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Geologic Analysis of Priority Basins for Exploration and Drilling

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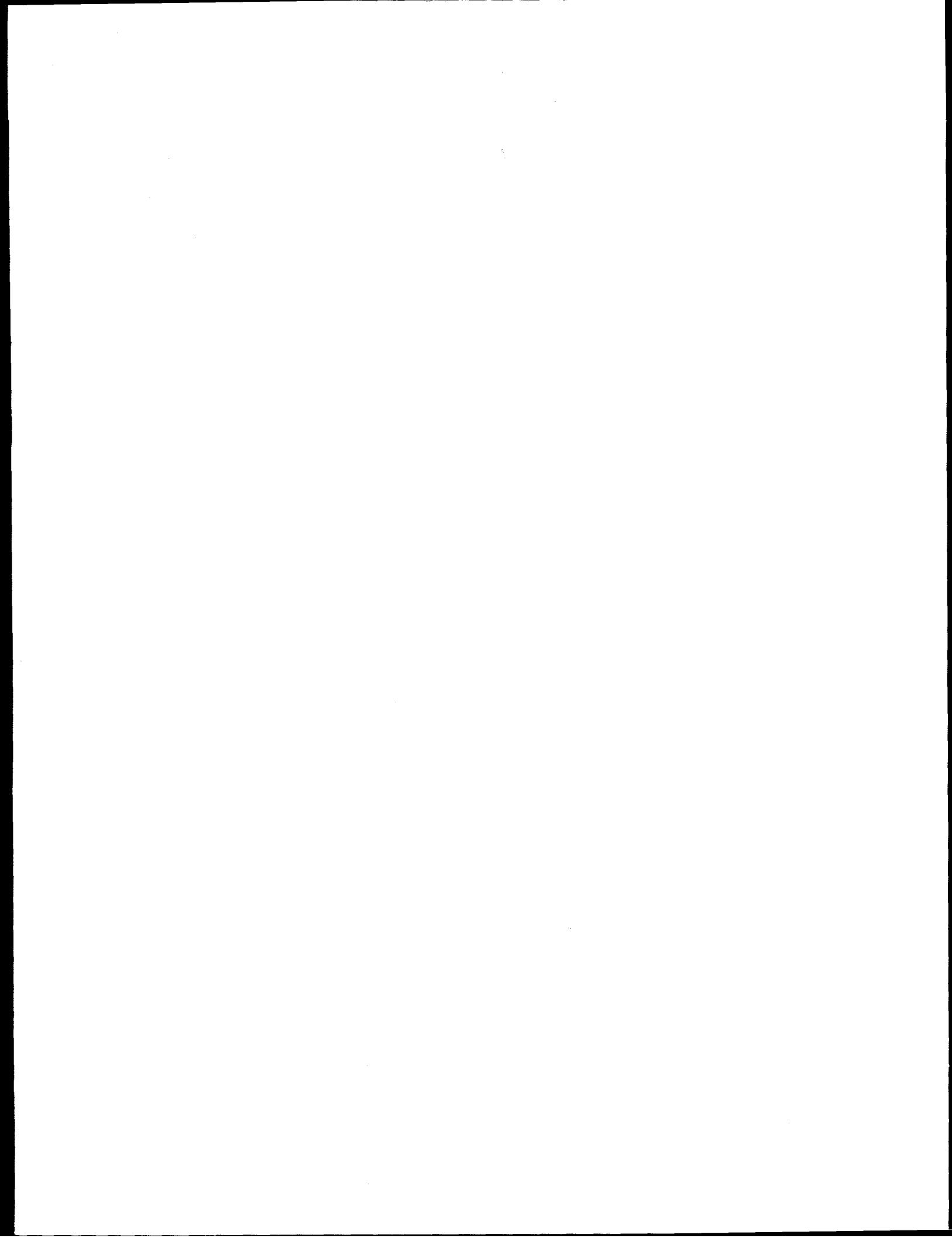
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ABSTRACT

There has been a substantial decline in both exploratory drilling and seismic field crew activity in the United States over the last 10 years, due primarily to the declining price of oil. To reverse this trend and to preserve the entrepreneurial independent operator, the U.S. DOE is attempting to encourage hydrocarbon exploration activities in some of the underexploited regions of the United States. This goal is being accomplished by conducting broad regional reviews of potentially prospective areas within the lower 48 states.

Data are being collected on selected areas, and studies are being done on a regional scale generally unavailable to the smaller independent. The results of this work will be made available to the public to encourage the undertaking of operations in areas which have been overlooked until this project.

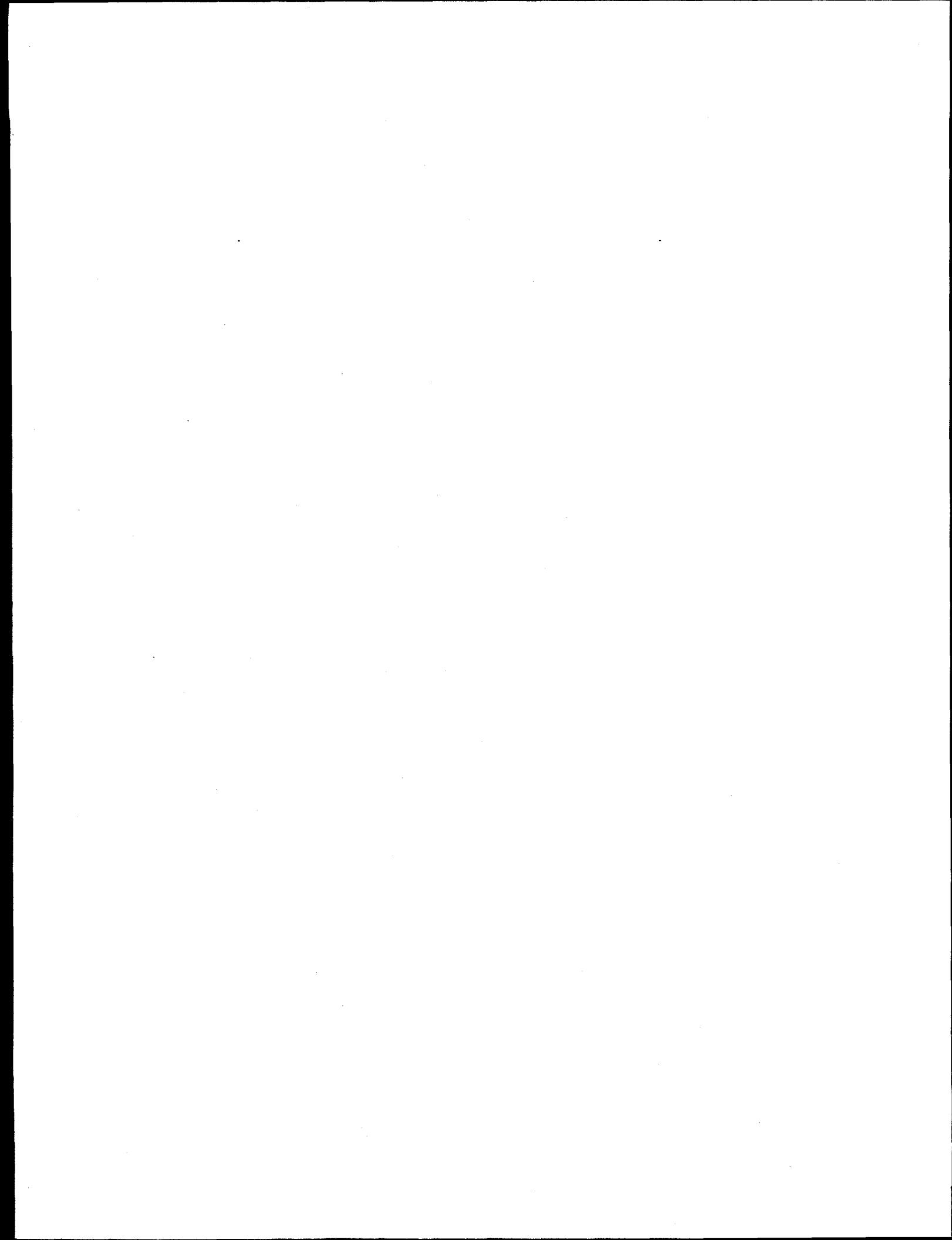
Fifteen criteria have been developed for the selection of study areas. Eight regions have been identified where regional geologic analyses will be performed. This report discusses preliminary findings concerning the geology, early tectonic history, structure and potential unconventional source rocks for the Black Mesa basin and South Central states region, the two highest priority study areas.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

The procedures used to select the basins that the Exploration and Drilling (E&D) group will study have been discussed in the accompanying report: *Selection and Prioritization of Basins for Study in the Exploration and Drilling Program*. This report will discuss some of the preliminary observations and conclusions concerning the study basins, including conventional and unconventional source beds, the deposition of potential reservoir units, trapping mechanisms, and possible migration paths in the subject basins.



2.0 GEOLOGIC ANALYSIS

The preliminary study identified eight regions that will be investigated during this project. The two top priority areas for study are the Black Mesa basin and a group of basins and associated structures in the southern Mid-Continent area. These regions are described in the following sections.

2.1 Black Mesa Basin

The Black Mesa basin is located near the Four Corners, in the northeast corner of Arizona. Figure 1 shows the tectonic setting of the basin and the surrounding uplifts and structural features.

There is well-established hydrocarbon production near the Black Mesa area in both the Four Corners area and from the Paradox basin, just across the Monument Valley upwarp from the Black Mesa. These areas predominantly produce oil, although some natural gas is known as well. The settings and internal structures of the Paradox and Black Mesa features are quite similar, and the presence of oil nearby to the north augurs well for prospects in the Black Mesa. The known oil shows in the basin also are encouraging.

The Black Mesa basin would have been explored in decades past if there had been clear title to the land and to potential oil and gas leases. A land dispute between the Navajo and Hopi tribes prevented exploration activity in the area for decades. Oil and natural gas exploration and drilling companies could not afford to spend money on prospecting or locating a potential resource with little or no chance of recovery or distribution. Seismic companies did not want to finance or promote extensive surveys on lands that could not be leased, in areas where they could not get permits for seismic shooting, etc.

The tribal disputes have recently been settled, making it possible now for seismic companies to get access to the land and for independent operators to obtain leases and to initiate exploration activities and drilling in the Black Mesa.

The Black Mesa basin offers a rare opportunity for the E&D group. Here it will be possible to make a large impact quickly in a true exploratory effort. Most basins in the United States have been crossed by several to many regional seismic lines and have a number of deep wells penetrating the sedimentary section. In the Black Mesa, there has been minimal drilling, so many details of the stratigraphy remain to be identified. The gross sedimentary section is known, but many subtle stratigraphic traps, some quite large, may be hidden in the geologic column in this basin.

Figure 2 shows the larger structural features within the basin. As can be seen, there are a number of large anticlines cutting across the region. Much work needs to be done to determine the timing in the formation of these structures and the migration of hydrocarbons in the area. Some testing has taken place on the crests of some of the structures, with signs of hydrocarbons but no substantial production. It may be that large traps exist in sedimentary pinchouts on the flanks of these features. Faulting and fracture patterns need to be identified and studied for potential clues to migration paths and timing and zones of sedimentary porosity.

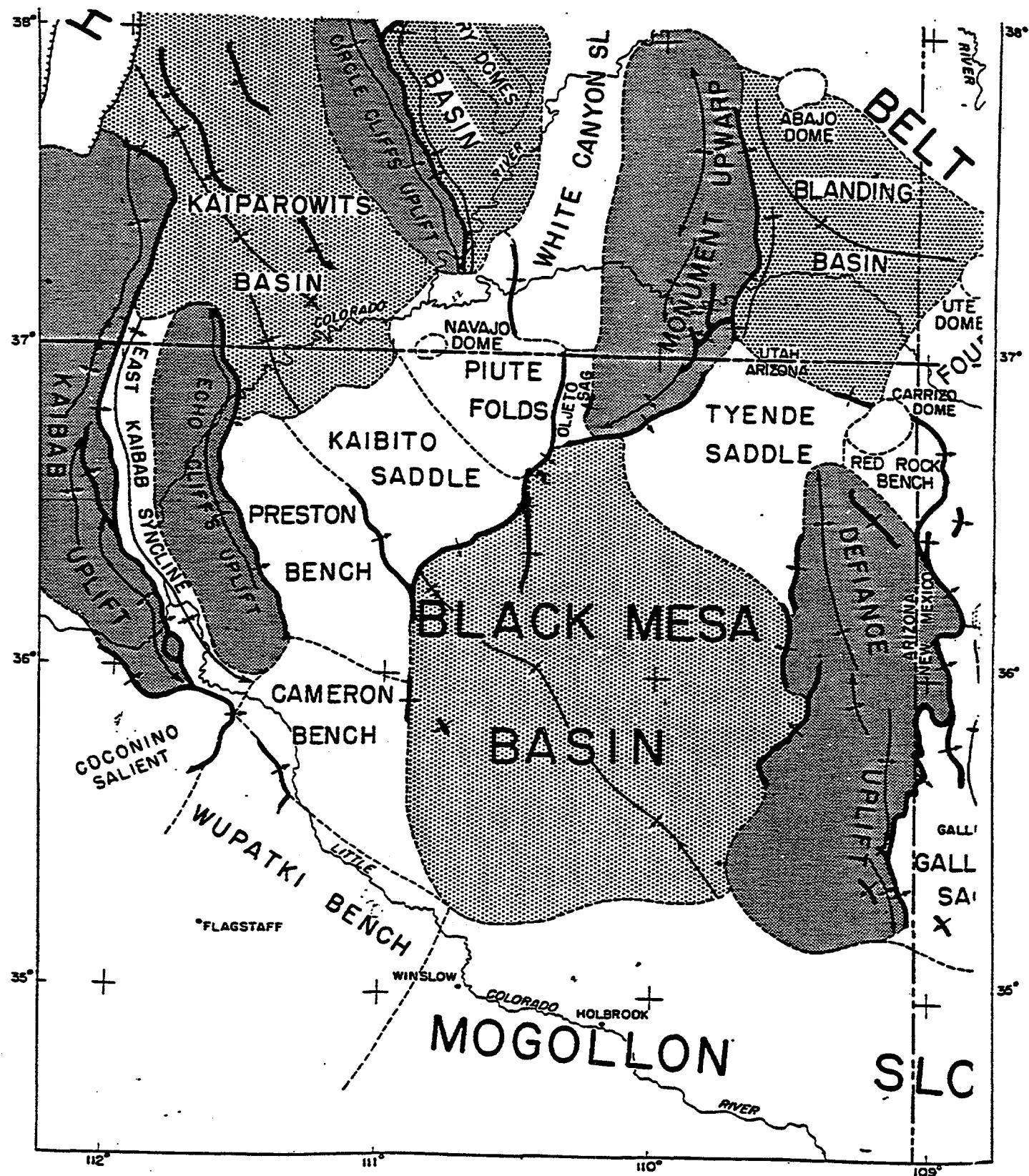


Figure 1 Index Map to Tectonic Divisions in the Black Mesa Basin Region.

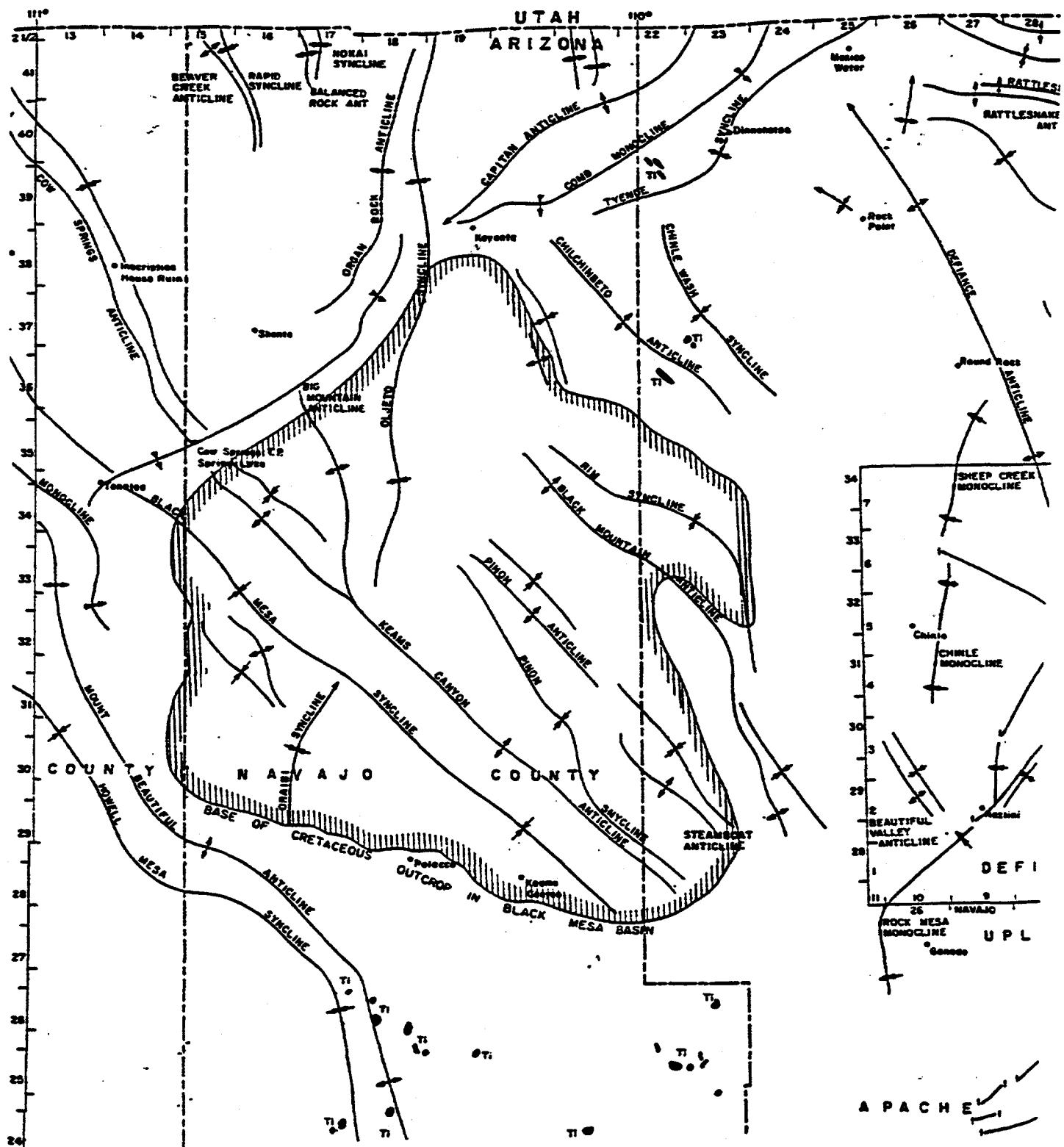


Figure 2 Major Structural Axes in the Area of the Black Mesa Basin

Figure 3 shows the Upper Precambrian sedimentary section for the northeastern Arizona-southern Utah region. The Precambrian Chuar Group has recently been identified as an organic-rich unit, a potential hydrocarbon source. The Chuar is believed to have been eroded under much of the Black Mesa basin, but additional work needs to be done on the details of structure and relief on the Precambrian erosional surface to see if erosional remnants may remain in grabens or on monadnocks. The various members of the Chuar have been tested from drillholes in Utah and Arizona and on outcrops in the Grand Canyon. There they have been found to have high percentages of organic material, even in well-weathered outcrops from the canyon wall. With the recent recognition of Precambrian-sourced hydrocarbon shows and production from numerous locations around the world, the oil and natural gas industry has been paying much more attention to ancient source beds and reservoirs. The industry is beginning to recognize that the explorationist who refuses to waste time looking for Precambrian hydrocarbons is unlikely to find them. For decades Europeans, especially the Russians, and geologists on other continents like the Australians and, recently, the Chinese, have been more open-minded. Many of them have explored for and found Precambrian oil and/or natural gas. The potential presence of Chuar rocks in the region near the Black Mesa is an encouraging indicator of possible deep reserves in the basin.

The Paleozoic section includes a number of potential reservoir units, from the Cambrian through the Cretaceous. Figures 4 and 5 show east-west cross-sections at two locations across the Black Mesa basin. The Devonian section contains the primary reservoirs on these two illustrations. Figure 6 is a map-view of the Devonian isopach for the basin area. The well locations shown on this map make the point that there are a large number of productive holes on the northeast flank of the basin, but very few tests within the basin itself.

The Black Mesa basin will be a potentially high-profile area for exploratory activity. Industry is aware of the opening of this new area and will be interested in any new data coming out of the basin.

This basin contains extensive tribal lands, and the tribal councils are interested in cooperating on exploration activity in the region. Willing operators have already been identified who will work with the project team in the area.

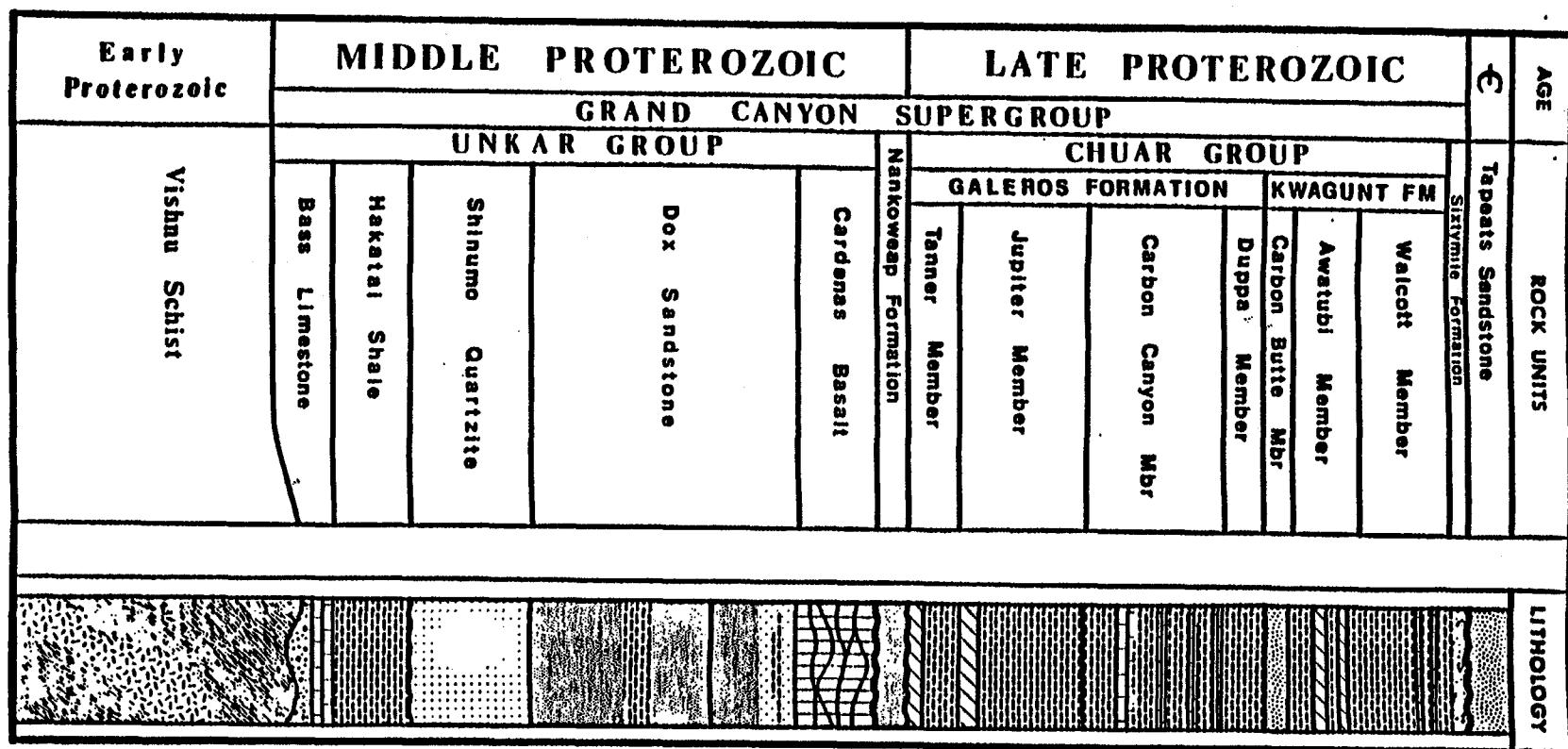
The Black Mesa basin will be a good candidate for early work by the E&D group.

2.2 The Mid-Continent Region

A long, linear magnetic and gravity trend, known as the Mid-Continent Geophysical Anomaly (MGA), has been recognized for decades in the region that stretches from Michigan, north through Lake Superior, and then southwest through Iowa to Kansas. It was long known that the rocks in this region included an extensive volcanic suite and a strange, Precambrian-aged shale that wept live oil in a copper mine near the shore of Lake Superior. The nature of the rocks elsewhere along the trend was essentially unknown, however. Except for the area around Lake Superior, the feature was generally buried under a Paleozoic cover of varying thickness.

Figure 3

Upper Proterozoic Stratigraphic Column for Northeastern Arizona.



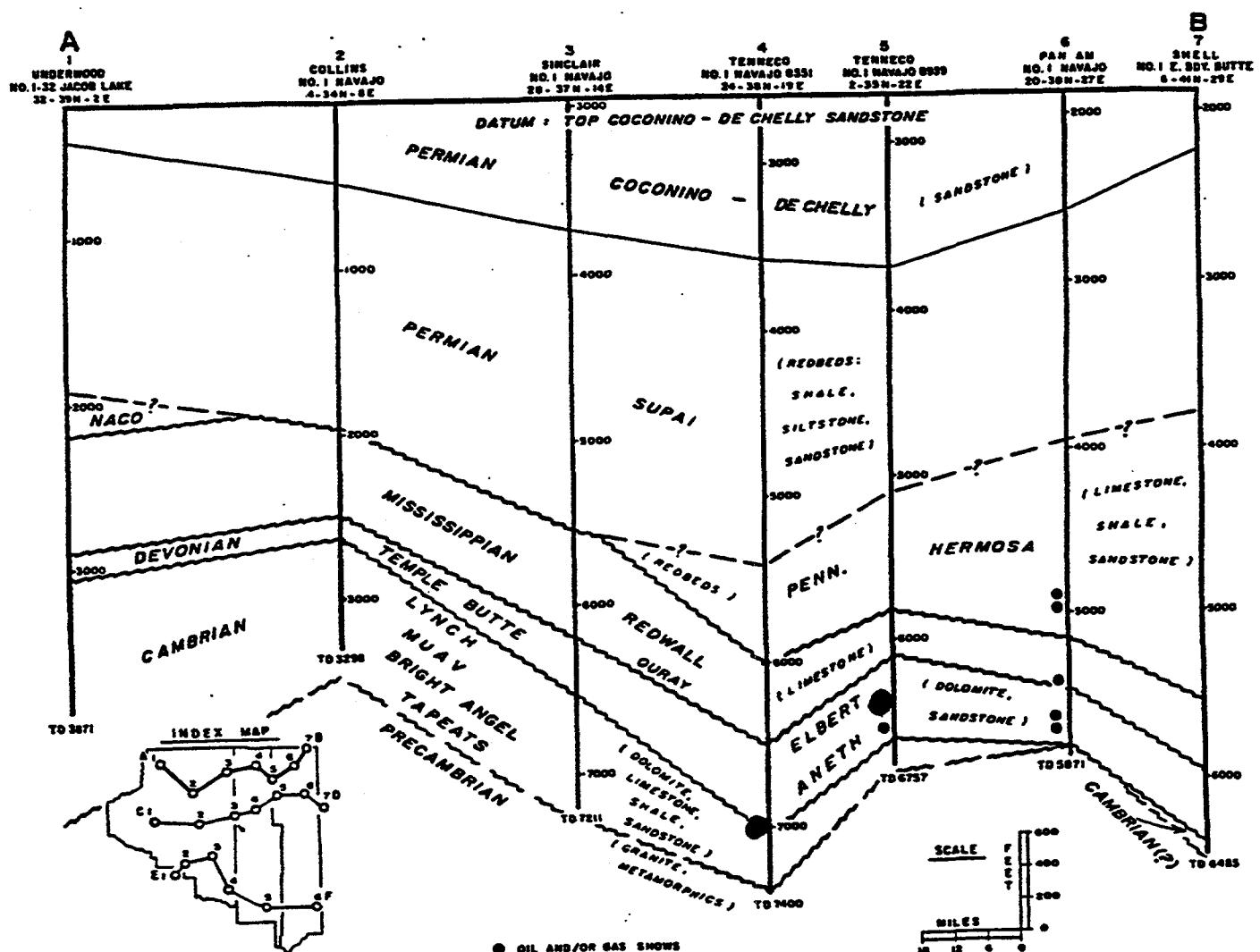


Figure 4

East-West Cross-Section Through the Northern Black Mesa Basin

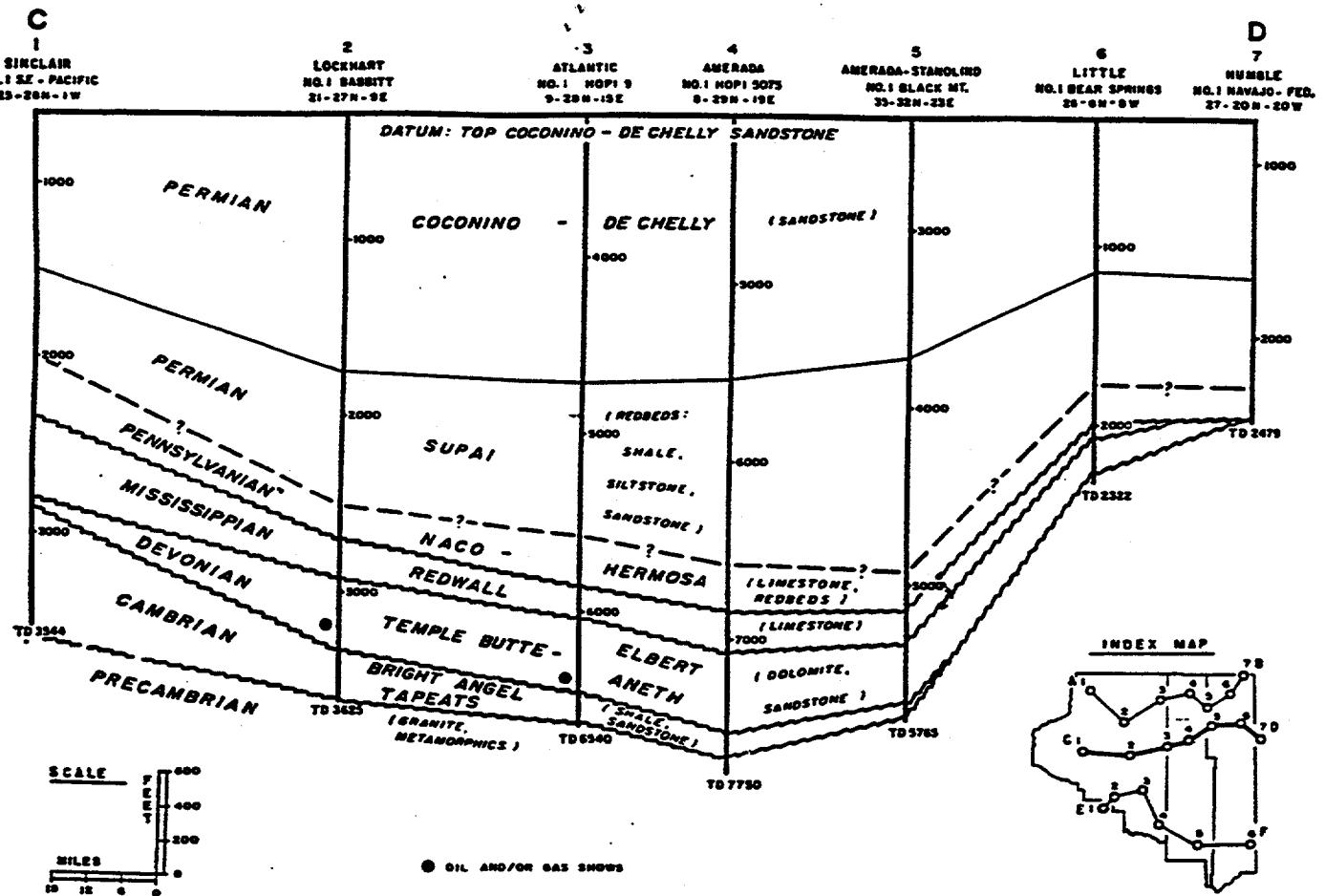


Figure 5 East-West Cross-Section Through the Central Black Mesa Basin

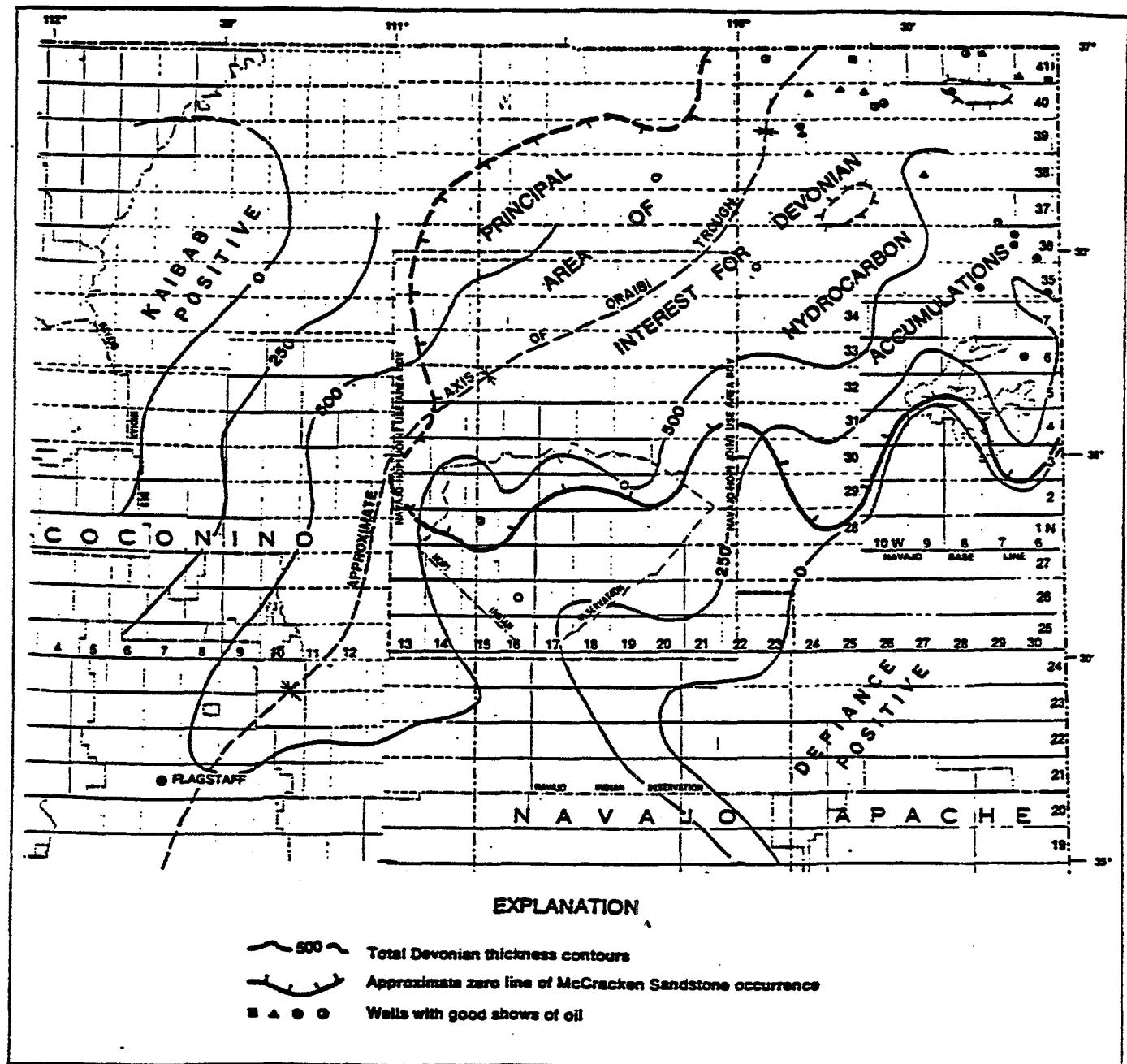


Figure 6

Isopach of Devonian-Aged Rocks in the Black Mesa Basin Region

The suite of rocks in the MGA and its origin were not recognized until the last few years. It has recently been discovered that the trend marks the course of an ancient (1.2 GA) crustal failure zone where the North American Superior Craton began to break up and an ocean almost formed. Before a full ocean floor developed, however, the rifting ceased, and the system froze in place within the interior of the Craton.

Figure 7 shows the modern positions of North America and Scandinavia, for orientation purposes. All references to directions in these paragraphs use the modern orientations. Figure 8 outlines the Precambrian Shield portions of these continents. The interior portion of North America, the Superior Craton, had largely evolved and stabilized by 2.0 GA. The Siberian Shield is believed to have been attached to the southwestern margin of the Superior Shield during the Late Precambrian. The North Atlantic Craton (Greenland) and Sveconorwegian Shields are shown in their modern positions in this illustration. The dashed line on the Sveconorwegian block shows the inferred limit of the Shield (the southeastern portion, including Sweden) and the younger suspect terranes (along the Norwegian Coast).

The Late Precambrian eastern and southeastern margins of the Superior Craton presumably extended further to the east than the line shown, possibly several hundred miles beyond the limits depicted in this illustration. This margin of the continent was greatly modified and ultimately obliterated at approximately 1.0 GA by the Grenville Orogeny. The eastern portion of the Superior Craton was overridden at that time by the Grenvillian Craton. An unknown section of the continental margin was obducted below Grenvillia, and altered beyond recognition. The eastern - southeastern margin of the Craton shown in this figure marks the approximate trace of the Grenville Front, the western limit of the overriding Grenville Continent, not the original limit of the Superior Craton.

The Superior Craton may also have extended further to the south than the boundary shown in the area through Arkansas, Oklahoma, and Texas. Rifting at approximately 0.6-0.5 GA apparently succeeded in breaking off a section of the original Superior Craton in this region. Later continental collisions and orogenic activity have made it difficult or impossible to reconstruct the Late Precambrian configuration in this area.

Figure 9 depicts the repositioning of the North Atlantic (Greenland) block and Sveconorwegian back to their Late Precambrian locations. A portion of the Great Lakes and Hudson Bay are shown for orientation purposes. The crustal sliver between the North Atlantic Craton and Sveconorwegia represents Scotland. The three lines cutting across the illustration are reconstructions of the position of the Equator at various points during the Late Precambrian. These show that the climate in the Great Lakes and Central States region would have been tropical during the Upper Proterozoic or Late Precambrian time period.

The Craton experienced a series of tectonic events during the period between roughly 2.0 GA and 1.65 GA, but these were generally limited to the area around the North Atlantic Craton. There were three significant episodes of rifting, during which the Craton began to break up, but each of these ended in failure. In each case, an incipient ocean almost opened, froze, then closed, with the formation of a suture zone and a band of mountain building. Figure 10 shows the location of the three major disturbed belts created during this time period. This was the general appearance of the continent at the time when the Mid-Continent rift began to open.

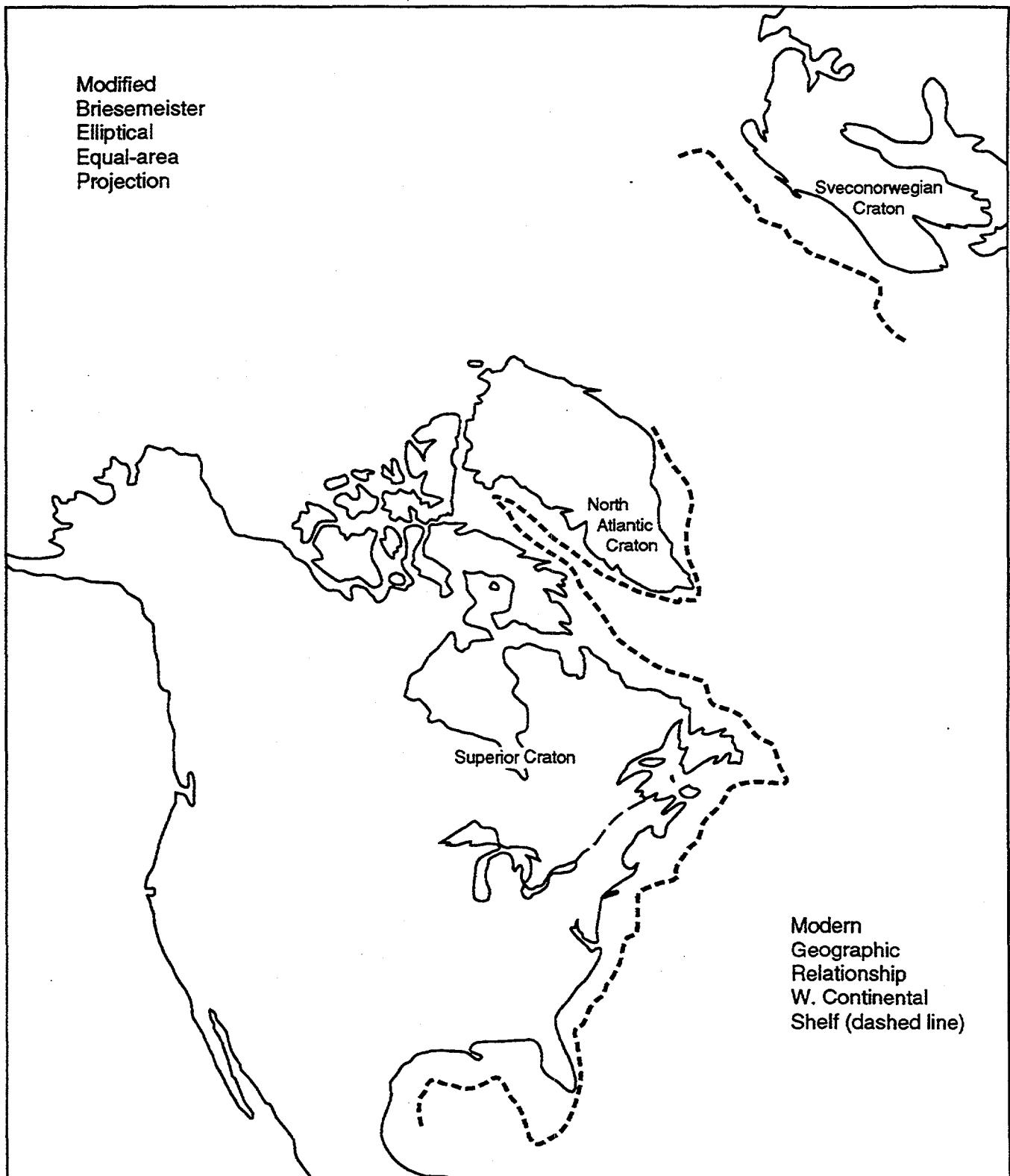


Figure 7

Orientation Map of North America and Scandinavia

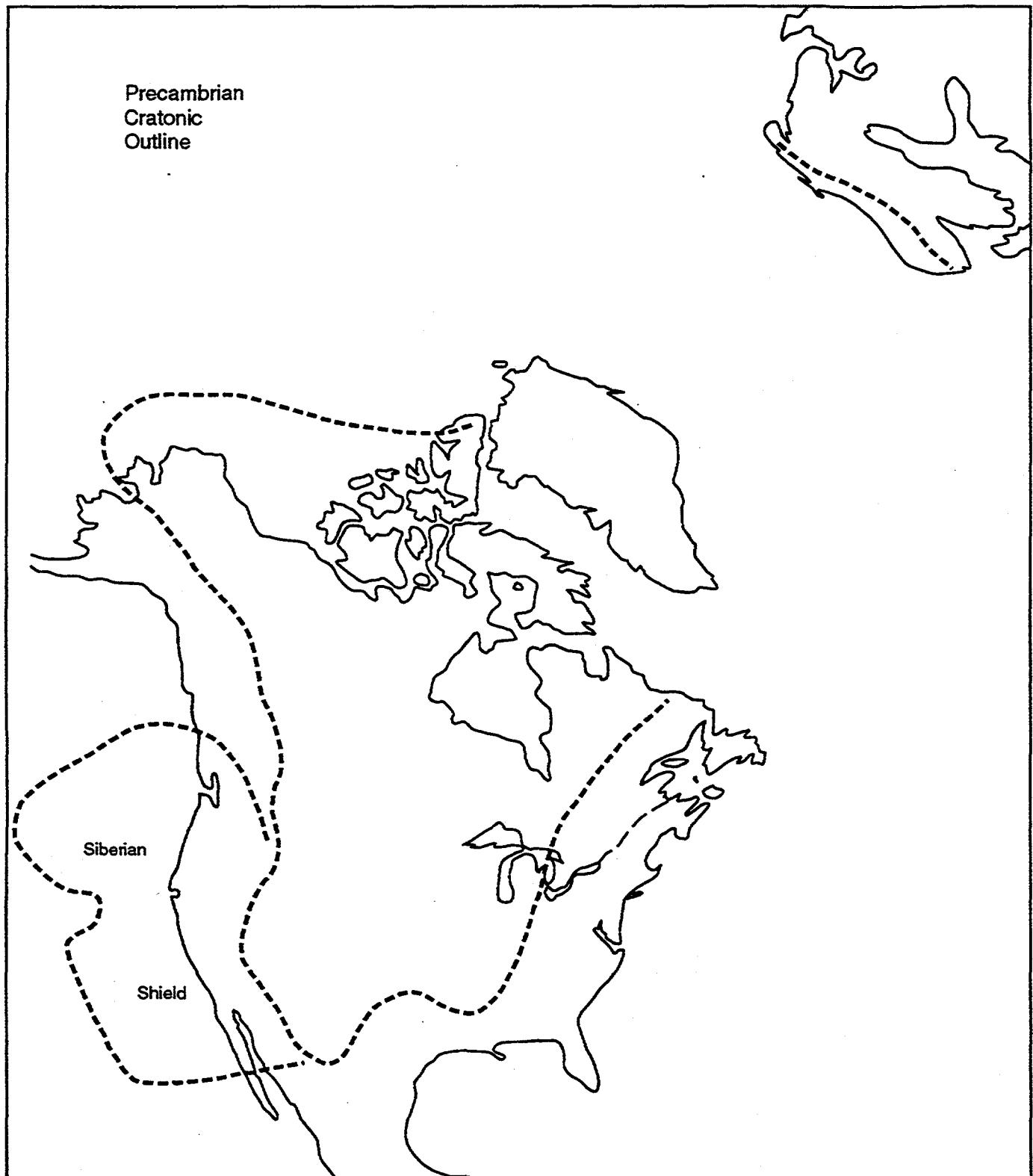


Figure 8 Cratonic Outline of Superior and Sveconorwegian Shield Areas

Reassembly of Pre-Grenville Craton

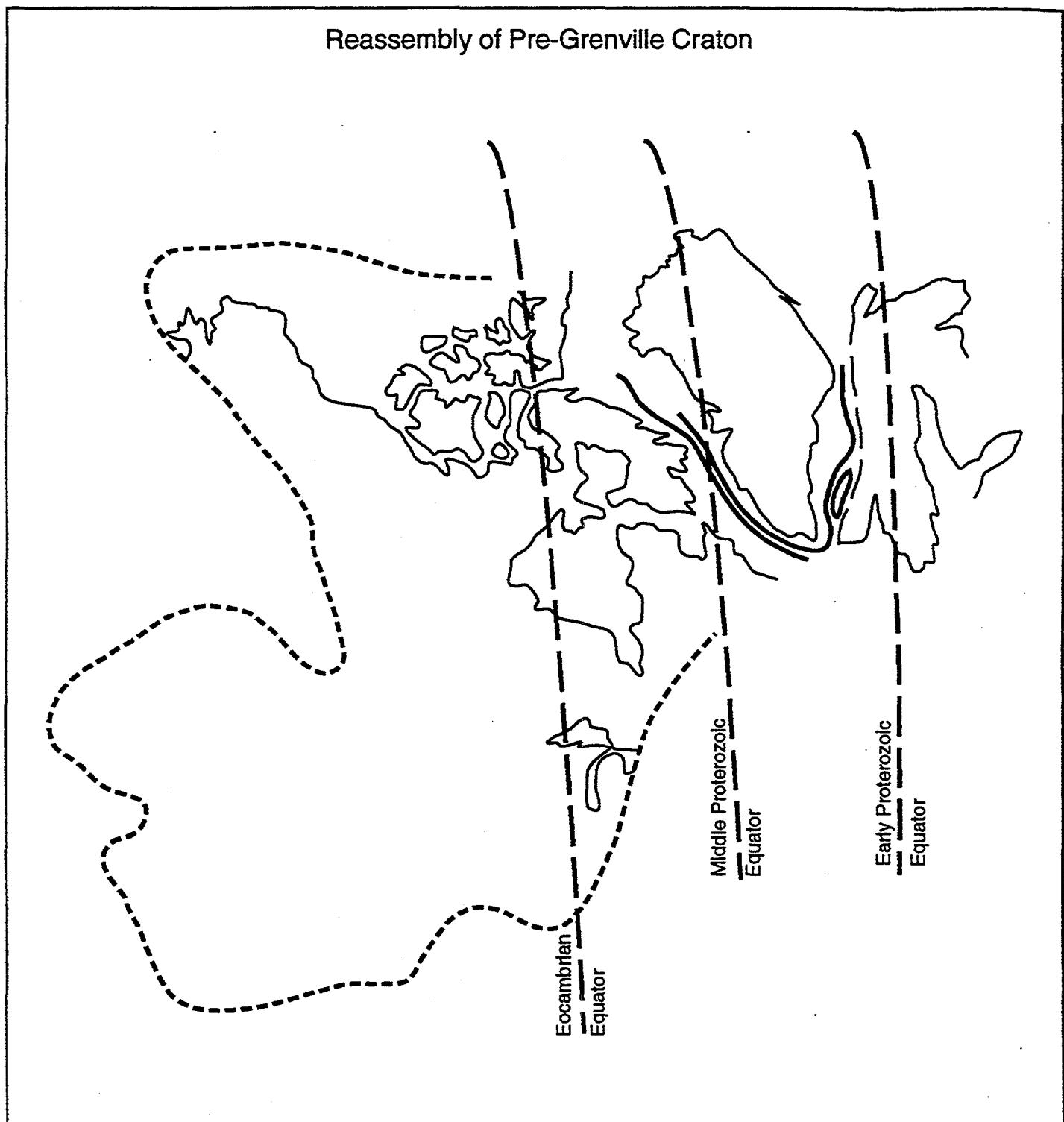


Figure 9

Reassembly of Proterozoic Shield Areas for North America and Contiguous Continental Blocks.

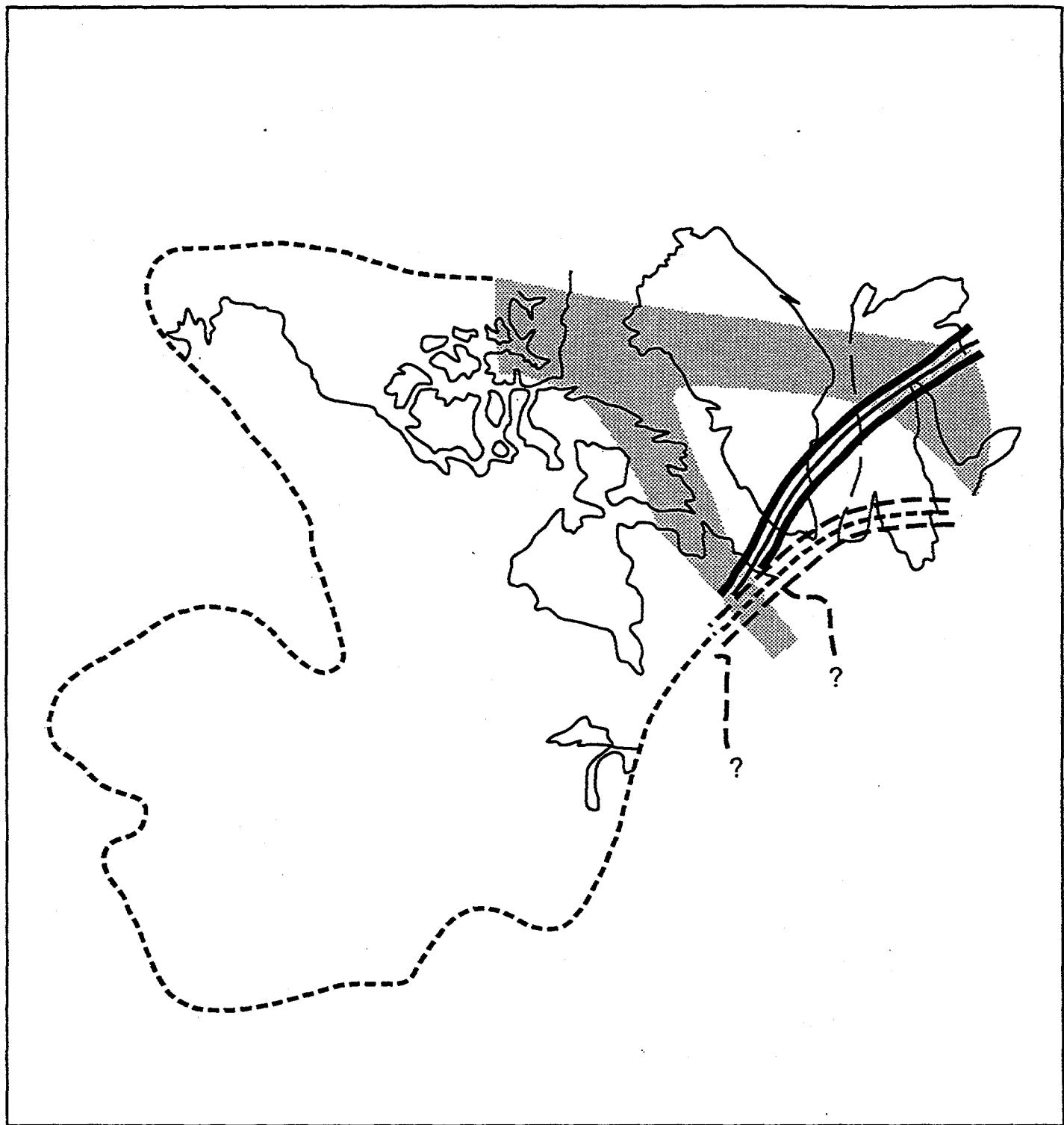


Figure 10 Location of Proterozoic 2.0-1.65 GA Orogenic Zones in the Superior Craton

At approximately 1.2-1.1 GA, the Mantle beneath the Great Lakes-central states region went through an episode of heating and tremendous thermal expansion. The continent above this region was greatly stretched, and huge listric faults formed, cutting completely through the Crust. The material on the hanging walls subsided into the extended areas, in several areas almost to the Moho. Giant valleys opened in the continental crust. The current recognized trace of the rifting begins in Kentucky, Ohio, and Michigan, runs to the north, through Lake Superior, and then continues to the southwest, through Iowa, and into central Kansas (Figure 11). This giant feature is known as the Mid-Continent Rift (MCR).

Postrifting tectonic events at the east and southwest ends have obscured the original length and extent of the MCR, but geophysical studies have indicated that this is the deepest failed or healed rift on the planet. Many other rifts have formed, then continued to open, and eventually formed seas or open ocean basins, but no other rift appears to have proceeded to open so deeply, then stopped, without becoming an ocean. This has left an extraordinary accumulation of plutonic, volcanic and sedimentary rocks in the system.

As discussed above, the original eastern margin of the Superior Craton may have extended well to the east of the present-day Grenville Front in Ohio. A portion of the Superior Craton may be buried below parts of the Appalachian region, underneath the Grenvillian plate. Subtle magnetic and gravity anomalies in Ohio and Pennsylvania, well east of the Grenville Front, may represent the trace of rift material in the overridden, obducted Superior Plate showing through the gravity and magnetic elements of the superposed Grenvillian Crust. A number of peculiar structural features within the Rome Trough in eastern Kentucky may represent the effects within a younger, 0.6-0.5 GA, east-west rift in an overriding Grenville plate that developed above a much older, 1.2 GA, healed, northwest-southeast rift in the underriding, obducted Superior plate. With the complexities of the Grenvillian Orogeny, it is unlikely that the exact nature of the eastern end of the MCR will ever be understood.

Figure 12 shows the classic interpretation of the extent of the MCR, which prevailed through the mid-1980s. This view was based almost purely on the gravity and magnetic signature of the feature. As explained above, the geology of the MCR may be much more complex than revealed by the geophysical maps, and this may not be an accurate depiction of the eastern end of the trend.

In the last few years, it has been recognized that the MCR appears to have an additional, possibly noncontiguous, segment in Ohio (Dickas et al., 1992) (Figure 13). The existence of this feature has been confirmed by drilling, samples, and core studies, although the exact extent and course of the trend are still being discussed. Some evidence suggests that faulting may continue some distance to the north, then northwest, into Indiana. Other work suggests that the northern end of the feature is confined to Ohio. A third interpretation would continue the faulting into Michigan. The southern end of this feature has variously been projected along a sharp bend to the southwest or southeast into Kentucky, or by Dickas et al., to the south, along the Grenville Front, as far as Tennessee, as shown in Figure 13.

There is also ambiguity about the southwestern end of the trend in Kansas. The gravity and magnetic signatures of the MGA end abruptly in the center of the state, but the termination of the geophysical anomaly may not mark the end of rift-related faulting. The southern limit of the MCR may have originally continued beyond this point. Yarger was projecting the rift structure southward to

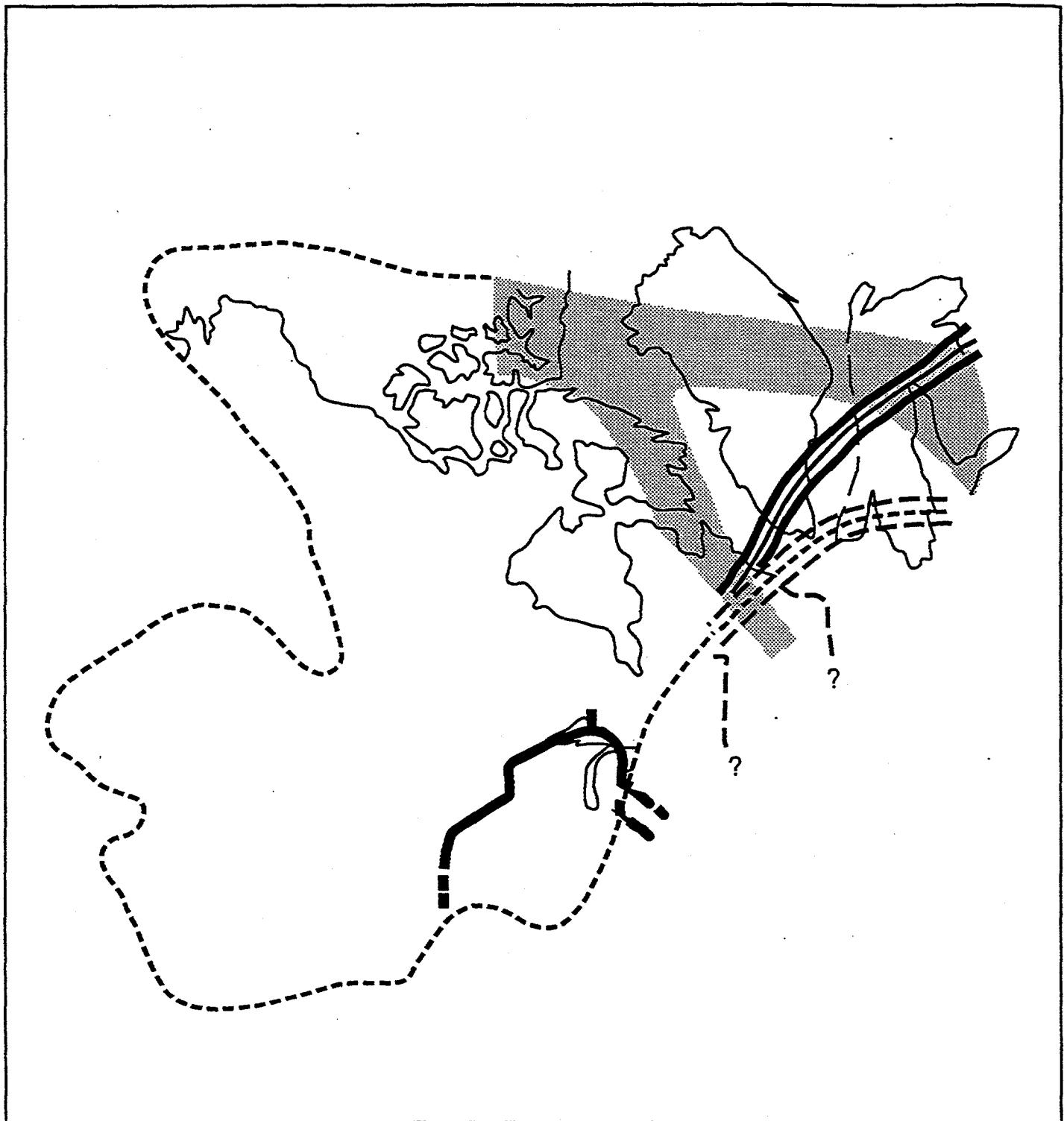


Figure 11 Location of the Mid-Continent Rift

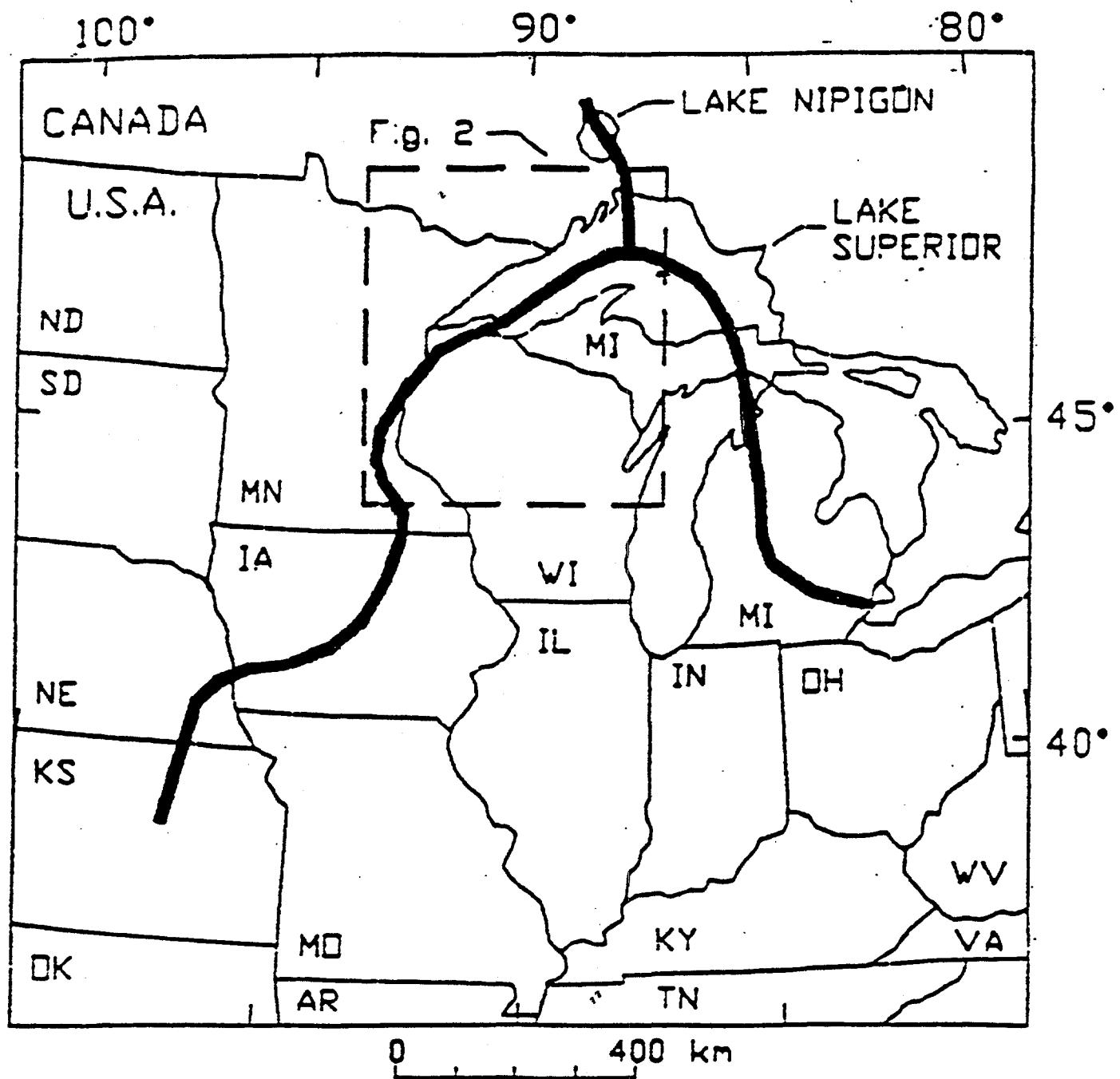


Figure 12

The Mid-1980s View of the Extent of the Mid-Continent Rift (after Van Schmus and Hinze 1985), Based Solely on Gravity and Magnetic Data

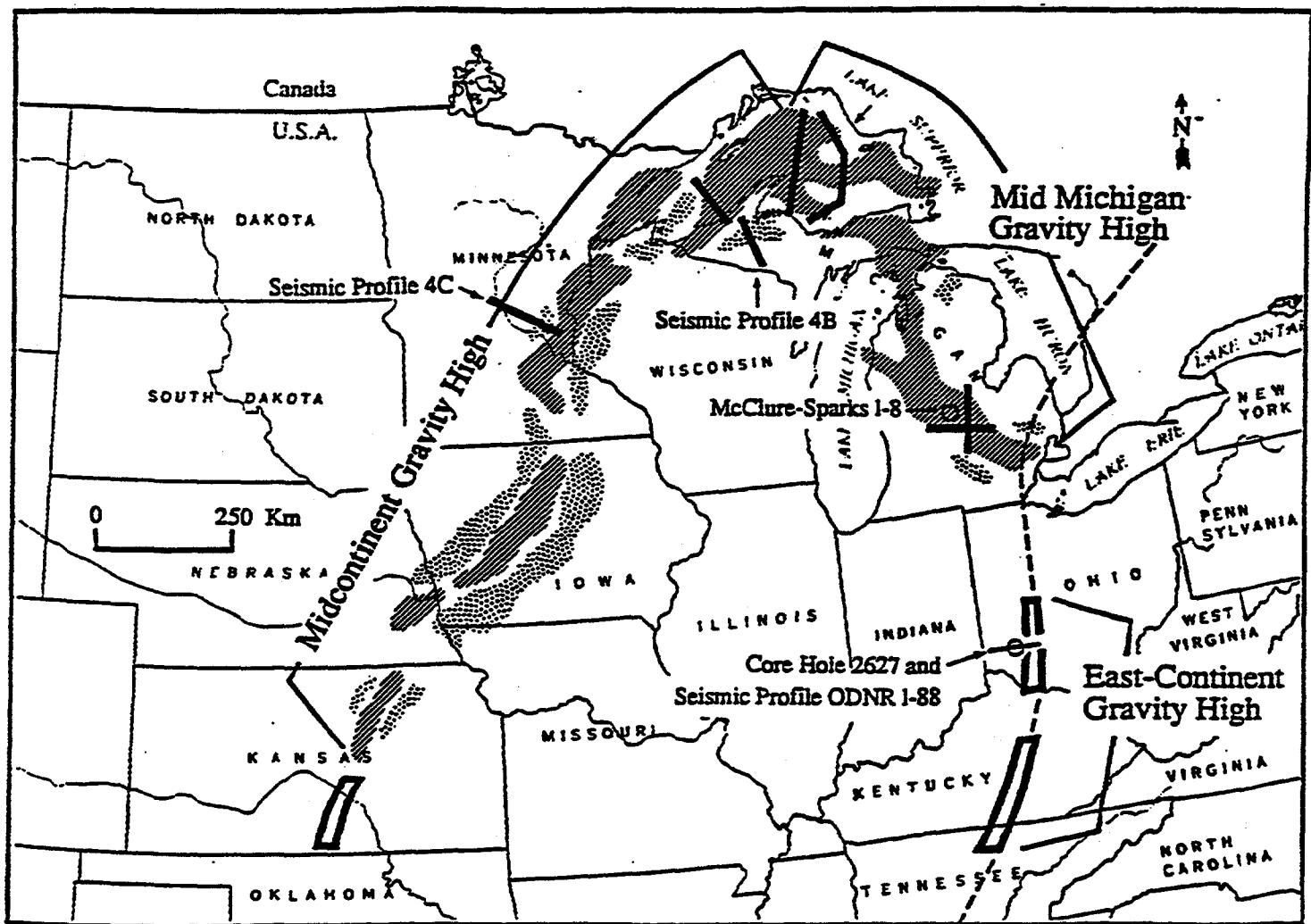


Figure 13

An Interpretation (by Dickas et al., 1992) of Newly Recognized Extensions on Both the Eastern and Western Ends of the Mid-Continent Rift.

the Oklahoma border as early as 1983, as shown in Figure 13, based on his interpretation of geophysical data available to the Kansas Geologic Survey. Paleozoic structural events may have obscured or obliterated the southern limits of the MCR.

The southern end of the MCR runs along the flank of a Paleozoic positive feature, the Nemaha uplift. This structure rose during the late Paleozoic, along a line that marks a direct projection of the Mid-Continent rift. This close alignment and association strongly suggest that there was an ancient rift, fault system, crustal sag, or zone-of-weakness, related to the MCR, which continued to the south from central Kansas, through southern Kansas, and even into Oklahoma. This rift, or Basement sag, underlay the central axis of a large basinal area that formed in the south-central states area during the Lower Paleozoic. This basin, or sag, centered on the Precambrian zone of weakness. The six study areas in the south-central states all lay within or along the margins of this depocenter.

Figure 14 shows the southwestern end of the MCR and its projection and relationship with the Nemaha uplift. The track of the MCR has influenced a number of Paleozoic depocenters. At the recognized eastern end of the feature, the Michigan Basin developed in the Early Paleozoic at a triple point, or sharp bend in the rift. Just to the north, modern Lake Superior, the largest depression in the Great Lakes system, is centered above the Nipigon triple point in the rift. The large offset along the MCR, where it shifts from southern Minnesota to north-central Iowa, has been interpreted as a mega-shear zone. If it exists, this shear zone cuts not only the MCR, but lies along the axes of the Illinois and Williston Basins. At the proximate recognized southern end of the rift complex are the Salina and Forest City basins. These originally formed as a single basin during the Lower Paleozoic, centered on the axis of the MCR.

Along the extended trace of the southern MCR, the ancestral Salina-Forest City basin was contiguous with additional sections of a regional depocenter that included the Seminole Arch and Cherokee Platform, portions of the Central Kansas uplift, Cambridge arch and Sedgwick basin, and possibly even the fringes of the Arkoma, Ardmore, and Anadarko basins. The commonality of fundamental structure, and the common early history of these basins makes it logical to study them together as a unit. The Anadarko Basin is not included in the unit because its history is more closely related to the evolution of the Southwest Oklahoma Aulacogen than it is to the MCR. The Anadarko has also been well-studied and heavily drilled, so was not considered appropriate for extended E&D study.

All of the south-central study area basins may have been charged by hydrocarbon sources from the rift area. Figure 15 is an interpretation of a seismic section across the MCR at Lake Superior. In this illustration, Ba represents basement or crustal material. The shaded band, M, represents the Moho and top of Mantle. The main faults are shown as dashed lines. The main seismic reflectors are shown as solid, subhorizontal traces. The shaded material has been interpreted as almost pure ultra-mafic plutonic rock. The shallower, unshaded rift fill represents a mixture of sediments and igneous rocks. The floor of the rift here is below 10 seconds, and could approach 11, or even 12 seconds. This represents a rift depth of over 20 miles. The Moho in this area is at 14 seconds. This leaves only two to three seconds-worth of crustal material below this rift. There is no other place on the planet where the Crust is known to have been distended to this extent, without actually opening into oceanic crust. The giant faults shown on the section are listric (spoon shaped). The crustal extension took place as the blocks on the hanging walls slumped and rotated down into the rift. Subsidence of these blocks allowed the crust to stretch across the rift.

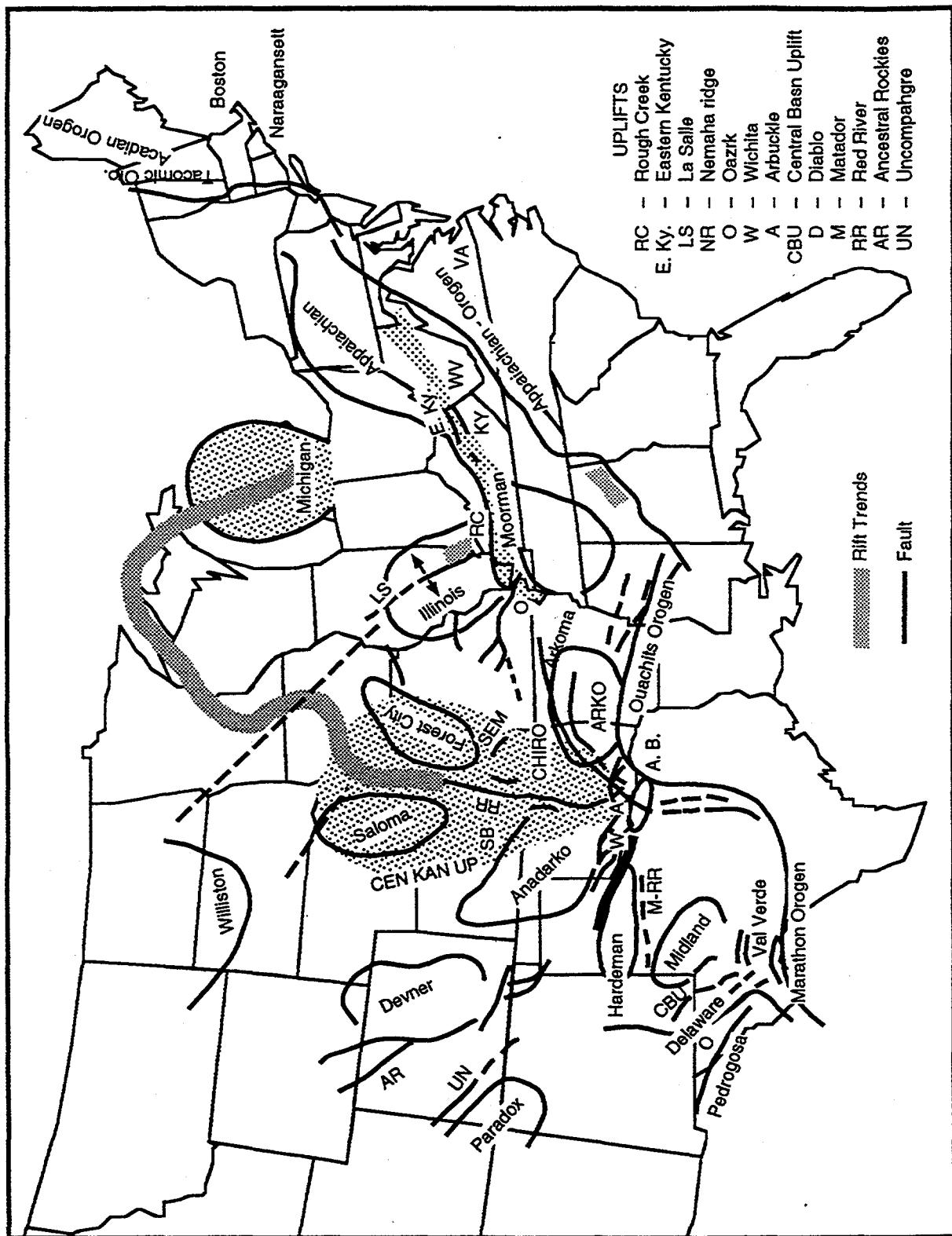


Figure 14

Relationship of the Mid-Continent Rift and Basins Along its Length. Michigan and South-Central Basins are Shaded.

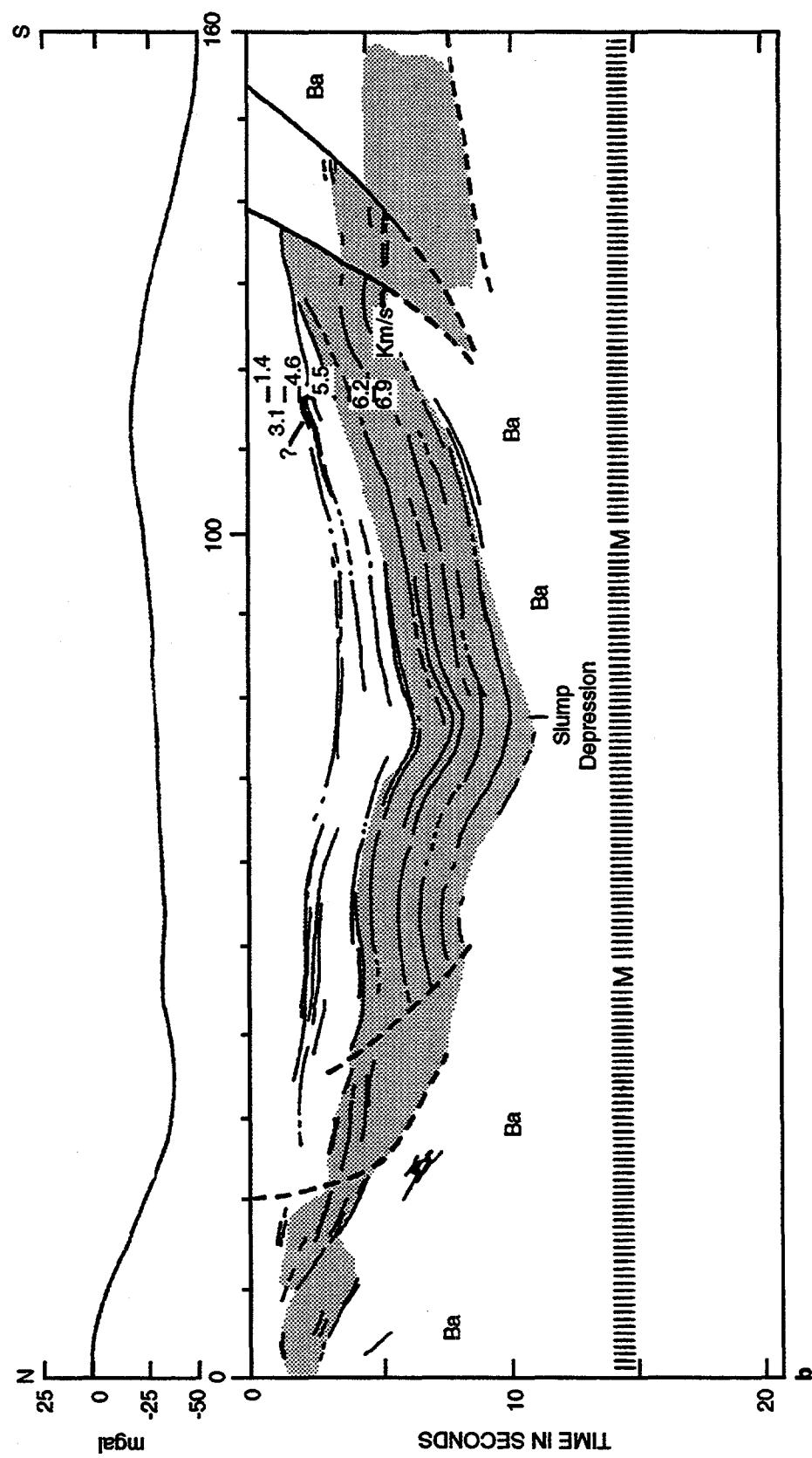


Figure 15

Interpretation of a Seismic Profile Through the Mid-Continent Rift at Lake Superior

As these huge faults formed, cutting through the Crust and reaching down to the Mantle, large amounts of ultramafic mantle material began to leak out along the fault planes. Figure 16, based on the work of Cannon et al, illustrates the development of such a rift system. View A illustrates the early expansion stage. At this point, the ductile mantle is expanding slightly, due to heating. The much more rigid, overlying crust fails in a brittle manner with the initiation of listric faulting and associated volcanism. A mantle expansion will generally manifest itself at the surface as a highland area, due to the swelling of the mantle under the entire region. Eventually, the overlying crust will fail, and a series of valleys will form down the center of the region. Depending on the activity level and rate of rifting, some of these rift valleys may be quite deep. Many of the valleys will include large lakes along the faulted margins of the structure. Volcanoes often line the edges of the valleys.

The mantle expansion, rise of the Moho, and crustal extension continues in B, as the flow of mafic igneous material increases. At this stage, the greatest bulk of the deep-trough fill accumulates. Volcanoes become more numerous and active in a setting like this. Tilting of the rift blocks generally increases, and the lakes may deepen dramatically. Earthquake activity becomes more common, and individual lakes often survive only for brief periods of time, geologically, before the land shifts and a new series of lakes forms. These lakes can become chemical soups, with various fluids leaking into the waters from fissures originating deep in the complex geo-plumbing system. The waters are often warmed by geothermal activity. Volcanoes frequently line both sides of the central valley by this stage of rifting. Although B suggests that the rift-fill is totally comprised of igneous rocks at this point, in fact, it generally includes a large amount of sediment, much of it very coarse-grained, and potentially of good reservoir quality. The highland rim will be eroding quickly, and the trough will contain a mixture of volcanic material and, generally, tilted, chaotically bedded sediments.

By C, the Crust has thinned to a few slumped slivers at the base of the trough. The Mantle has swelled to its maximum extent. This is the period when the middepth rift-fill is accumulating. Large quantities of sediment will be mixed in with the volcanics during this period. The region will still be a highland area, with lava flows and volcanic detritus extending out over the flanks of the main rift. If the heat source that has been spurring this activity continues, large-scale mantle convection cells can form. Then the pull-apart can progress to the point where the continental crust is completely attenuated, and new sea or ocean is formed at the position of the former rift. In the case of the MCR, the rifting seems to have proceeded just to the brink of opening into a sea, then stopped.

If the heat engine driving the system begins to fail, an ocean will not form, and the amount of volcanic activity will gradually decrease. At this point, clastic sediments will begin to dominate the fill material. The end of rifting occurs when the mantle finally ceases to expand and the system reaches equilibrium. As the mantle expansion ends, the stresses stretching the crust relax. Eventually, the mantle cools back to normal temperatures, contracts, and the crust actually subsides. Volcanism ceases, and no substantial additional volcanics reach the rift. Clastic units now totally dominate the rift deposits.

The end-of-rifting stage is depicted in D, where the Moho has returned to its original level. At this point, the attenuated crust has sunk well below its original base level, reflecting the thinning of the material. The former highland region is now a low depocenter, and large amounts of sediment accumulate in the resultant crustal sag. This partially explains the large Paleozoic basinal areas at

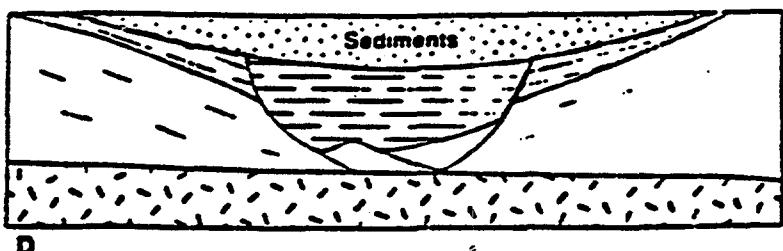
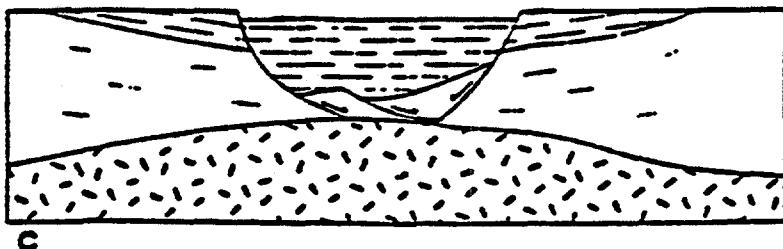
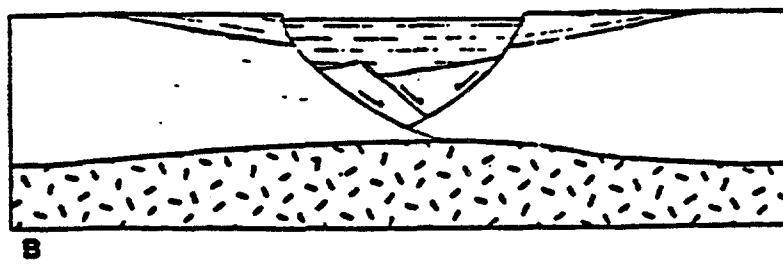
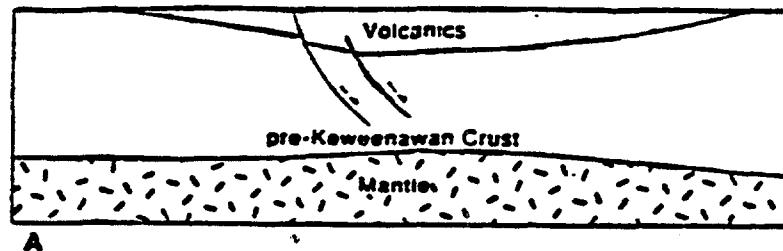


Figure 16 Stages in the Evolution of a Rift - Post Rift Sag Structure

the Michigan and south-central ends of the MCR. It is the reason for suggesting that the large, multistate, early Paleozoic sag through the region from Kansas, Nebraska, and Iowa, south through mid- or southern-Oklahoma, may have overlain a section of the original MCR Mantle-bulge.

Continental rifts are generally the site of extensive, elongate, lake systems, as can be seen along the East-African rift today. Although rifted regions are generally uplifted by Mantle expansion into highland areas, the valley floors can be quite low, compared to the surrounding volcanoes and flanking ridges. Lakes form in these lows. Frequent faulting shifts the location of the lowest areas within the troughs. These frequent movements tend to form new, deep, lakes before the older lakes can get filled up. With all the introduced chemicals in the rift lakes, and the elevated temperatures, single-celled life forms tend to flourish. Algal blooms are common in the East African rift lakes, and a variety of fungi thrive in the waters there and periodically go through explosive periods of growth and large-scale die-offs.

The Late Proterozoic MCR formed at a time when single-celled life forms had evolved into relatively complex forms of algae and fungi. The Late Precambrian Superior Shield lay at tropical latitudes (Figure 9) during the episode of rifting. This suggests that the MCR lakes may have been the site of vibrant Precambrian-life communities.

The Nonesuch Shale, from the MCR at Lake Superior, is well known due to its high organic content and live oil that seeps from the shale in the walls of a copper mine along the shores of the Lake. This Precambrian oil is the best-known hydrocarbon from the MCR area, although there have been other hydrocarbon indications found in Michigan and Nebraska, along the MCR.

Precambrian oil has long been considered exotic in the United States, but this may be in part because American geologists seldom look for it. The Russians have major production from Precambrian units in their Irkutsk basin, Lena-Tunguska Province fields. There is Precambrian production in the Middle East in Oman from the Birba Field, and Precambrian gas production in Australia in the Amadeus Basin. Precambrian shows are known at a variety of locations around the former Soviet Union, along the Pacific Rim, and in the McArthur basin in Australia. China is conducting a number of surveys and drilling presumed Precambrian oil at several locations.

There is disagreement in the literature as to whether all of this Precambrian resource is biogenic. Some students of Precambrian hydrocarbons argue that some, or much, of it originally leaked directly from the Mantle. They feel that there are large amounts of methane and other hydrocarbons in the Mantle, which are slowly working their way to the surface over the eons. If the abiogenic, Mantle-derived theories are correct, then the MCR is again an excellent area in which to prospect, due to the size and depth of the faults that cut nearly to the Mantle along the edges of the MCR.

This means that the MCR is a prime prospect area for hydrocarbon products generated from algal or fungal blooms, or for Mantle hydrocarbons leaking out along fundamental faults. The sediments in the MCR include known source rocks, like the Nonesuch Shale, excellent, coarse-grained, potential-reservoir sediments from the rift, and good cap rocks like numerous other shale and silt sequences or various tight lava flows. The extensive faulting along the rift traces has provided, alternately, traps or migration paths, depending on the timing and configuration/juxtaposition of various units over time.

If good hydrocarbon histories can be documented for the units within the rift sequence, Then there have been numerous opportunities for the MCR rocks to charge the deeper units within the south-central states Lower Paleozoic basin. The Salina-Forest City basin complex was not separated into two isolated structures until the compression associated with the Ozark uplift caused the Nemaha structure to rise, right along the central axis of the ancient sag. This uplift seems to have modified the gravity and magnetic nature of the area, and may have obscured the evidence of the original extent of the MCR.

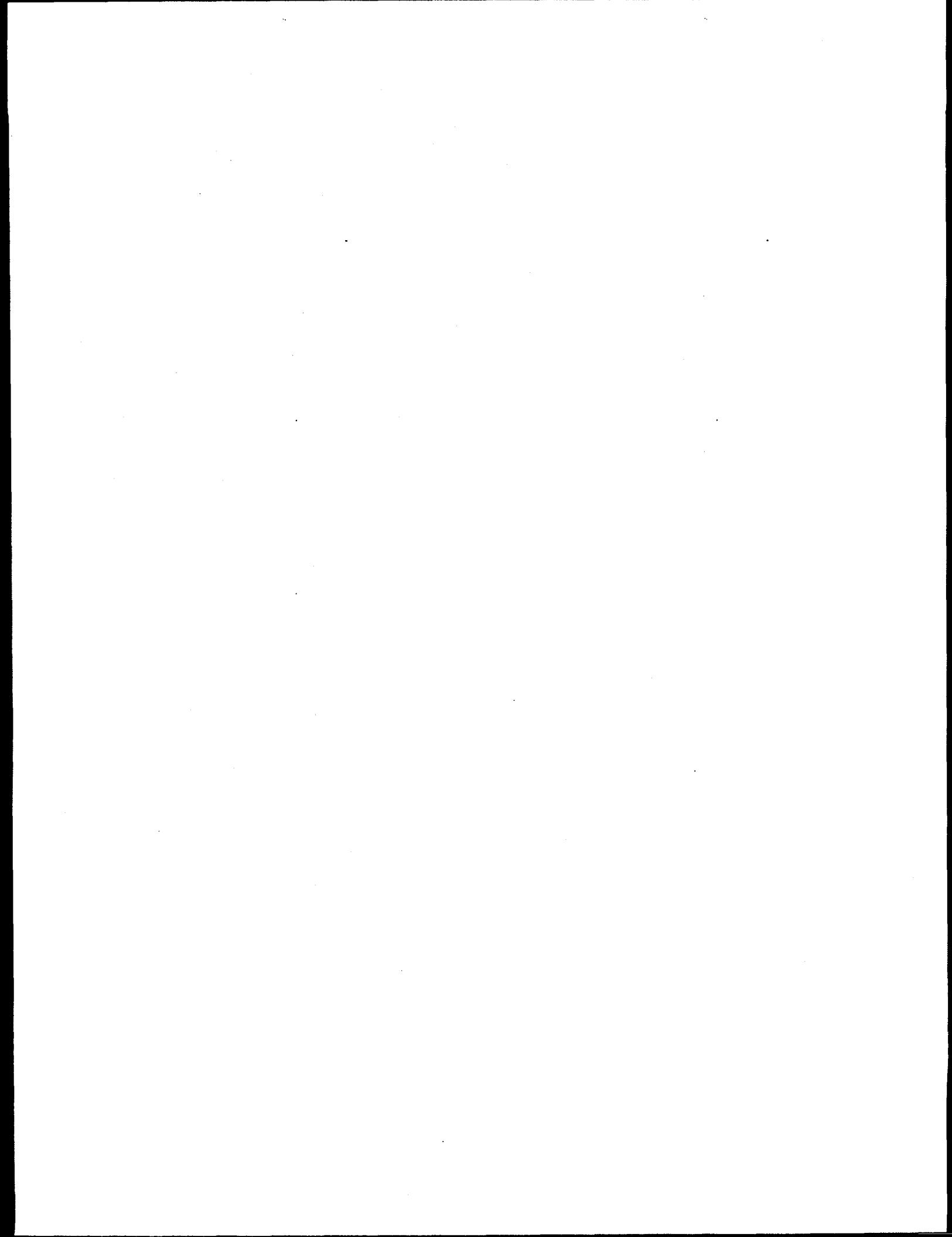
The E&D team plans to look at the area of this older sag to see if the sedimentary and hydrocarbon regime may extend to the south, from Kansas to the Ardmore/Arkoma areas. Work will be done on sources, including possible Precambrian sources, maturation, and possible migration histories, as well as other often-overlooked regional features.

3.0 Summary

The E&D group will be focusing its initial efforts on two areas, the Black Mesa basin and the south-central states region. The Black Mesa is a pure exploratory play. This is an untouched basin with good potential from conventional reservoirs, and with possible deep, Precambrian Chuar Group sources.

The south-central states region includes a number of small basins and structures that formed originally as part of a large regional sag, possibly related to the Mid-Continent Rift System. This rift has a high potential for hydrocarbons, and may have charged the deep sediments across this entire area. The E&D group will work to establish the early history of the region, when the component structures were part of a single, large sag.

The goal of the exploration portion of the E&D work will be to increase the finding rate and to reduce exploration costs in these basins. This work will be conducted in concert with drilling and completion engineering research, which will also attempt to lower operating costs. A risk-based decision-management portion of the project will be aimed at decreasing risk by eliminating the high-risk decision options at an early stage.



4.0 References

Barghoorn, E. S., Meinschein, W. G., and Schopf, J. W., Paleobiology of a Precambrian Shale: *Science*, V 148, pp. 461-472, 1965.

Behrendt, J. C., et al., Crustal Structure of the Midcontinent Rift System: Results from GLIMPCE Deep Seismic Reflection Profiles: *Geology*, V 16, pp. 81-85, 1988.

Cannon, W. F., et al., The North American Midcontinent Rift Beneath Lake Superior from GLIMPCE Seismic Reflection Profiling: *Tectonics*, V 8, pp. 305-332, 1989.

Cannon, W. F., Peterman, Z. E., and Sims, P. K., Crustal-Scale Thrusting and Origin of the Montreal River Monocline —A 35-KM Thick Cross Section of the Midcontinent Rift in Northern Michigan and Wisconsin: *Tectonics*, V 12, pp. 728-744, 1993.

Dickas, A. B., Mudrey, M. G., Ojakangas, R. W., Shrake, D. L., A Possible Southeastern Extension of the Midcontinent Rift System Located in Ohio: *Tectonics*, V 11, pp. 1406-1414, 1992.

Lee, C. K., and Kerr, S. D., Midcontinent Rift —A Frontier Oil Province: *Oil and Gas Journal*, V 82, August 13, pp. 144-150, 1984.

Peterman, Z. E., and Sims, P. K., The Goodman Swell: A Lithospheric Flexure Caused by Crustal Loading Along the Midcontinent Rift System: *Tectonics*, V 7, # 5, pp. 1077-1090, 1988.

Shumaker, R. C., Structural Development of Paleozoic Continental Basins of Eastern North America: Proceedings of the 6th International Conference on Basement Tectonics, pp. 82-95, 1986.

Van Schmus, W. R., and Hinze, W. J., The Midcontinent Rift System: *Annual Review of Earth and Planetary Sciences*, V 13, pp. 345-383, 1985.

Yarger, H. L., Regional Interpretation of Kansas Aeromagnetic Data: *Geophysics Series I*, Kansas Geologic Survey, Lawrence, Kansas, 35 p., 1983.