFIELD COAL
(Sullivan and Ault in Buschbach, 1978)

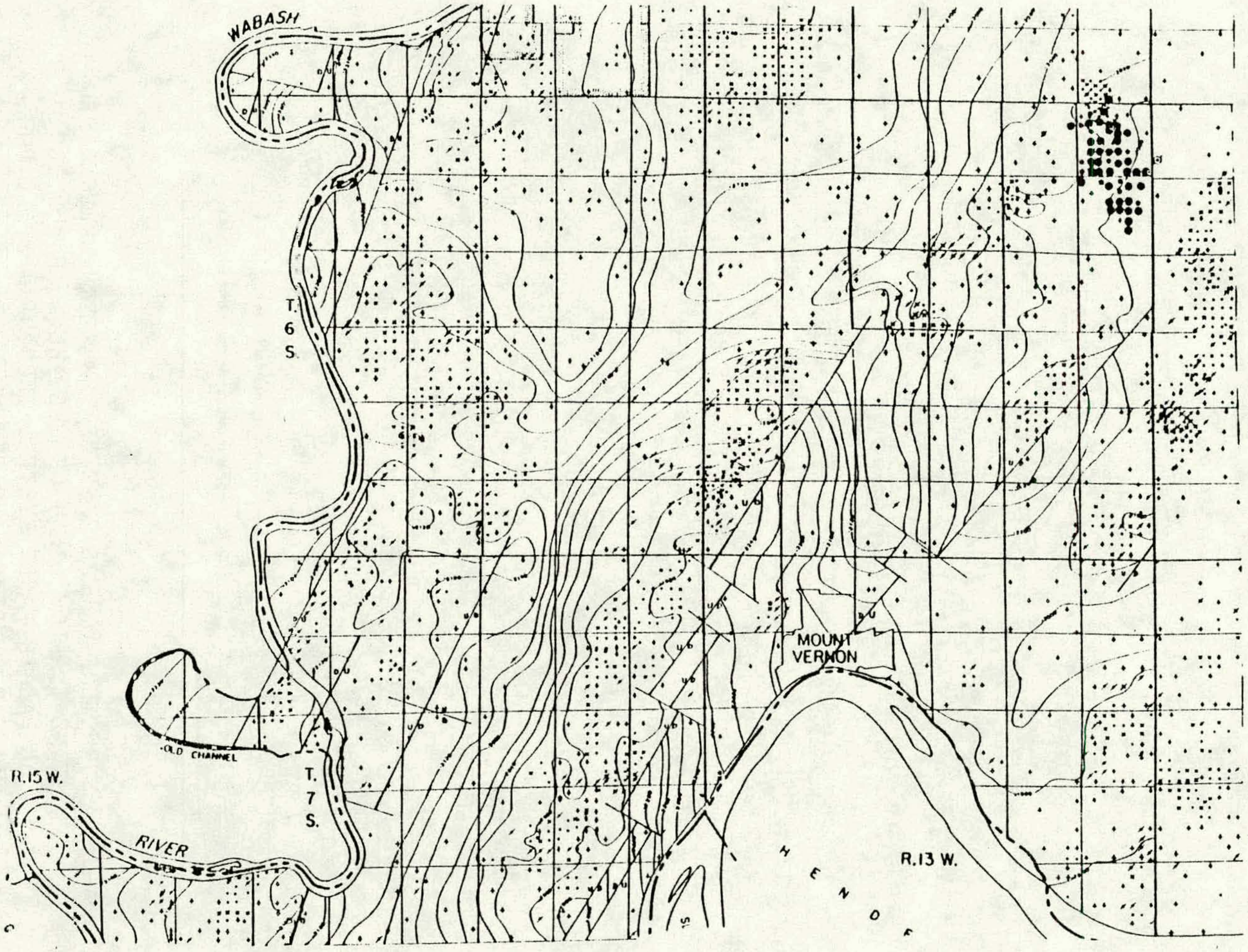


Figure A-34. STRUCTURE ON TOP OF CYPRUS

(Sullivan and Ault in Buschbach, 1978)

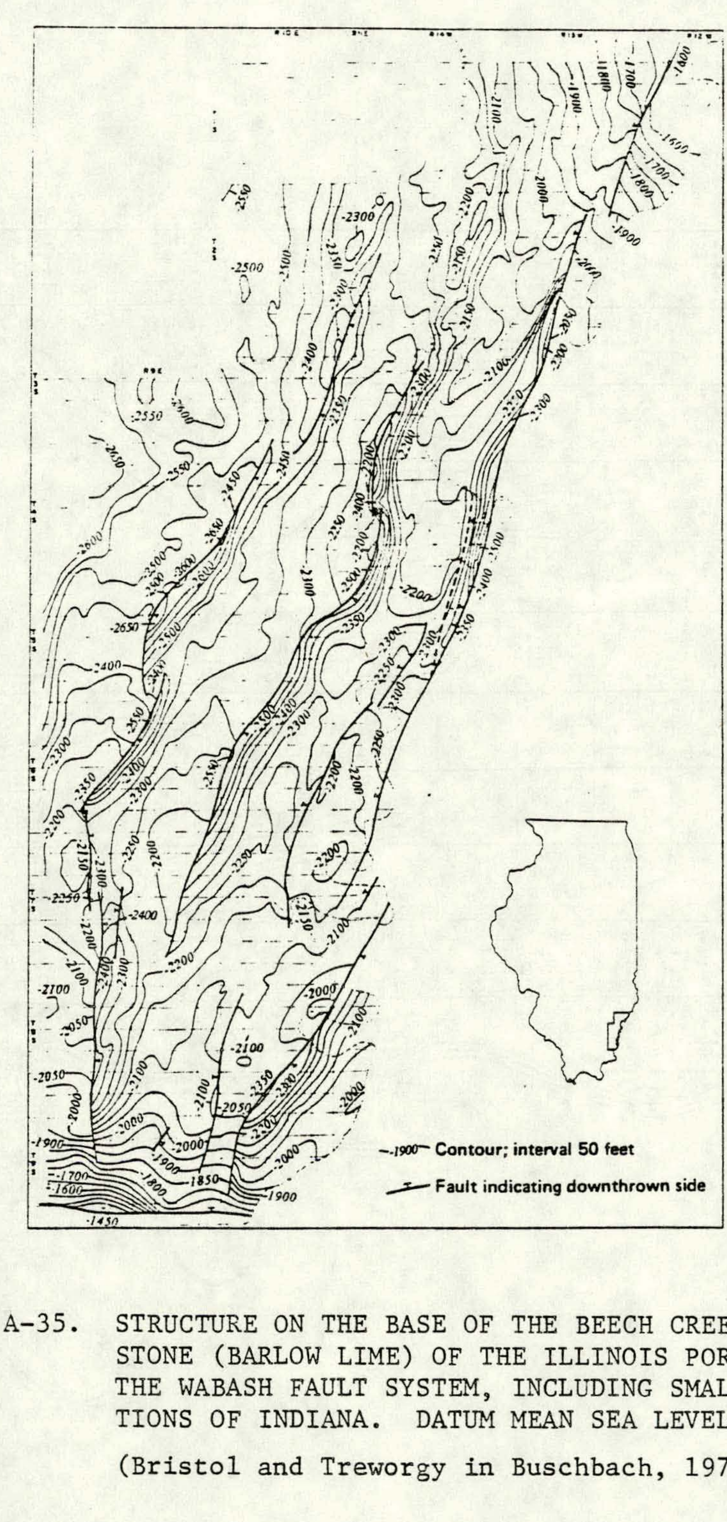


Figure A-35. STRUCTURE ON THE BASE OF THE BEECH CREEK LIMESTONE (BARLOW LIME) OF THE ILLINOIS PORTION OF THE WABASH FAULT SYSTEM, INCLUDING SMALL PORTIONS OF INDIANA. DATUM MEAN SEA LEVEL.

(Bristol and Treworgy in Buschbach, 1978) the fault surfaces without major flexing or drag, but Figure A-36 shows roll-over into the fault near the surface. These observations are not incompatible as the observed roll-over relates to extension across the fault zone rather than any drag phenomena. Variance in style and complexity of both the Wabash system and the Southern Illinois graben compared to faults to the south of the Rough Creek fault system suggest that the crustal block north of the Rough Creek system reacted in a different manner to the late Paleozoic disruptive deformation compared with that south of the fault. One might suggest that the Moorman Synclinal block thrust over the Illinois Basin block during the Upper Paleozoic deformation, and that the normal faults of the Wabash system are the tensional reaction of the block margin to this overriding from the south.

A.3.3. MISSISSIPPI EMBAYMENT FAULT SYSTEM

The faults along the western margin of the study area are part of the fluorspar and the Mississippi Embayment fault systems (Figure A-37). These faults have a long and complex history, but perhaps uniquely, these faults have demonstrable Mesozoic and recent movement. The complexity of the fault pattern is visible at the surface, and the intensity of the deformation is also reflected by the crypto-explosion structure found at Hicks Dome. It seems likely, as Bucher argued, that Hicks Dome is not a meteor impact structure, for the meteor creating the dome would have had to been a geologically accurate missile hitting precisely on the bull's eye intersection of the east-west and north-south structural trends (Figure A-1). The trend of fluorspar faults is demonstrably northeast-southwest, out of the embayment. This is the same direction and on trend with the Wabash system, but the pattern is more shatter-like in detail with many irregular cross faults. The faults of the embayment bend toward the east into the Moorman Syncline, and as they do so they become simpler with less throw (Figure A-38). Cross-sections through the faults show

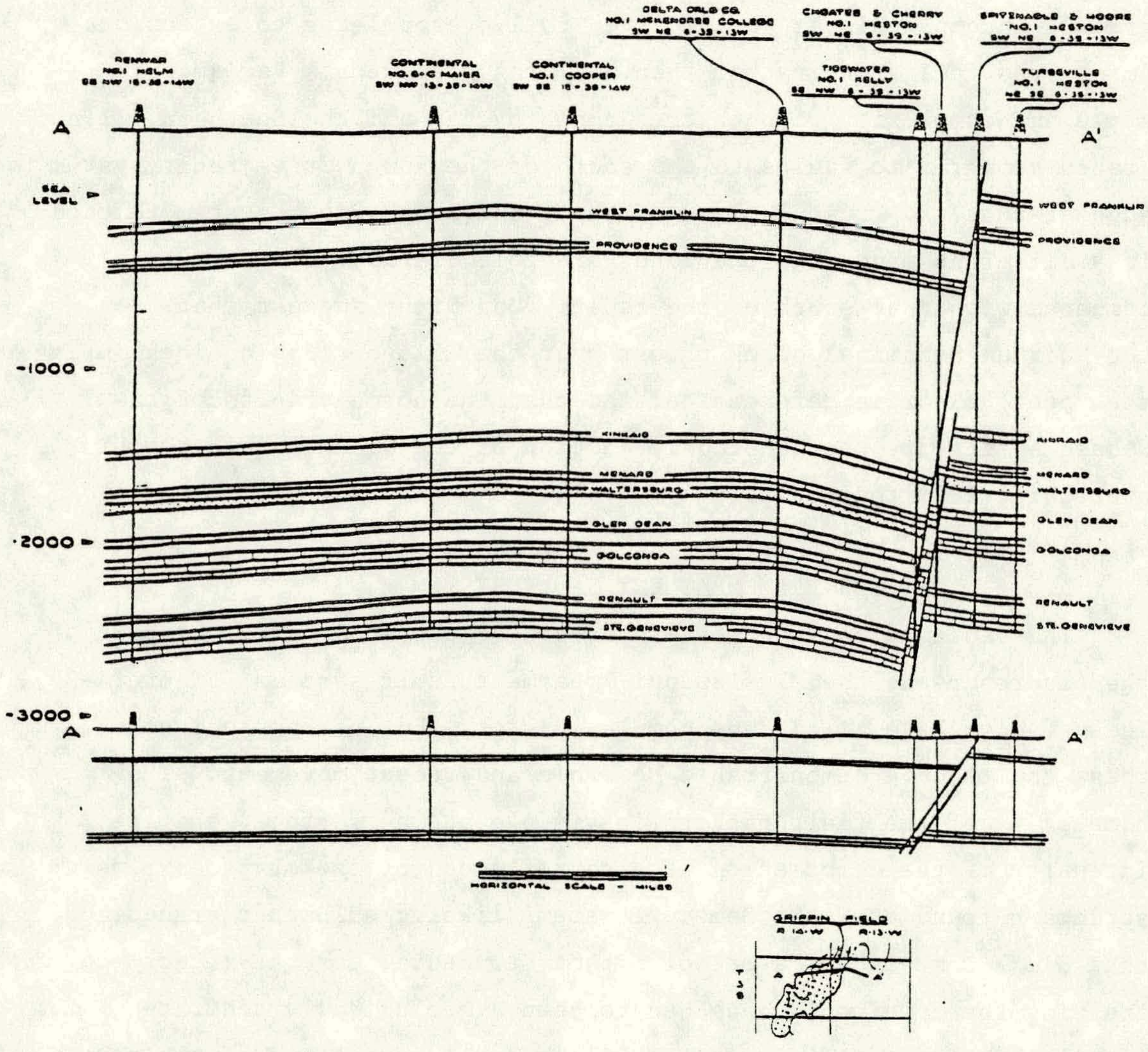
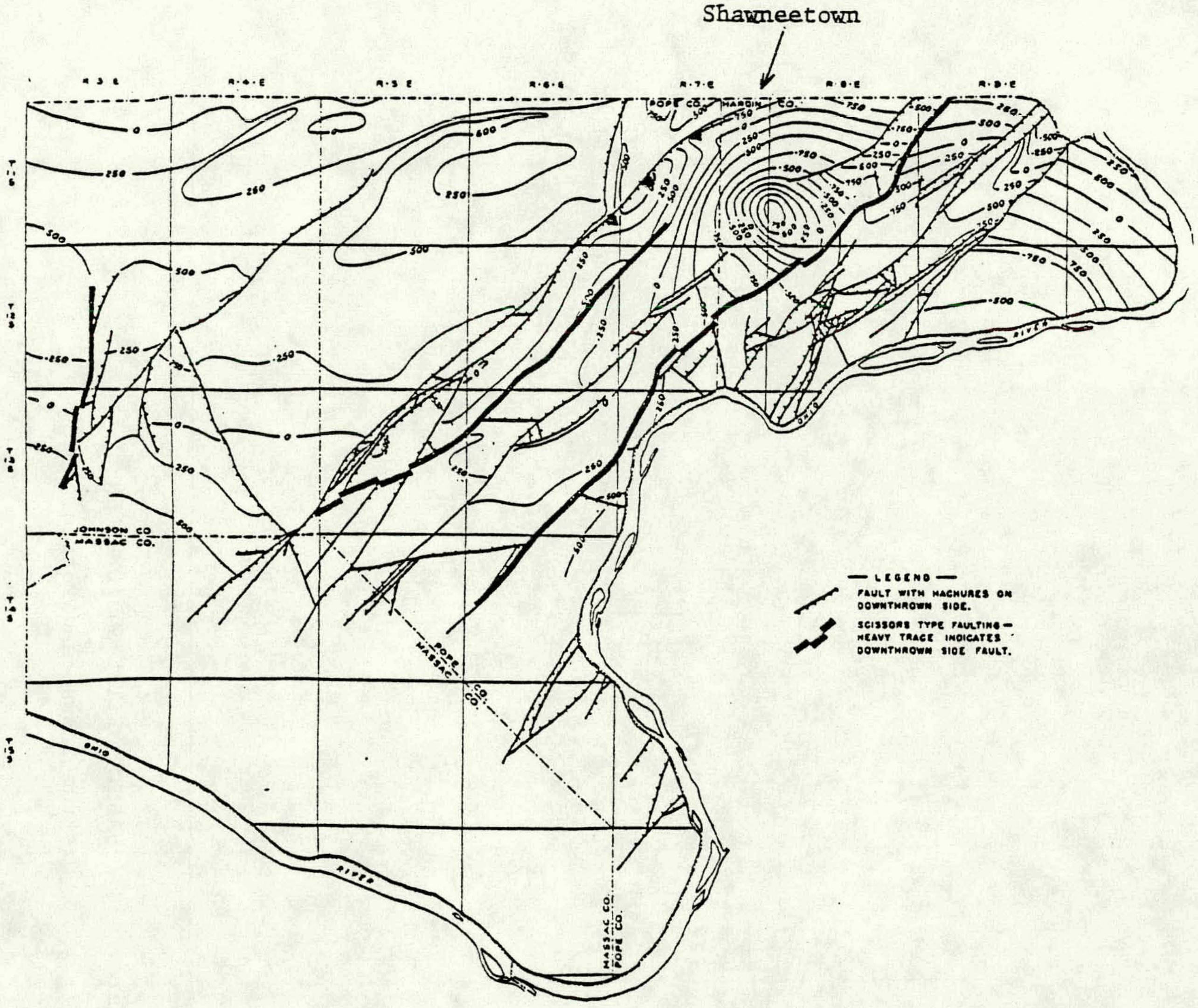


Figure A-36. WEST-EAST CROSS SECTION, GRIFFIN FIELD, GIBSON COUNTY, INDIANA

(Clark and Royds, 1948)



(FROM PLATE I, ILLINOIS STATE GEOLOGICAL SURVEY,
REPORT OF INVESTIGATIONS NO. 71, 1940, BY J. MARVIN WELLER.)
STRUCTURE CONTOURS ON VARIOUS MISSISSIPPIAN & PENNSYLVANIAN HORIZONS.

Figure A-37. STRUCTURE CONTOUR MAP OF EXTREME SOUTHERN ILLINOIS (Clark and Royds, 1948)

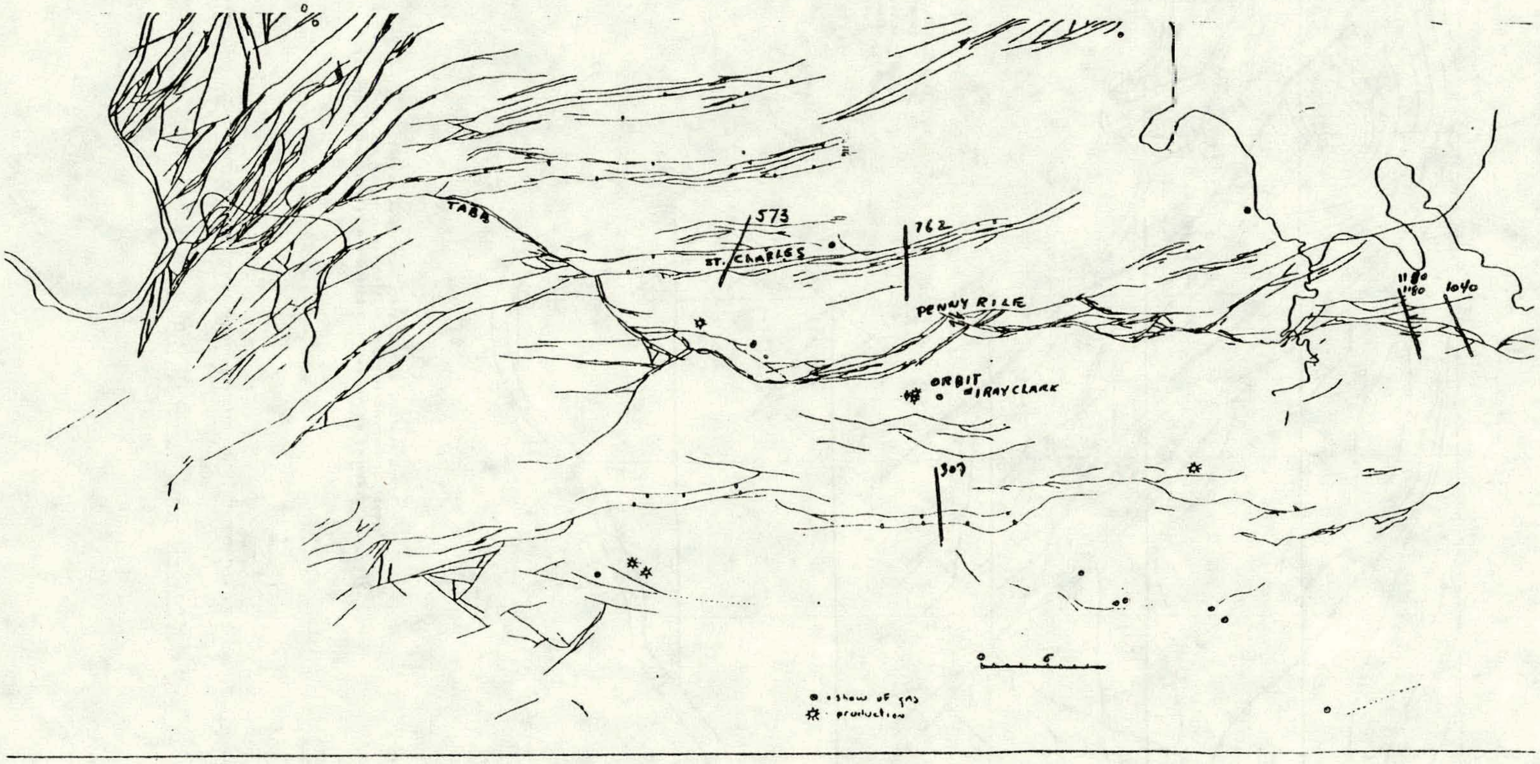
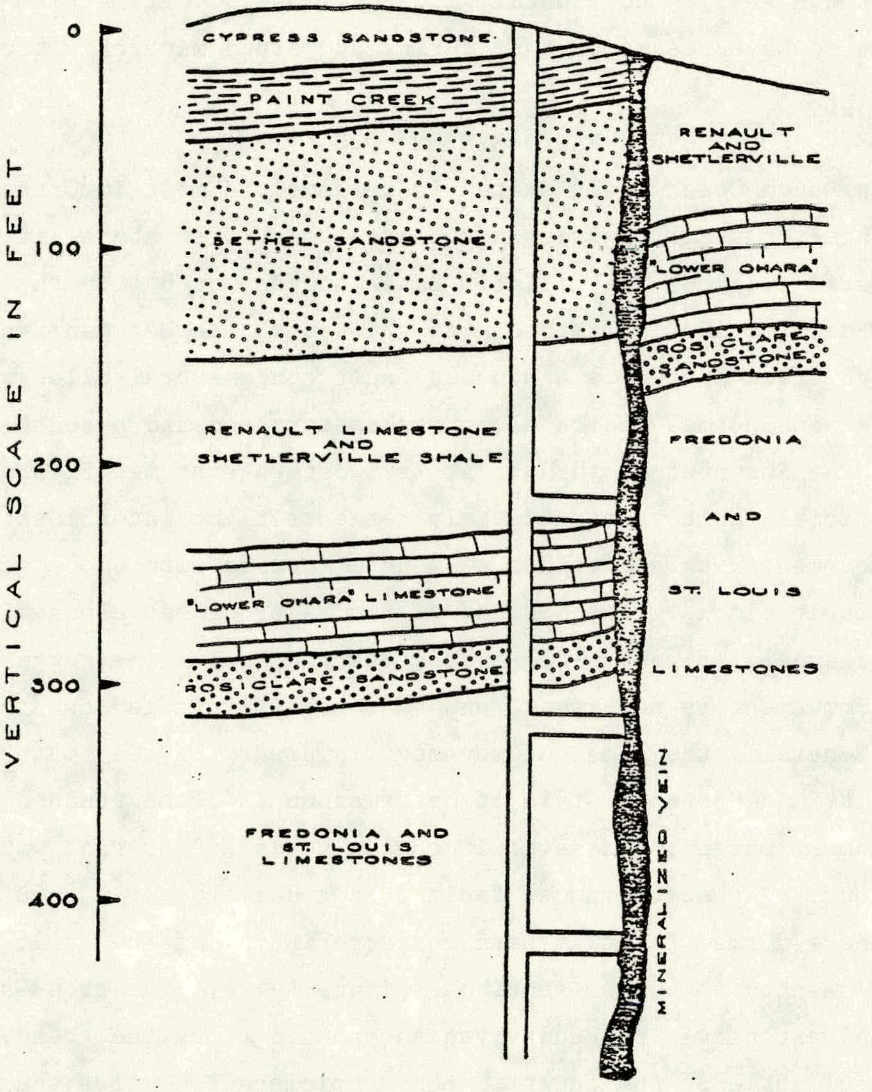


Figure A-38. FAULTS OF THE SOUTHERN SHELF
(From Schwab and Potten, 1978)

the fault planes to be vertical and extensively mineralized (Figures A-39 through A-41). Horizontal slickenslides indicate strike-slip movement to have been important during and after mineralization.

A.3.4 ROUGH CREEK FAULT SYSTEM

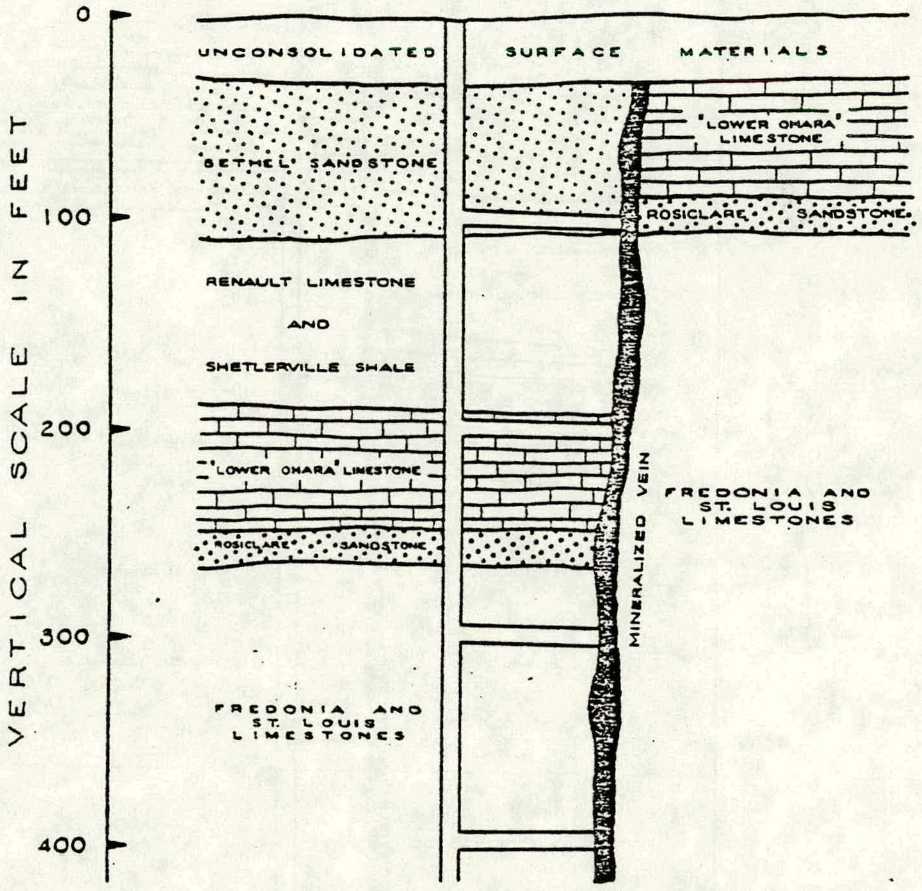
The Rough Creek fault system is perhaps the most important fundamental crustal flaw within the area. As noted above, it separates the crustal block of the Illinois Basin on the north from the more intense deformation in the block to the south, the Moorman Syncline. The Rough Creek system is a sinuous fault zone several miles wide that contains normal faults along its eastern end and a south-curving thrust, the Shawneetown thrust, at its western extreme (Figure A-36). The surficial fault pattern clearly reflects right lateral strike-slip fault movement with a distinct element of compression or convergence of the fault blocks. The absence of any major offset along Mississippian stream channels (Figure A-22) that cross the fault zone suggest the lateral movement is not great, and that probably it is less than one mile. Generally the sense of movement is upward on the south side of the fault. An upthrust style of deformation is often found along the northernmost margin, and several echelon folds are present within the fault zone. The northernmost fault is not universally a thrust, and it may be a normal fault. These characteristics of the fault zone are clearly seen on the cross-sections (Figure A-42). The cross-sections also show extensive Pre-Pennsylvanian erosion along the trend. The structural style of the fault zone is reminiscent of trends and structures along other late Paleozoic upthrusts like those of the central basin uplift of the West Texas Basin and the Wichita Uplift of the Oklahoma Basin. Clearly the surficial faults along the northern margin of the zone are shears that should be tight without porosity. The faults should form seals for traps in adjacent rocks that contain porosity. Faults that trend at high angles to the zone, within the tension direction (T), might have open fracture porosity.



IDEALIZED GEOLOGIC SECTION THROUGH THE AIR SHAFT OF THE ROSICLARE MINE
HARDIN COUNTY, ILLINOIS
(FROM "GEOLOGY OF HARDIN COUNTY", ILLINOIS STATE GEOLOGICAL SURVEY, BULLETIN 41)

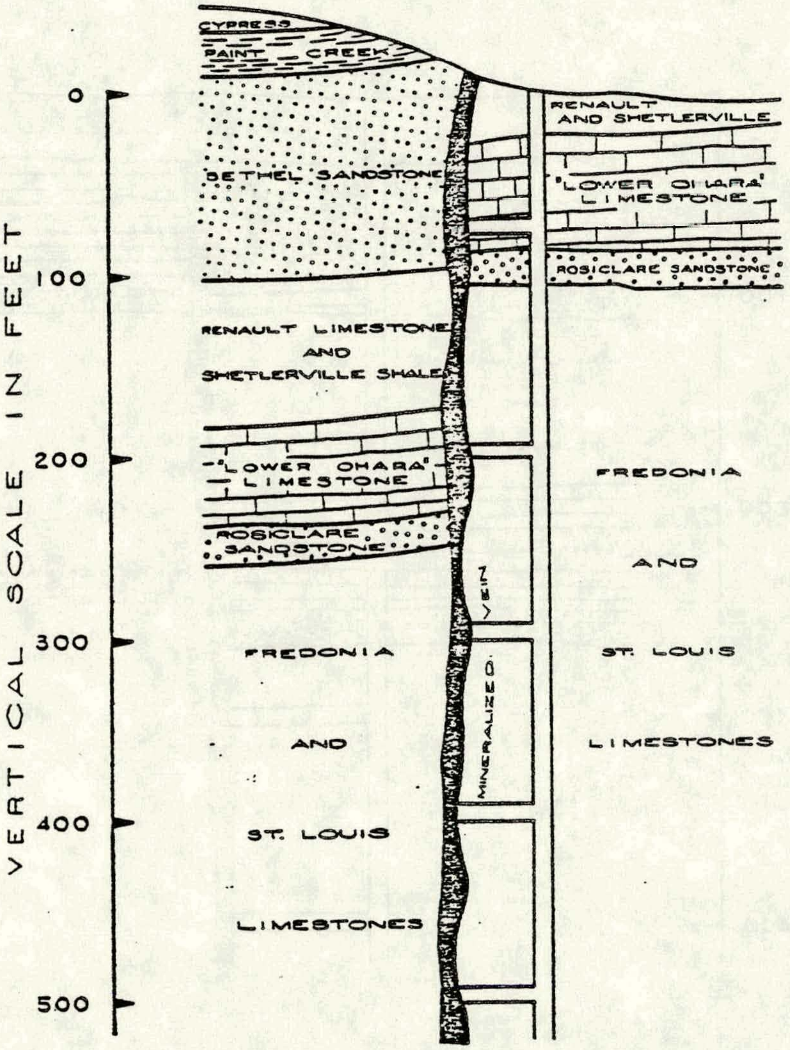
Figure A-39. IDEALIZED GEOLOGIC SECTION THROUGH THE AIR SHAFT OF THE ROSICLARE MINE, HARDIN COUNTY, ILLINOIS

(Clark and Royds, 1948)



(FROM "GEOLOGY OF HARDIN COUNTY", ILLINOIS STATE GEOLOGICAL SURVEY, BULLETIN 41)

Figure A-40. IDEALIZED GEOLOGIC SECTION THROUGH THE ANNEX MINE SHAFT, HARDIN COUNTRY, ILLINOIS
(Clark and Royds, 1978)



(FROM "GEOLOGY OF HARDIN COUNTY", ILLINOIS STATE GEOLOGICAL SURVEY, BULLETIN 41)

Figure A-41. IDEALIZED GEOLOGIC SECTION THROUGH THE NEW GOOD HOPE MINE SHAFT, HARDIN COUNTRY, ILLINOIS
(Clark and Royds, 1948)

2

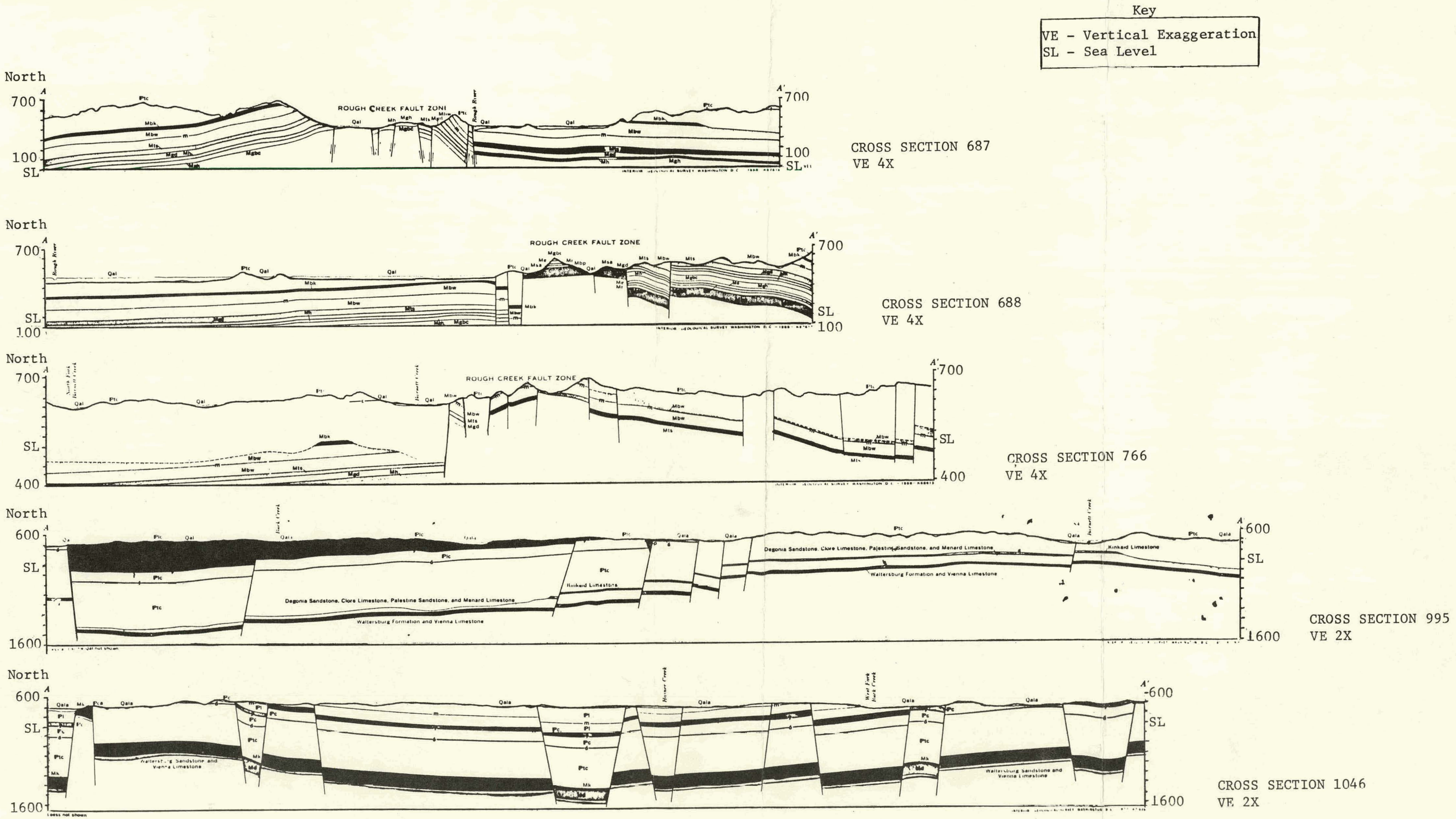


Figure A-42. ROUGH CREEK FAULT SYSTEM CROSS SECTIONS
(See Figure A-43 for lines of section)

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Because the eastern end of the system appears to be tensional, and because of the shows from the New Albany Shale in that area, the eastern area should be considered prospective (Figure A-43).

A.3.5 THE SOUTHERN SHELF FAULT SYSTEM

Faults along the Southern Shelf probably deserve the most attention within this study as they are normal (tensional) structures, and as such, they should have fracture porosity associated with the faulting. The main problem here will be too much permeability with attending loss of hydrocarbon along the fault planes. The prospectiveness of the area is enhanced by shallow depths to the selected shale reservoir and the numerous shale gas shows that occur within the shale reservoir in this area (Figures A-38, A-44). The fault system is composed of two or three narrow, elongate grabens that regionally step down northward forming the south flank of the Moorman Syncline. Faults generally increase in offset and complexity as they approach the Mississippi Embayment, but on approaching the embayment they also intersect a southeast trending arch and fault system (Tabb) that presumably is an extension of the Paleozoic St. Genevieve fault system. Mineralization occurs within the St. Genevieve system, but such mineralization is not within the east and northeast trending shelf faults. The shelf faults generally are normal, steeply dipping and the throws at the surface are usually less than three hundred feet (Figure A-45). The isopach of the New Albany Shale indicates downwarping of the Moorman Syncline occurred during the Devonian. Presumably this was accomplished along these faults by dip slip movement. They are, therefore, growth faults. Surface structure patterns generally support the extensional dip slip movement, but offset of certain structural features suggests slight strike slip movement. The sense of offset is not always consistent, but the best data suggest right lateral movement comparable to that found along the Rough Creek system. The greatest offset measured on detailed maps of the area suggests that lateral movement

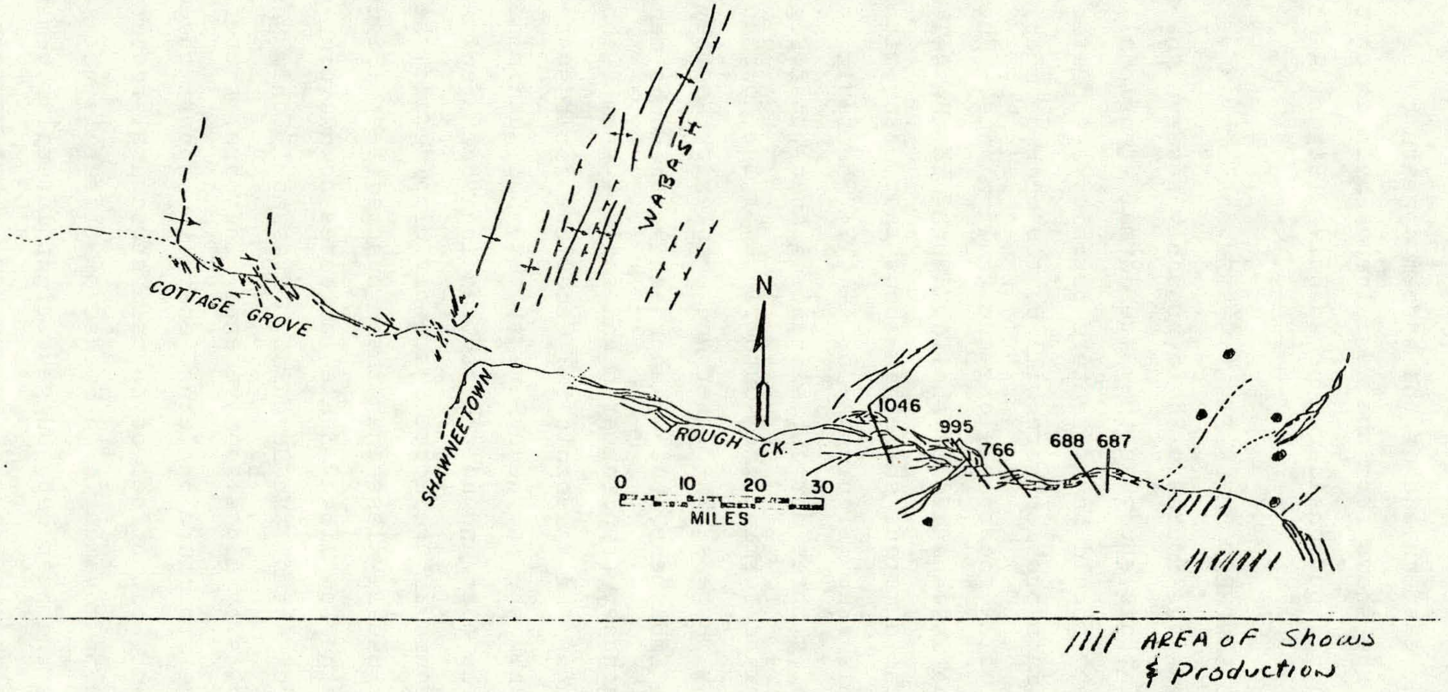

Figure A-43. ROUGH CREEK FAULT SYSTEM

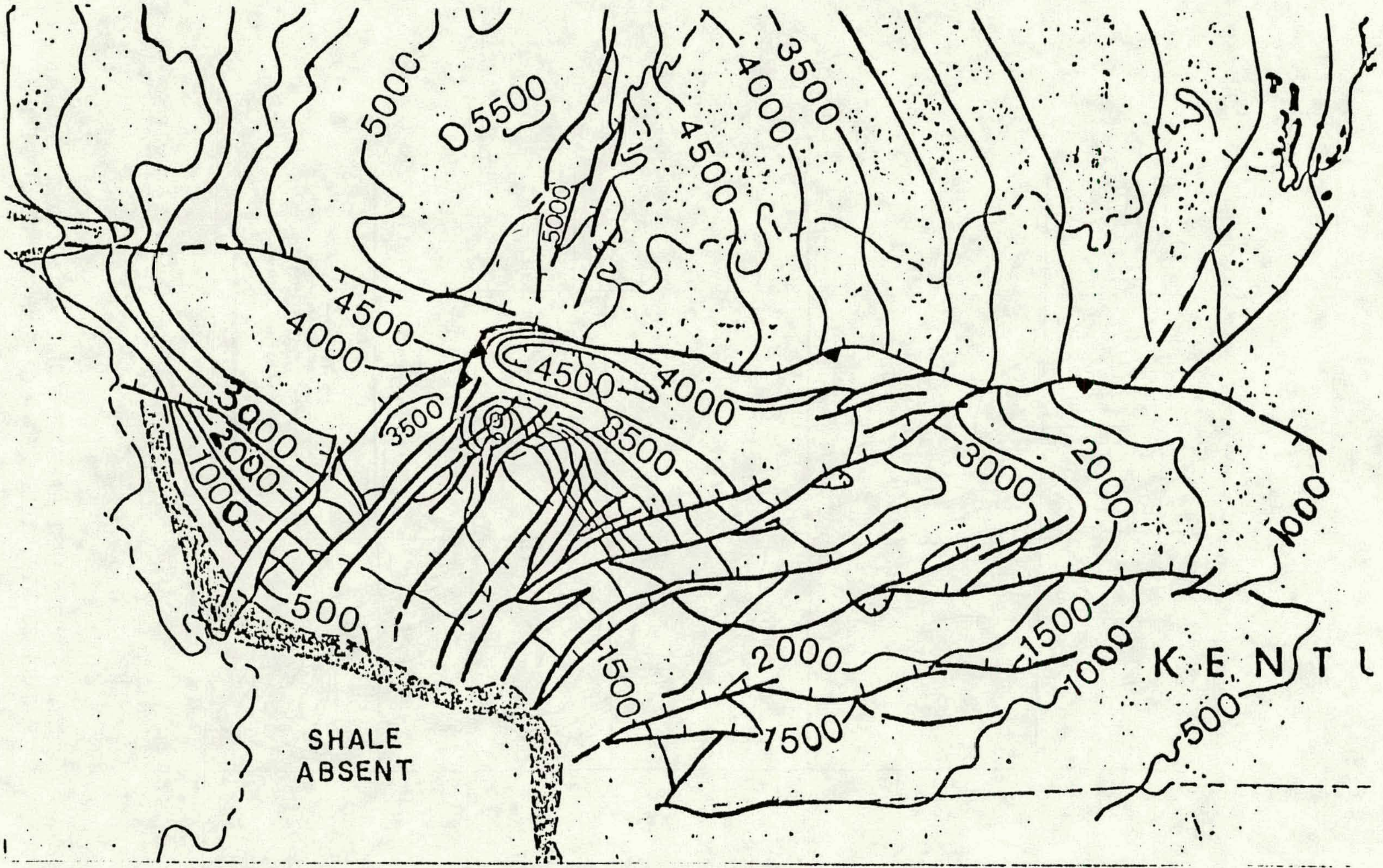

Figure A-44. DRILLING DEPTH TO NEW ALBANY SHALE (DEVONIAN)
(Schwalb and Potter, 1978)

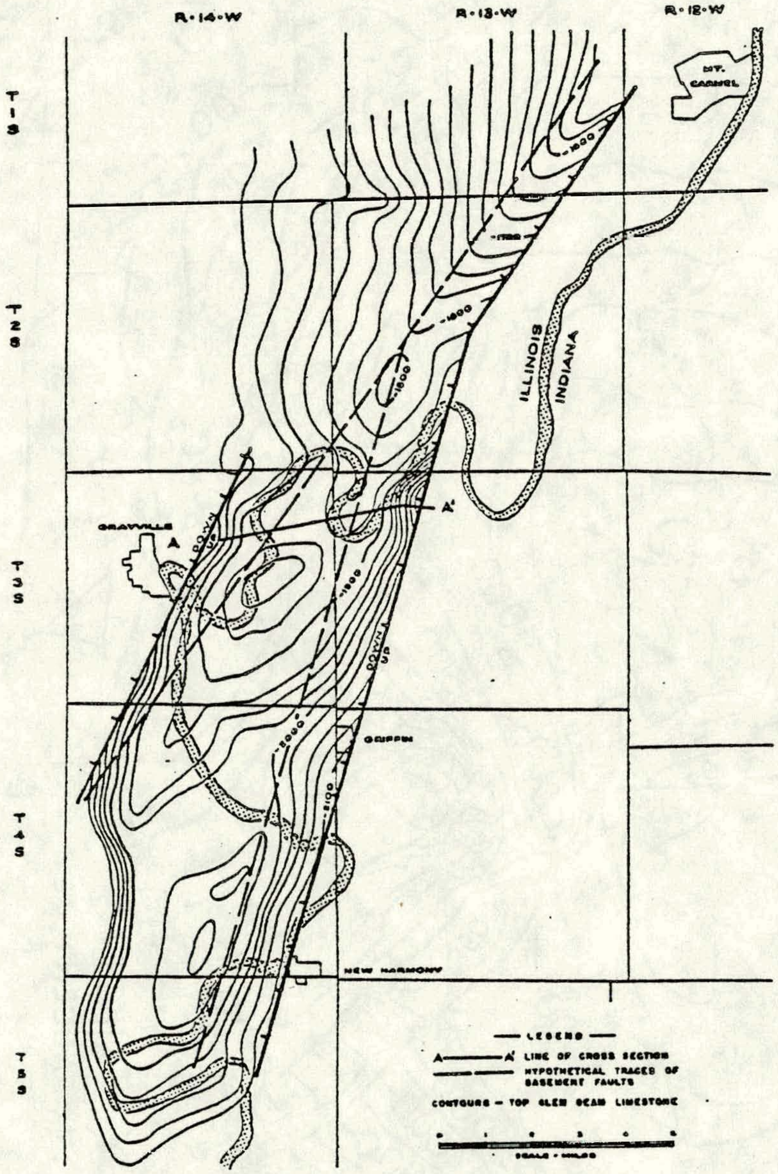

Figure A-45. MT. CARMEL - NEW HARMONY FAULT AND ADJACENT FOLDING, WABASH COUNTY, ILLINOIS - GIBSON COUNTY, INDIANA

(Clark and Reynolds, 1948)

was less than a few thousand feet. The general absence of compressional features suggests any lateral movement was accomplished within a tensional domain involving distension of the fault walls. This interpretation fits well with the Rough Creek data, and it suggests the Moorman Syncline, which is the Upper Paleozoic expression of the Avalonian Rough Creek graben, was driven slightly northwestward during the Ouachita deformation. It has been noted that the Moorman Synclinal block reacted as a unit as suggested by the abrupt change in fault intensity north and south of the bounding fault zones of the syncline.

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APPENDIX A
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Appendix B

GEOMORPHOLOGY OF PORTIONS OF WESTERN KENTUCKY AND ADJACENT AREAS

by

RONALD R. DILAMARTER

B.1 INTRODUCTION

This report provides a geomorphological background of the study area to aid interpreters in evaluating imagery of the present land surface. The report thus complements investigations of the subsurface geology.

Variety in landforms and deposits characterizes the study area. The diversity is the product of several geomorphic processes and agents working over long periods of time under different structural influences and changing climates. Fluvial, glacial, eolian, lacustrine and karstic environments have left their mark on the landscape.

The report is primarily an overview of past geomorphic developments which have led to the variety in the surface configuration and deposits of the present terrain. A geomorphic history and description of the larger study area is presented first followed by brief dicussions of three small subareas (Figure B-1).

B.2 PHYSIOGRAPHIC SETTING

Most of the study area lies within the Interior Low Plateaus Province. West of the Tennessee River is a portion of the Coastal Plain, and at the northwest a small glaciated area is in the Central Lowlands (Thornbury, 1965).

The lithologic and structural pattern of Mississippian and Pennsylvanian rock strata has yielded grossly concentric rings of cuestaform topography at the south and east. Within this general framework extensive flat bottomlands separate hilly uplands, with some upland areas also exhibiting low relief. A simplified physiographic diagram is shown in Figure B-2. Physiographic subdivisions of the study area (Figure B-3) are described briefly in the following subsections.

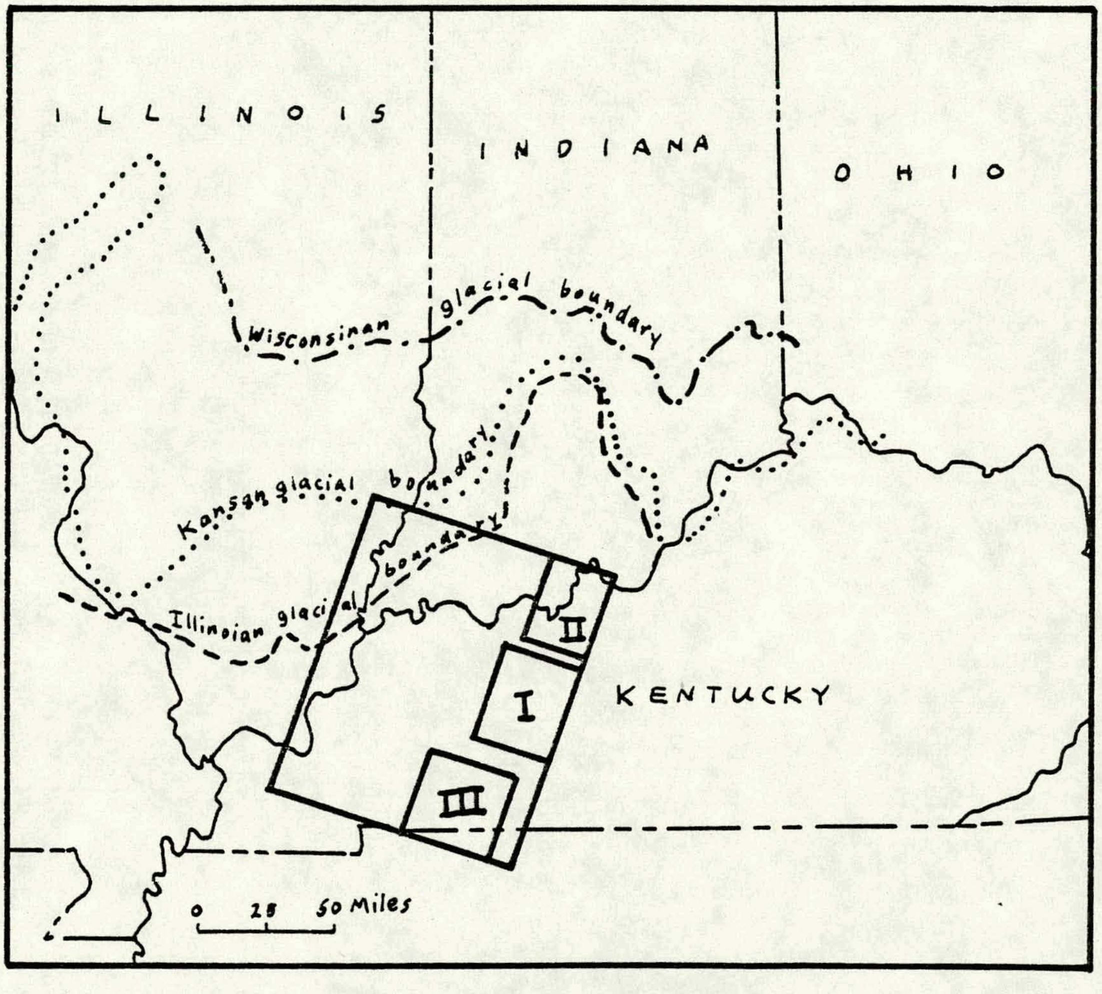
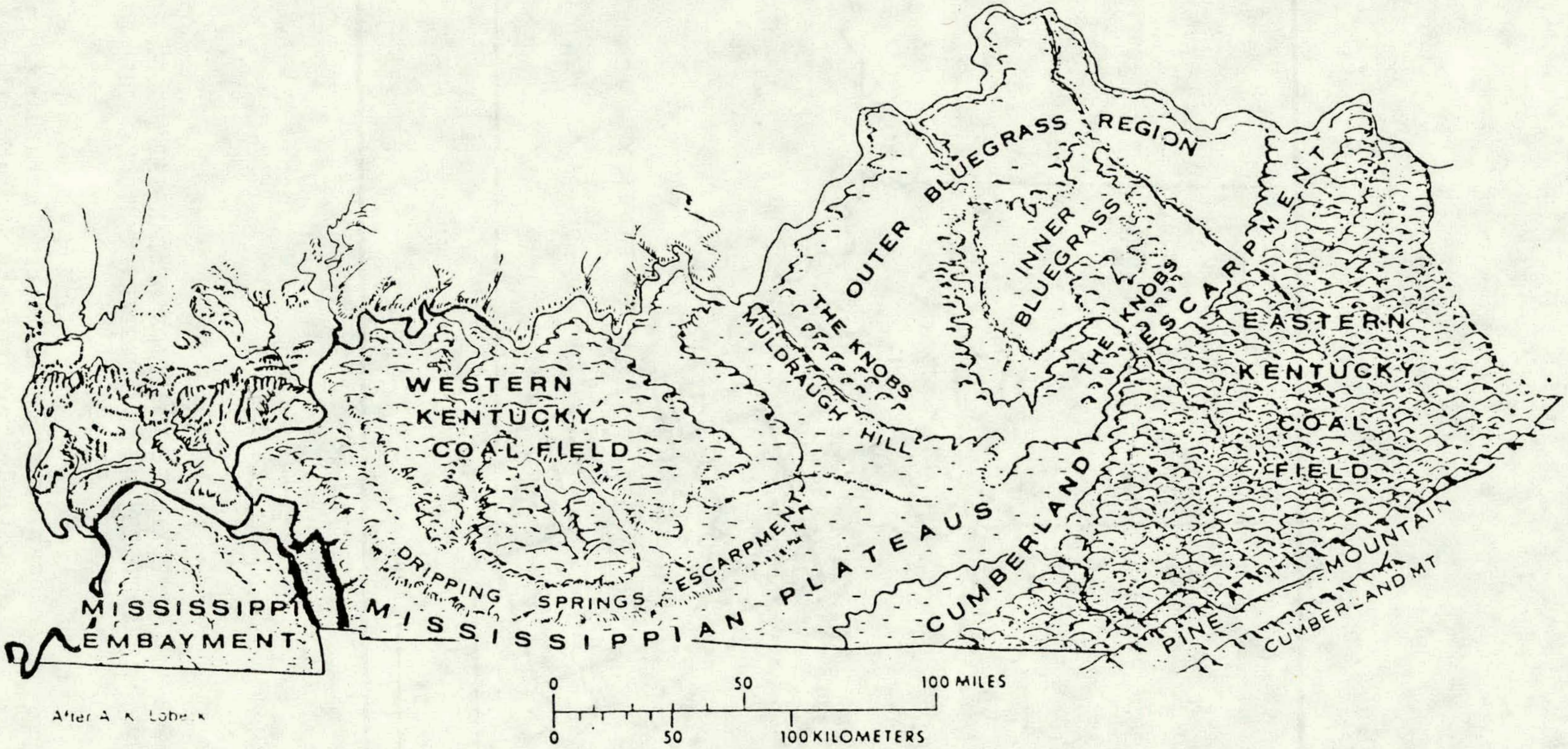


Figure B-1. APPROXIMATE POSITION OF LANDSAT FRAME, PATH 23/ROW 24, WESTERN KENTUCKY AND ADJACENT STATES

(Roman numerals indicate 3 subareas specified for more detailed attention.)



After A. K. Lobeck

Figure B-2. PHYSIOGRAPHIC DIAGRAM OF KENTUCKY AND AREAS OF INDIANA AND ILLINOIS INCLUDED IN STUDY AREA. KENTUCKY PORTION FROM KENTUCKY GEOLOGICAL SURVEY MAP.

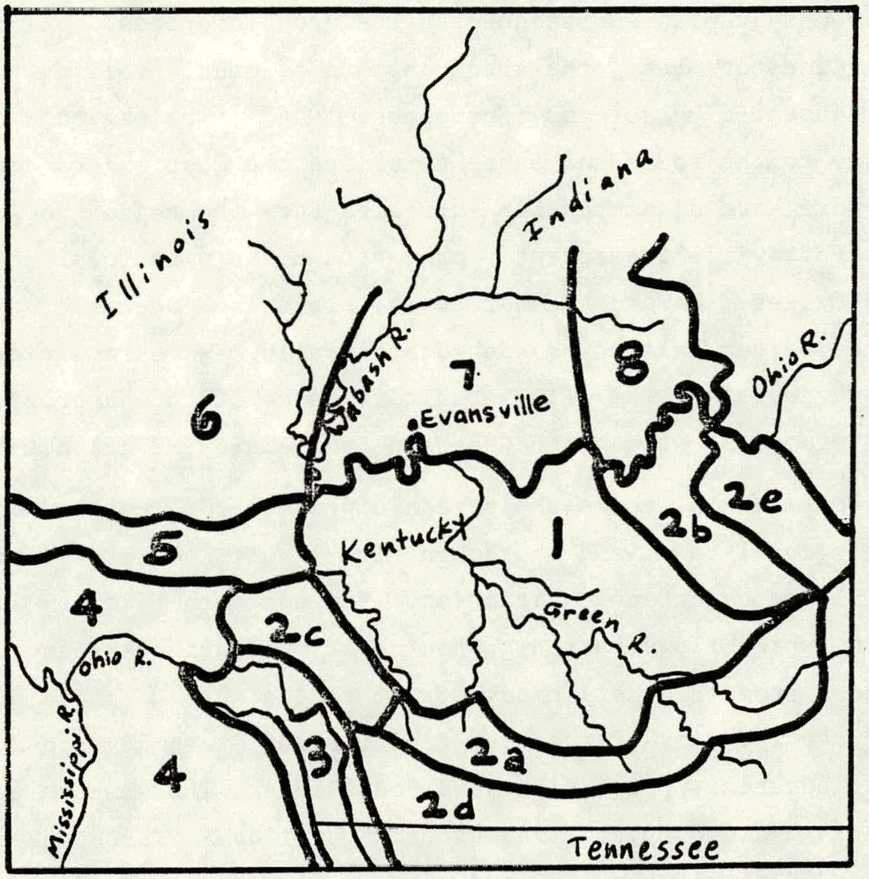


Figure B-3. OUTLINE OF STUDY AREA PHYSIOGRAPHIC REGIONS

1. Western Kentucky Coal Field
2. Mississippian Plateaus
    - 2a. Southern Clifty Area
    - 2b. Northern Clifty Area
    - 2c. Marion Area
    - 2d. Pennyroyal Plain
    - 2e. Elizabethtown Area
3. Land Between the Lakes
4. Coastal Plain (Jackson Purchase in Kentucky)
5. Shawnee Hills
6. Mount Vernon Hill Country
7. Wabash Lowland
8. Crawford Upland

B.2.1 WESTERN KENTUCKY COAL FIELD

This physiographic region is the heart of the study area. Underlain by Pennsylvanian sandstones, shales, conglomerates, coal measures, and some limestone beds, the area consists of gently rolling to hilly uplands dissected by streams (Burroughs, 1924). The region's outer periphery, to the south and east, comprises the most rugged topography. Here streams have dissected the strata to form the ragged and discontinuous "Pottsville escarpment", or cuesta hills with local relief of 200 to 300 feet. Toward the northwest, elevations decrease, deeply alluviated stream valleys broaden dramatically, and upland ridges narrow and become isolated. The alluviated bottoms constitute approximately one quarter of the area of the Western Coal Field (McFarlan, 1943).

In very general terms the strata dip westward, but the Moorman Syncline, local folds and the Rough River Fault Zone provide much structural and topographic variation. The northern boundary is the Ohio River, which flows past high bluffs at the northeast, and lower hills and a broad floodplain downstream to the west. The major stream draining the interior of the coal field is the Green River and its larger tributaries, Rough River and Pond River. The western end of the area is drained by the Tradewater River (locally pronounced "Tredwater"), a tributary of the Ohio.

B.2.2 MISSISSIPPIAN PLATEAUS IN KENTUCKY

Beyond the outer boundary of the Western Coal Field in Kentucky is a semicircular zone, part of the Mississippian Plateaus. Cropping out from beneath the Pennsylvanian margin are Chesterian sandstones and limestones that form dissected plateau areas. Their outer margin is the Dripping Springs (or Chester) Escarpment. Along various portions of its extent, it ranges from a prominent scarp to a hilly zone with many outlying hills. Relief of 100 to 200 feet and more separates the surface of the Chester cuesta from a lower plateau formed on older Mississippian rocks (Meramec and Osage series).

In the southern part of the study area the Chester Plateau is part of the Southern Clifty Area and in the northeast it comprises part of the Northern Clifty Area (Sauer, 1927). In Western Kentucky the Dripping Springs Escarpment and both plateau surfaces are lost in a maize of faults (Thornbury, 1965) in an area (Sauer, 1927) called the Marion Area, the zone between the Tradewater, Ohio, and Cumberland Rivers.

The plateau south of the Dripping Springs Escarpment in the study area is part of the Pennyroyal* Plain (Sauer, 1927). The karstified plain, extending into Tennessee as part of the Highland Rim, has low relief, generally measured in tens of feet, except in areas of deep sinkholes and residual knobs near the escarpment. Numerous shallow sinkholes and **subterranean** streams are characteristic of the area. Some surface streams help drain this part of the Pennyroyal Plain, joining the Red River and the Little River, south- and west-flowing tributaries of the Cumberland.

The Pennyroyal Plain has a stratigraphic and topographic equivalent in the vicinity of the northeast part of the study area. It is the Elizabethtown Area (Sauer, 1927), a karst plain having extensions westward through the Dripping Springs Escarpment into the Northern Clifty area.

B.2.3 LAND BETWEEN THE LAKES

A dissected upland separates Kentucky Lake (Tennessee River) and Lake Barkley (Cumberland River). This area, which has Cretaceous exposures, and a narrow zone to the east and west, is an area of transition between the Mississippian Plateaus and the Coastal Plain (McFarlan, 1943).

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*Also termed "pennyrile".

B.2.4 COASTAL PLAIN

West of Kentucky Lake is the head of the Mississippi Embayment, known as the Jackson Purchase in Kentucky, with plains and low hill topography broken by several prominent valley systems (Davis, 1923). The Coastal Plain extends northward across the Ohio River into Illinois as far as the southern edge of the Shawnee Hills, where eroded Cretaceous and Tertiary sediments overlap Paleozoic rocks (Leighton, Ekblaw, and Horberg, 1948).

B.2.5 SHAWNEE HILLS

In Illinois, north of the Coastal Plain, is a complex dissected upland, underlain by Mississippian and Pennsylvanian strata of varied lithology which dip toward the Illinois Basin. Faulting and folding have added structural complexity to the rugged hill land (Leighton, Ekblaw, and Horberg, 1948; Thornbury, 1965).

B.2.6 MOUNT VERNON HILL COUNTRY

Located north of the Shawnee Hills in Illinois is the Mount Vernon hill country, a portion of which is in the study area, bounded on the east by the Wabash River. The area is a surface of low relief formed on Pennsylvanian strata and thinly mantled with glacial till and loess (Leighton, Ekblaw and Horberg, 1948).

B.2.7 WABASH LOWLAND

East of the Wabash River, north of the Ohio, is the Wabash Lowland (Malott, 1922). It is a broad plains area of low relief with some hills north and east of Evansville, Indiana. The bedrock is Pennsylvanian, a northward extension of the Western Kentucky coal field strata. Lacustrine deposits, outwash sands, loess, and dunes are present within various parts of the Wabash Lowland.

B.2.3 CRAWFORD UPLAND

Located east of the Wabash Lowland is the Crawford Upland, the greatly dissected dipslope of the Chester cuesta. The upland is an extension into Indiana of that part of the Kentucky Mississippian Plateaus called the Northern Clifty Area by Sauer (1927).

Outside the study area to the east is the outer margin of the Crawford Upland, the Chester Escarpment, which trends southward into Kentucky as the Dripping Springs Escarpment. In the Crawford Upland sandstones and shales overlie limestones which, still farther east, crop out to form the karstified Mitchell Plain, the Indiana equivalent of Kentucky's Elizabethtown Area.

B.3 GEOMORPHIC HISTORY

Reconstruction of the geomorphic history of the study area, especially as compiled from older literature sources, reflects early models of long-term landscape evolution. Such models may not be correct in all their assumptions, but nevertheless permit a reasonably satisfactory account of the origin and development of terrain and deposits.

B.3.1 MESOZOIC ERA

Within the Interior Low Plateaus province evidence is lacking to point to a clear sequence of geomorphic events during the long interval between Pennsylvanian and later Tertiary times. It is generally believed that subaerial erosion and deposition have dominated the region since the end of late Paleozoic sedimentation. Cretaceous sediments, essentially nonmarine, outcrop in the land between the lakes. Westward toward the Mississippi River they are overlain by younger nonmarine deposits (McFarlan, 1943). By the end of the Mesozoic Era, ancestral versions of major modern rivers drained toward the head of the Mississippi Embayment. Gross patterns of today's landscape were being developed, although they were to be modified by later events.

B.3.2 TERTIARY PERIOD

Regional crustal stability in the Interior Low Plateaus is thought to have permitted the formation of at least one widespread surface of low relief during the Tertiary Period. Known as the Lexington Plain (Campbell, 1989, cited by Thornbury, 1965) in the northern part of the province, and the Highland Rim (Hayes, 1899, cited by Thornbury, 1965) in the southern area, the erosion surface has been correlated with uplands in Indiana (Malott, 1922) and possibly with old surface relics in the Shawnee Hills of Southern Illinois (Fenneman, 1938; Horberg, 1950). Extensive in some portions of the Interior Low Plateaus, the erosion surface has been greatly dissected where streams have been very active on weaker rocks. The ancient surface is inferred in some portions only by the presence of scattered accordant summits. Regional elevations range from more than 1000 feet in the Bluegrass Region in Central Kentucky to about 560 feet in Henderson County in Western Kentucky (Thornbury, 1965).

The age of the erosion surface ("peneplain") had been assigned by several early investigators to various portions of the Tertiary, but a widely accepted present view is that the plain was formed during the Miocene or early Pliocene Epoch (Thornbury, 1965). The surface may be correlative with the Harrisburg surface of the Appalachians, and other erosion surfaces recognized in the eastern United States (Table B-1).

Closely associated with the development and subsequent modification of the Lexington/Highland Rim surface are the "Lafayette Gravels" (Malott, 1922). Known also by other local and regional names,

Table B-1. CORRELATION CHART OF LATE CENOZOIC EROSION SURFACES IN EASTERN UNITED STATES

	AGE TO BASE (M.Y.)	INTERIOR LOW PLATEAUS	APPALACHIANS	INTERIOR HIGHLANDS	CENTRAL LOWLANDS
Pleistocene	2	Deep Stage	Valley Cycle	Valley Cycle Post-Osage Strath	Deep Stage Havanna Strath
Pliocene	7	Parker	Somerville	Osage Strath	Central Illinois
Miocene	26	Lexington/ Highland Rim	Harrisburg	Hot Springs/ Ozark	Lancaster/ Calhoun

Adapted from Melhorn and Edgar, in Melhorn and Flemal, 1975, p. 250.

the gravels consist primarily of insoluble residue such as chert, quartz and quartzite pebbles, and cobbles. They are known to include geodes, geodized fossils, sand, silt, and clay, and are commonly stained and cemented by iron and manganese oxides (Thornbury, 1965). The distinctive "bronzed" cherty gravels are called the "Luce Gravels" in Owensboro, Kentucky (L. L. Ray, 1965). Long controversial, the gravels are generally thought to be derived from Tertiary weathering, primarily of Mississippian and Pennsylvanian rocks. As a weathering residue they were probably widespread on the Lexington/Highland Rim erosion surface.

Streams flowing across the erosion surface apparently were rejuvenated by late Tertiary uplift, and dissection created many deep gorges. Intermittent stability, however, is thought to have alternated with uplift. It is likely that karstification of soluble rocks, including cavern formation, proceeded where favorable conditions existed. During stable times broad bottomlands were created by lateral stream migration. The old bottomland remnants are straths assigned to the Parker subcycle (Table B-1). Much of the residual regolith was stripped from the Lexington Plain and concentrated in the developing bottomlands. Thick deposits of the Lafayette Gravels in Western Kentucky are thought to be fluvial in origin (Theis, 1922, cited in Ray, 1965; Malott, 1922; Leverett, 1929; Potter, 1955), and rest on stream-cut bedrock benches. Potter (1955) concluded that the gravels near the head of the Mississippi Embayment are remnants of coalescing alluvial fans deposited by the ancestors of the region's major streams--the Tennessee, Cumberland, Ohio and Mississippi Rivers.

Following the time of Parker Strath formation, possibly in the Quaternary Period, further uplift and stream downcutting occurred regionally. Major rivers deepened their valleys on the order of 200 feet or more, in a phase called the Deep Stage (Ver Steeg, 1926). In some parts of the Interior Low Plateaus there is evidence to suggest that valley deepening was interrupted for a time, when valley broadening occurred. Extensive lowlands were formed in weak strata, for example, the Scottsburg Lowland of Indiana (Malott, 1922). This surface may correlate with the early Pleistocene Havanna Strath of Southern Illinois (Thornbury, 1965). In the lower Ohio River region, a bedrock bench buried by younger deposits was noted by Ray (1965) in the Owensboro, Kentucky, area, and by Theis in 1922 (cited by Ray, 1965) at Henderson, Kentucky.

By the time glaciation was approaching, the ancestral Ohio, Wabash, Green, Cumberland, Tennessee, and Mississippi Rivers had separated upland remnants of the weathered Tertiary plain. Lafayette gravel-capped rock benches flanked the deep inner valleys in places where conditions were conducive to their preservation. Although major streams today remain relatively close to their early positions, some reaches have changed location by many miles. The lower ends of the Ohio, Cumberland, and Tennessee Rivers, for instance, now have different courses. The Ohio River formerly crossed Southern Illinois through the Cache Lowland; possible causes of relatively recent channel abandonment in relation to the Tennessee and Cumberland Rivers are reviewed in Thornbury (1965). Lesser tributary streams are thought to have exploited weak rocks and fault zones as late Tertiary dissection proceeded. Numerous cases of stream diversion ("piracy") are noted for tributaries of the Tradewater and lower Green Rivers in Webster County, Kentucky (Glenn, 1922).

The age of deep valley cutting may be best assigned to the Plio-Pleistocene time transition. Deep channels were later filled with deposits that included thick sequences of glacial outwash. Valley incision was thus pre-glacial, but not necessarily pre-Quaternary, as global criteria for the world's Plio-Pleistocene time boundary need not depend upon arrival of continental glaciers at a particular region. Regardless of age assignment, deep valleys were characteristic of major drainage lines of the study area just prior to midwestern glaciation.

B.3.3 QUATERNARY PERIOD (PLEISTOCENE AND HOLOCENE EPOCHS)

1. Nebraskan Stage. The extent of the Nebraskan glacier is unknown and no deposits assignable to the Nebraskan Stage are known in Indiana (Wayne and Zumberge, 1965). It has been postulated that Nebraskan ice contributed valley train fills in the deep valley of the Ohio (Ray, 1965). To the north and east, Nebraskan ice may have been responsible for the diversion of parts of the ancient Teays River system into the Ohio Basin (Ray, 1965). The ancient Ohio River previously was a much smaller system. Different views of its extent and evolution are summarized by Thornbury (1965). In the study area the river's course was generally not far from its present location, except for the abandoned Cache Lowland. At Owensboro, Kentucky, for example, a bedrock contour map (Ray, 1965) shows most of the ancient course within a mile or two of the present channel.

2. Kansan Stage. Although Kansan drift is mapped in portions of southwestern Indiana and southern Illinois (Flint, et al, 1959), its occurrence is outside the study area a few miles to the north. Some further valley deepening may have occurred during the Kansan Stage, but a major net effect in the study area was probably alluviation. Kansan outwash is thought to have contributed to the lowest fills that now occupy the deep, buried bottoms of the preglacial valleys (Wayne and Zumberge, 1965). Additionally some loess deposition may have occurred (Ray, 1965).

3. Illinoian Stage. An early substage of the Illinoian resulted in till deposition in portions of the study area. North of the Shawnee Hills in Illinois, and in extreme southwestern Indiana, Illinoian till is mapped (Flint, et al, 1959). The ice blocked westward flowing streams in Indiana, creating extensive ponding and glaciolacustrine

sedimentation (Thornbury, 1936; Wayne and Zumberge, 1965). Most of the lake plains were later subject to flooding and sedimentation from Wisconsinan meltwater draining into the area from ice in central Indiana. In Kentucky, tributaries to the Ohio River, such as Green River, perhaps were ponded because of aggradation of the Ohio channel, although the major ponding seems to be attributable to the Wisconsinan Stage. Loess deposits referable to the Illinoian (Loveland Loess) have been noted along the banks of the Ohio River (Leighton and Willman, 1950; Ray, 1957).

4. Wisconsinan Stage. The study area was not glaciated during Wisconsinan time, but was affected by glacial outwash and loess deposition. The Ohio River aggraded its deep bedrock bed, creating levee-like dams at the mouths of tributaries such as Green River in Kentucky and the Wabash along the Indiana-Illinois boundary (Thornbury, 1965). Various flat bottomlands in Southern Indiana, Illinois, and Western Kentucky (Figure B-4) were long ago identified as old lake plains formed in ponded backwaters of tributaries whose mouths were dammed by outwash in the Wabash and Ohio Rivers (Shaw, 1915, cited by Thornbury, 1965). Projecting above the deeply alluviated valley systems in Indiana and Kentucky are partially buried bedrock hills called "island hills" by Shaw, and "hills of circumalluviation" by Fidlar (1948, cited by Thornbury, 1965). The lacustrine deposits are mainly heavy, blocky clays or silts. The direct cause of alluviation is thought to be mostly glaciofluvial action, but other possible contributing factors, including regional depression, are reviewed by Thornbury (1965).

Wisconsin loess mantles most of the study area landscape, and is thickest near riverine sources, thinning away from bottomlands. Windblown silt and reworked colluvium derived from it ranges generally from one to ten meters in thickness (Ray, 1965; Willman and Frye, 1970). The loess mantle in places is composed of two units of Wisconsinan age, one of Illinoian, and in places possibly Kansan (Ray, 1965).

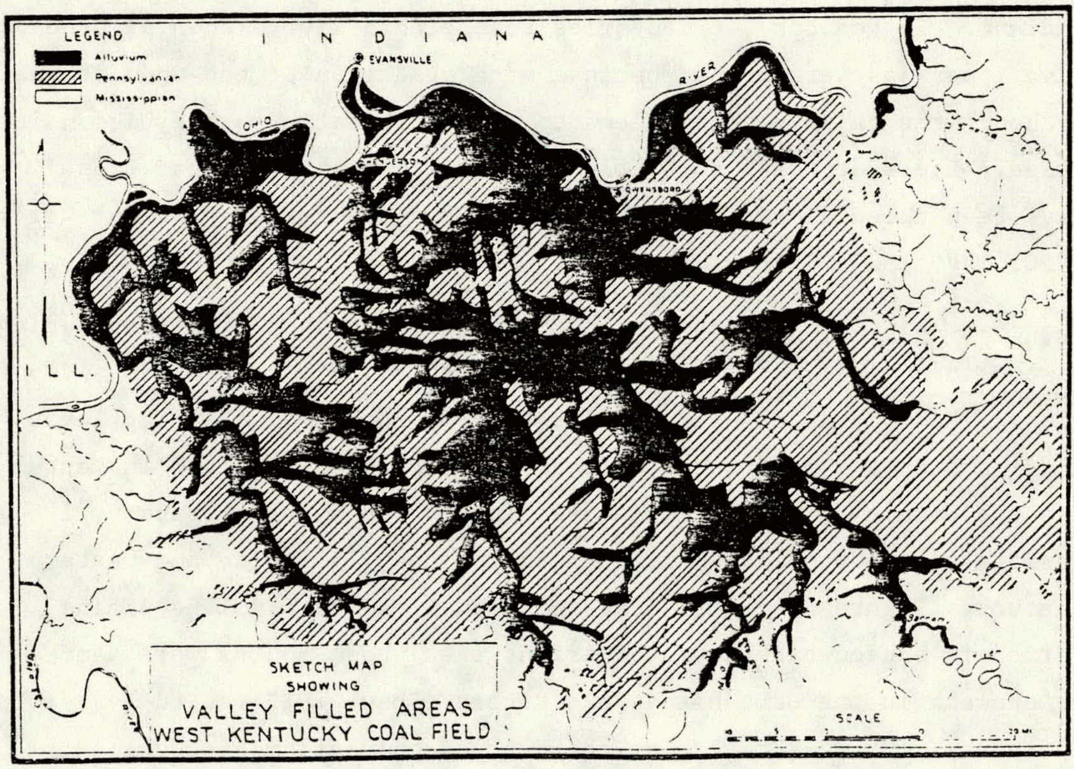

Figure B-4. ALLUVIATED AREAS IN THE WESTERN KENTUCKY COAL FIELD

(Adapted from Jillson, 1928, p 44)

5. Post-Glacial. Since deglaciation of the upper Midwest about 11,000 years B.P., the study area has been subject to erosional processes operating under Holocene climatic conditions more or less similar to those of the present. Major streams have reworked the upper levels of their thick fills, degrading their beds only slight (Ray, 1965). Climatic fluctuations and land use changes accompanying dam construction, mining, agriculture, and urban settlement of the region have contributed to surface modifications that are relatively minor in the context of the topographic texture of the entire study area.

B.4 GEOMORPHOLOGY OF THREE SPECIFIC ZONES

Within the wider study area, three smaller zones were specified for further discussion. Zones I, II, and III are in the eastern sector of the study area (Figure B-1) and are at or near the updip end of the Pennsylvanian strata of the Western Kentucky Coal Field. Zone I is mostly within the Coal Field; Zone II is centered on the Chesterian Mississippian Plateau strata; and Zone III is almost entirely in the Chesterian (north) and older Mississippian (south) plateau area.

B.4.1 ZONE I

Except for the northeast and southeast corners where Mississippian rocks crop out, this zone (Figure B-5) is within the Western Kentucky Coal Field of Pennsylvanian strata. Evidence of strip mining abounds in Zone I. Border areas of the Coal Field are generally rugged, in places having 200 and 300 feet of local relief, but westward toward the interior 150 feet or less is common (McGrain and Curren, 1978). Some of the ridges created by heavy stream dissection are relatively broad and level, but most are narrow and irregular in shape. Smaller tributary valleys tend to be V-shaped, but larger streams have entrenched steep-walled gorges with flat bottomlands. Extensive low, poorly drained flats are present in the western part of Zone I, the result of thick valley

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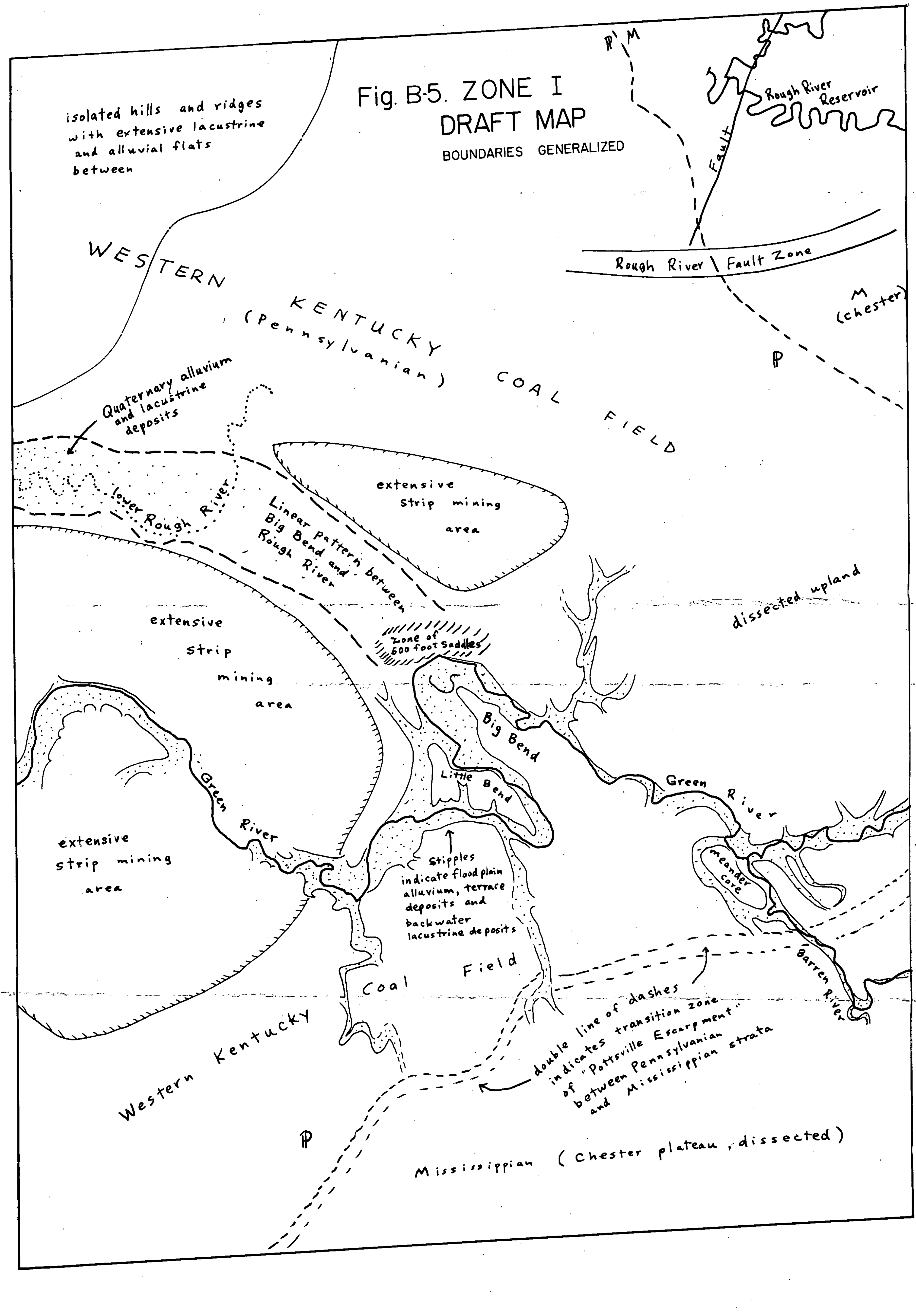

Fig. B-5. ZONE I DRAFT MAP

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fills. The level of Pleistocene ponding and lacustrine and alluvial sedimentation was approximately to the elevation of the modern floodplain. In various other parts of the Coal Field the maximum thickness of valley sediments approaches 200 feet (Jillson, 1928), although in Zone I the fills are thinner. They are part of deposits up to about 420 feet in elevation made in what has been called Green Lake by Shaw (1911, cited by Leverett, 1929).

Prominent faulting in the north (Rough Creek Fault Zone) has affected the topography by accenting differential weathering and erosion. To the south, the Green River fault system follows a trend more or less parallel to the Rough Creek Zone. Between the two fault zones is the Green River, master stream of the Coal Field.

Green River follows a rather sinuous route in a generally northwestward direction. In the central part of Zone I, however, the Green River doubles back to the southeast at Cromwell before resuming its path to the Ohio River. This part of the river is known locally as Big Bend. The narrow neck between parallel reaches is capped by loess-mantled Tertiary gravel at elevations ranging generally between 450 and 500 feet (Gildersleeve, 1975). The floodplain is approximately 410 feet A.M.S.L. North of Big Bend is a broad band of interconnected small valleys which forms a rather linear pattern of mostly lowlands trending northwest. It merges with the broad flat of the Rough River, joining the Green River a few miles west at Livermore. The appearance suggests that Green River formerly continued north and west from the Big Bend, but abandoned its course during entrenchment, perhaps utilizing nearby tributary valleys as its new channel. A zone of low saddles, only about 100 feet above the floodplain, separates the river from its apparent former valley. The saddles are at about the same elevation as the Tertiary gravels capping the Big Bend neck.

The northwestward trend, for many miles, of the Green River and its possibly abandoned course is but an extension of the Barren River's trend. In the southeastern part of Zone I, the Green flows from the east to receive Barren River, which has been flowing northwestward from the Pennyroyal Plain. Older literature generally presents the northwestward trend of Western Kentucky master streams as inherited from the Tertiary regional consequent slope on beds tilted toward the Illinois Basin.

B.4.2 ZONE II

Rolling topography is typical of much of Zone II (Figure B-6) which is primarily the northern section of the Chester Mississippian plateau (Northern Clifty Area). Sandstone beds dominate, more resistant to erosion than the limestones exposed in small areas in the northeastern portion. Thus a tableland appearance is given to parts of the area. Dissection and local relief increase westward into an area of Pennsylvanian strata, northward to the Ohio River, and south to the Rough River. Where erosion has breached the sandstones to expose underlying limestones, cliffs are prominent, with minor benches appearing to result from interbedded shales and limestones (Sauer, 1927). Sinkholes resulting from subjacent karst are present. The drainage system of Sinking Creek in Breckenridge County encompasses in part of its course broad limestone dolines flanked by sandstone uplands. Its mouth is at the Ohio River, but its headwaters extend eastward into the Elizabethtown area, the northern equivalent of the Pennyroyal Plain (Sauer, 1927). Zone II thus contains finger-like extensions of the karst plain. The plain is separated from the dissected tableland by the Dripping Springs Escarpment, and relief of more than 200 feet (McGrain and currens, 1978).

North of the Ohio River in Indiana is a highly dissected extension of the Mississippian plateau, the Crawford Upland (Malott, 1922). It is part of the Hoosier National Forest.

Fig. B-6. ZONE II DRAFT MAP

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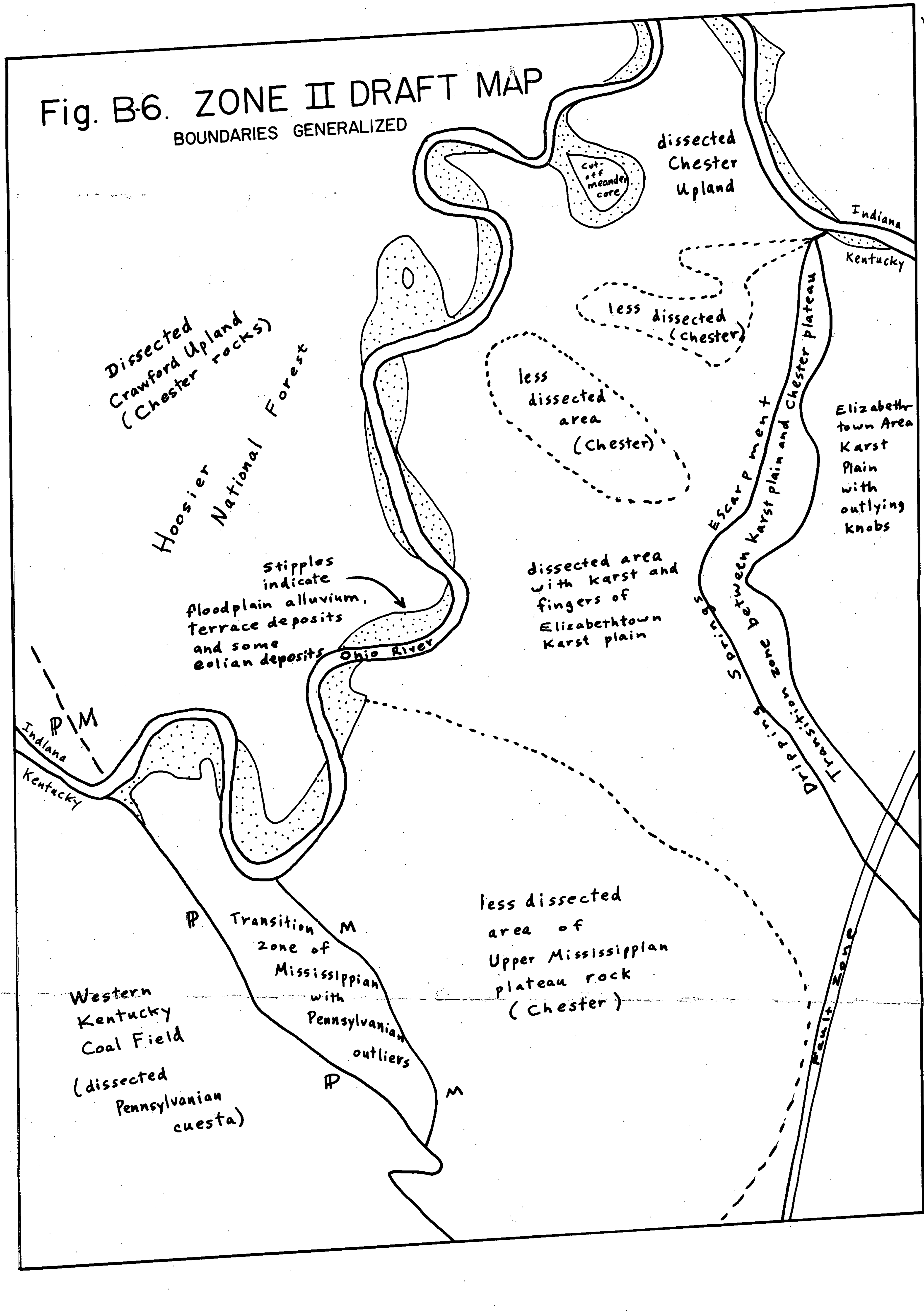

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B.4.3 ZONE III

Located at the southern portion of the wider study area, Zone III (Figure B-7) is divisible into several generally east-west belts strongly influenced by lithologic and structural factors. With an overall northward dip toward the axis of the Moorman Syncline, successively older truncated rocks are exposed in a southerly direction.

At the northern part of Zone III is a small area of Pennsylvanian Coal Field strata, locally ending at fault lines separating them from Mississippian rock. The Pennsylvanian strata constitute the irregular edge of a south-facing dissected cuesta ("Pottsville Escarpment") with generally narrow ridgetops, and local relief up to about 200 feet (McGrain and Currents, 1978).

South of the Pennsylvanian rock, the Mississippian Chester rocks crop out, forming another dissected plateau. Extensive smooth uplands underlain by sandstone are present, separated by deep gorges. Locally karstification has occurred in the underlying limestones, especially at the southern margin. This plateau is a less karstified continuation of the "Mammoth Cave Plateau", beneath which the Mammoth-Flint Ridge Cave system developed farther to the east, in south central Kentucky. The plateau surface is separated from a karst plain to the south by a scarp and outliers constituting the south-facing Dripping Springs Escarpment.

The Pennyroyal Plain is a gently rolling plain with shallow sinkholes called basin karst by Dicken (1935). Nearest the Dripping Springs Escarpment the karst plain is formed mostly on Ste. Genevieve limestone, and farther south on St. Louis strata. Sinking streams, springs, and relatively small caverns are present. Lithologic differences, especially the presence of chert beds, give local variation to the sytle of karstification. Several feet of red earth mantle the surface of the upland swells and sinkhole bottoms. Although

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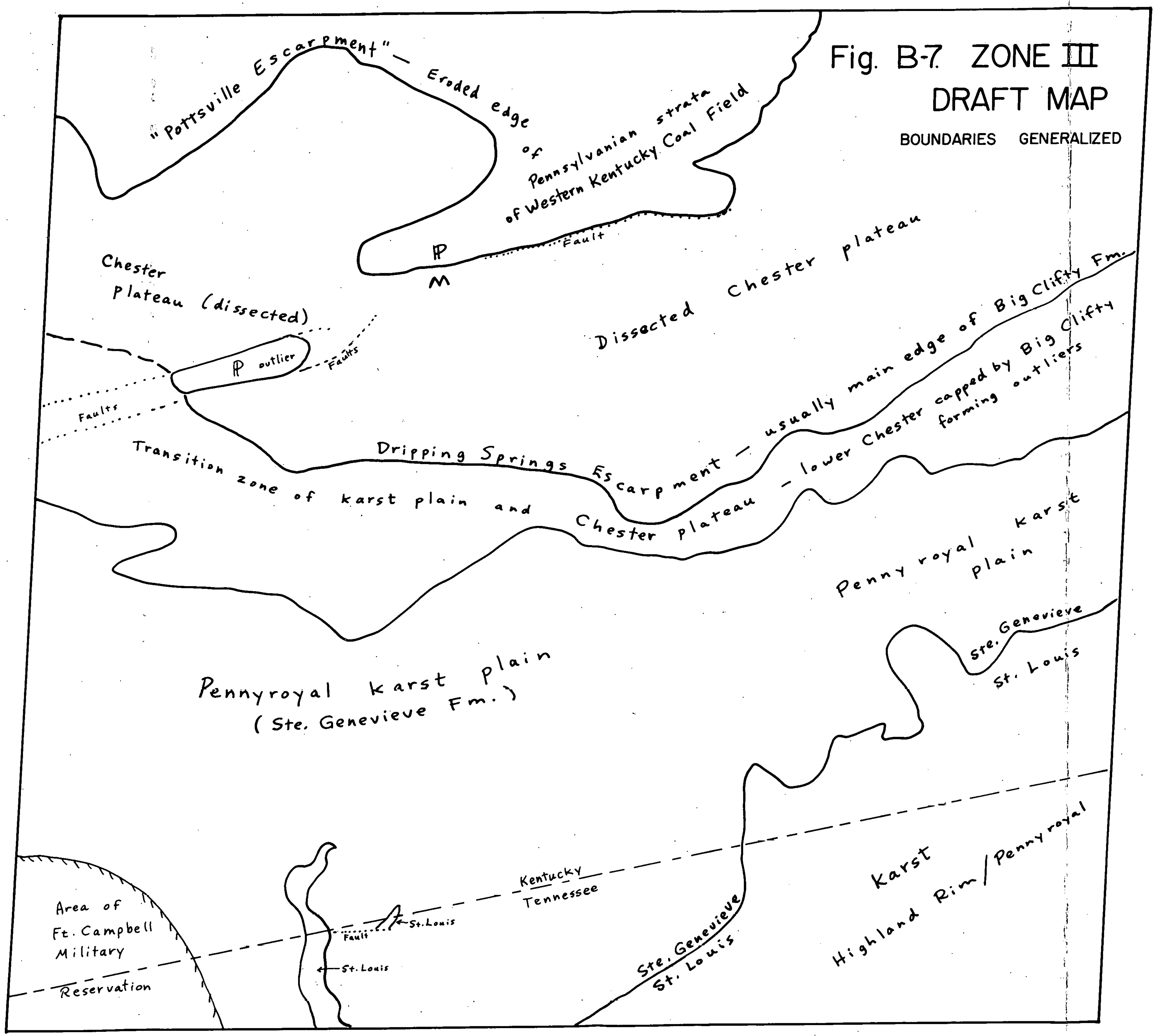

Fig. B-7 ZONE III DRAFT MAP

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usually referred to as residuum, the red silty clay has likely undergone great amounts of reworking to form colluvium and alluvium, and mixed with loess.

Several small surface streams, fed in part by emerging subterrainean waters, aid in drainage. Most head in the Chester plateau area and drain southward in entrenched valleys to the Cumberland River. However, some portions of the karst plain serve as headwaters for streams draining northward downdip through the Dripping Springs and Pottsville Escarpments to enter the basin of Green River in the Coal Field. A small part of Zone III occurs in Tennessee, where the plain is considered part of the Highland Rim.

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APPENDIX B
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