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DOE/MC/28136-3373

Stratified Precambrian Rocks (Sedimentary?) beneath the Midcontinent Region of the U.S.

Final Technical Report

E.C. Hauser

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Work Performed Under Contract No.: DE-FG21-91MC28136

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Institute for the Study of the Continents (INSTOC)
Cornell University, Ithaca, New York

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ABSTRACT

A thick sequence of layered rocks occurs beneath the Phanerozoic platform strata which blanket the U.S. midcontinent. Observed on COCORP deep reflection data in southern Illinois and Indiana and in SW Oklahoma and adjacent Texas, this sequence is locally 1-3 times as thick as the overlying Paleozoic cover, but the origin of this sequence and its ultimate lateral extent are unknown. However, the occurrences of Precambrian layered rocks on both the COCORP profiles and reprocessed industry seismic reflection data from the region lie within regions of generally low amplitude and low frequency aeromagnetic anomaly, suggesting an even greater distribution. Unmetamorphosed Precambrian sedimentary rocks have been recovered from drill holes in southwest Ohio and adjacent northern Kentucky and southwesternmost Indiana. These Precambrian sedimentary rocks lie above and may be part of an underlying package of strongly layered rocks imaged on a short and shallow seismic profile in southwest Ohio. These Precambrian sedimentary rocks were originally viewed as part of a late Precambrian (Keweenawan?) rift; however, in light of Grenville foreland structures seen on the COCORP profile to the north in west-central Ohio, these Precambrian strata may (1) be part of a heretofore unrecognized Grenville foreland basin, or (2) indicate that unmetamorphosed Precambrian sedimentary material may be an important constituent of the layered rocks observed on COCORP beneath southern Illinois and Indiana.

ACKNOWLEDGMENTS

The following companies provided data that were incorporated in this study: Amoco, Chicago Metropolitan Water District, Citizens Gas & Coke Utility, EXXON, ENRON, Illinois Power, NOMECO, Northern Illinois Gas (NIGAS), Northern Indiana, Public Service Company (NIPSCO), and People's Gas. The seismic data were processed at Cornell University using the ProMAX, SIERRASEIS, and MEGASEIS processing systems. S. Gallow at Cornell was instrumental in processing system maintenance and data management assistance, and J. Weaver assisted in data conversion and archiving. Institute for the Study of the Continents contribution number 868.

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EXECUTIVE SUMMARY

Reprocessing and analysis of industry data, in conjunction with the COCORP deep seismic profiles indicate that a Precambrian layered sequence underlies large parts of the U.S. midcontinent. In addition to the layered sequence identified on early COCORP data in southwest Oklahoma and adjacent Texas, similar layered rocks are observed on COCORP and industry seismic reflection data beneath southern and central Illinois and southern and western Indiana, which may correlate with layered rocks observed on limited seismic reflection data beneath southwestern Ohio. This is probably a minimum extent; based upon a correspondence of these occurrences with regions of characteristically low amplitude and low frequency aeromagnetic anomaly pattern within the broader Granite-Rhyolite province of the U.S. midcontinent, the ultimate distribution of these layered rocks is likely much larger.

Questions remain regarding the precise correlation of the layered rocks from different regions. However, in southwest Ohio and adjacent parts of northern Kentucky and southeast Indiana, layered Precambrian rocks are in some way associated with unmetamorphosed sedimentary rocks recovered from drill holes. Although considered by some workers to be part of a late Precambrian (Keweenawan?) rift basin, these Precambrian sedimentary rocks may instead be part of a heretofore unrecognized Grenville foreland basin, or be an integral part of the sequence of layered rocks observed within the broader Granite-Rhyolite province. The latter model would suggest that unmetamorphosed sedimentary material may be an important constituent of the thick sequence of Precambrian layered rocks observed regionally on COCORP and reprocessed industry data.

INTRODUCTION

One of the most exciting new developments in midcontinent geology is the recognition that in places a thick sequence of Precambrian layered rocks underlies the platform strata which conceal the basement across most of this region. On the COCORP deep seismic reflection transect across southern Illinois and Indiana (Figs. 1 and 2) this thick sequence of layered rocks is observed for close to 200 km in an E-W direction with individual reflections continuing for as much as 80 km (Pratt and others, 1989). This layered sequence is in places 1 to 3 times as thick as the overlying Paleozoic cover (Fig. 2).

A grossly similar layered assemblage was imaged by COCORP several years ago beneath southwest Oklahoma and adjacent Texas (Figs. 1 and 3) (Oliver and others, 1976; Brewer and others, 1981). Based upon the occurrence of the Precambrian Tillman greywacke in local drill holes in that region (Ham and others, 1964) these layered rocks were interpreted as part of a Precambrian sedimentary basin (Oliver and others, 1976; Brewer and others, 1981).

Together these occurrences demonstrate that thick layered sequences (exclusive of the better-known Keweenawan or Midcontinent Rift System, Fig. 1) are a major component of the Precambrian 'basement' of the U.S. continental interior. However, the nature, composition, origin and distribution of these layered rocks remains poorly known. Are these occurrences of layered rocks associated or interconnected; do they have a common origin? Considering the potentially huge volume of stratified rock present, if a significant part of this sequence is sedimentary, the implications for resource potential (i.e., deep gas?) can not be ignored.

PURPOSE

The objectives of this effort were to begin to assess and constrain the distribution, composition, origin, and evolution of these newly identified stratified sequences beneath the midcontinent, especially regarding the existence of sedimentary material and hydrocarbon potential. Because of the local abundance of industrial seismic reflection data in the Paleozoic basins in the region collected in the course of oil and gas exploration, an important element of this effort involved the reprocessing and analysis of newly available industry seismic data. These data were integrated with the COCORP deep seismic reflection profiles and other geophysical data, and

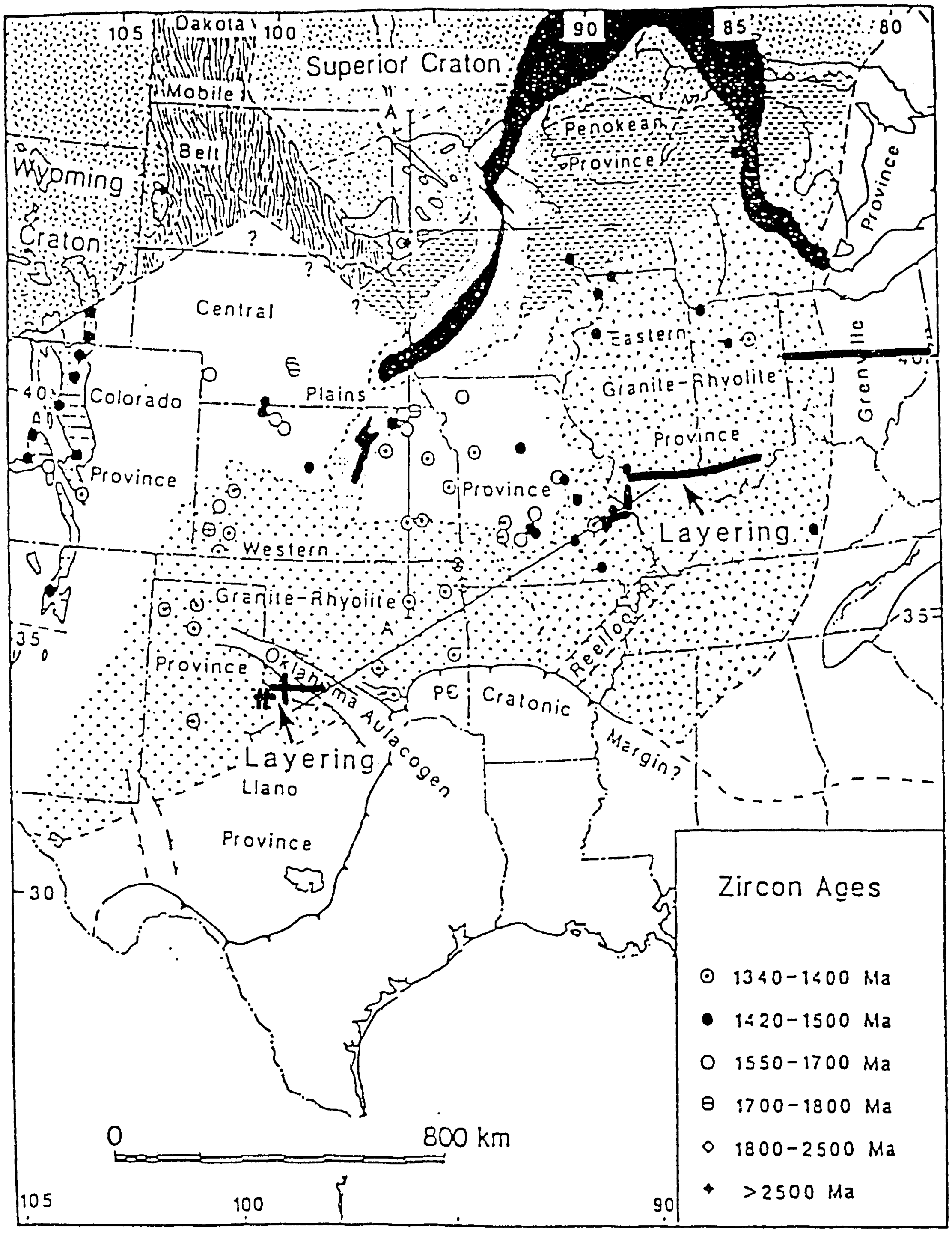

Figure 1. Summary Geologic Map of Precambrian Basement Terranes of the U.S. Midcontinent. Bold Lines Denote COCORP Lines.

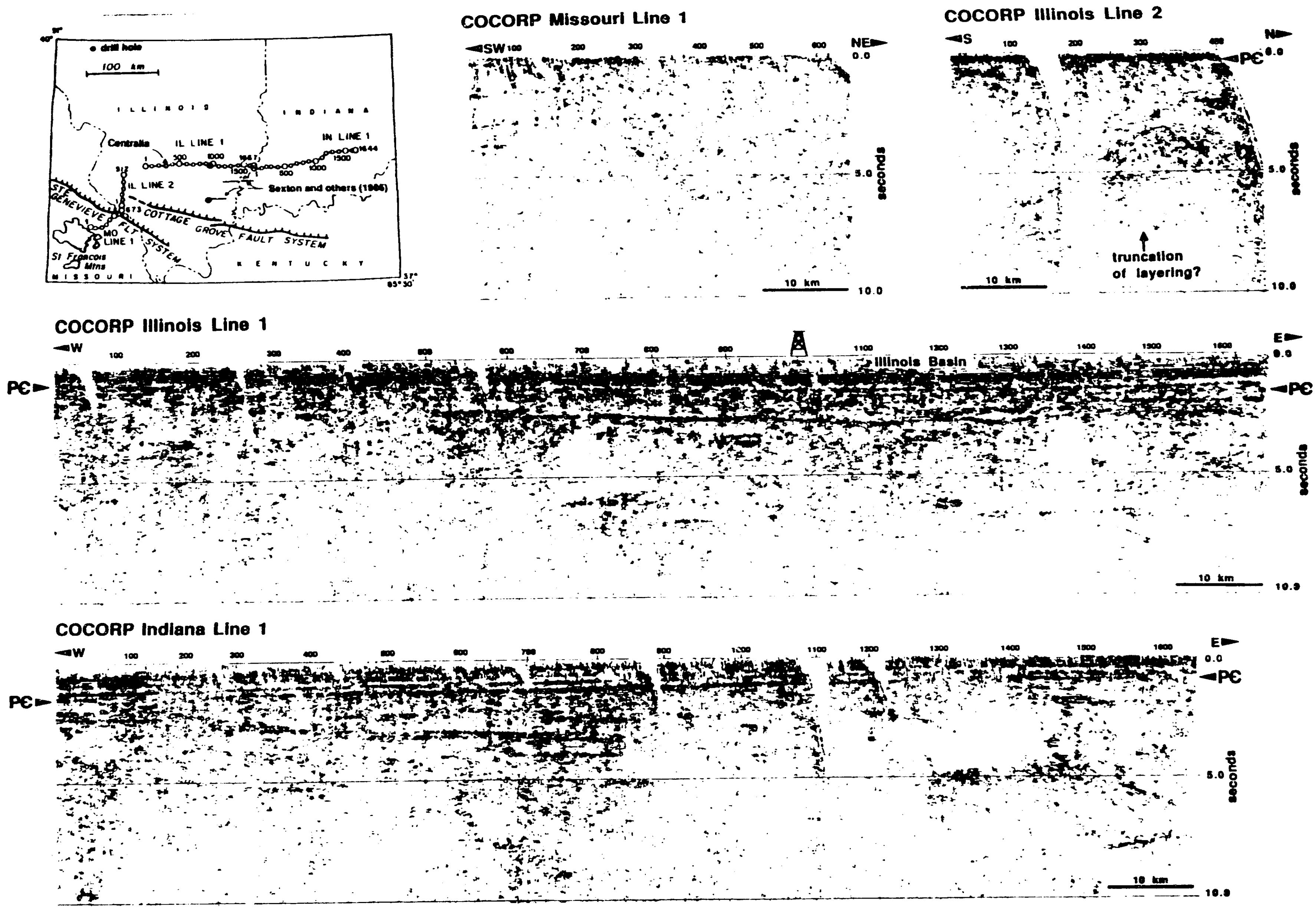

Figure 2a. COCORP Data from Southern Illinois and Indiana Showing Thick Proterozoic Layered Sequence. Well Symbol Denotes Location of Cisne Community No. 1 Well Discussed in Text. Arrows Denote Top of Precambrian. (From Pratt, Hauser, and Nelson, 1992)

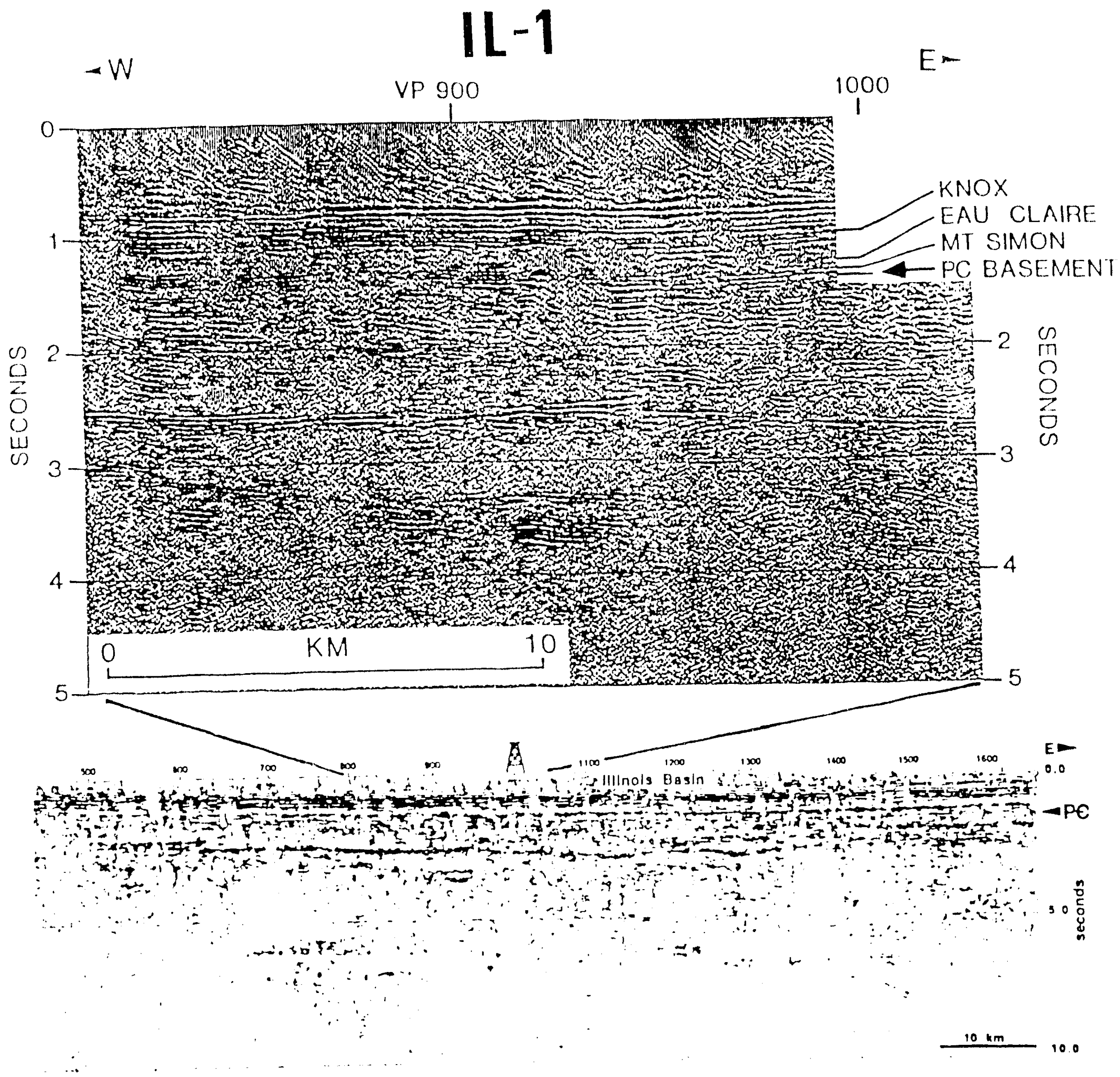

Figure 2b. Sample of COCORP Data from Southern Illinois at Location of the Cisne Community No. 1 Well (See Fig. 2a) Showing Thick Proterozoic Layered Sequence. Arrows Denote Top of Precambrian.

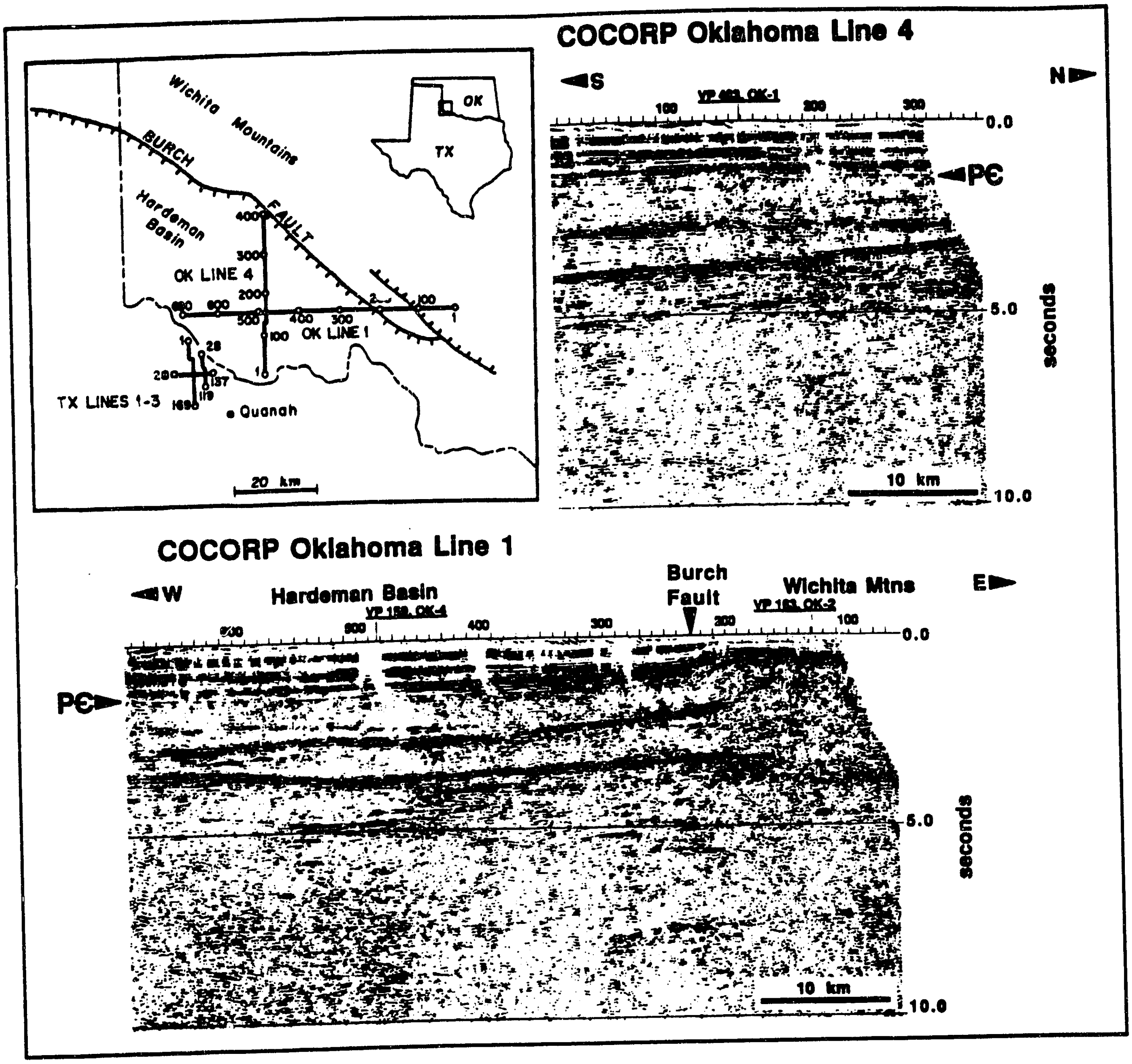

Figure 3. Sample of COCORP Data from SW Oklahoma Showing Proterozoic Layered Sequence. Arrows Denote Top of Precambrian.

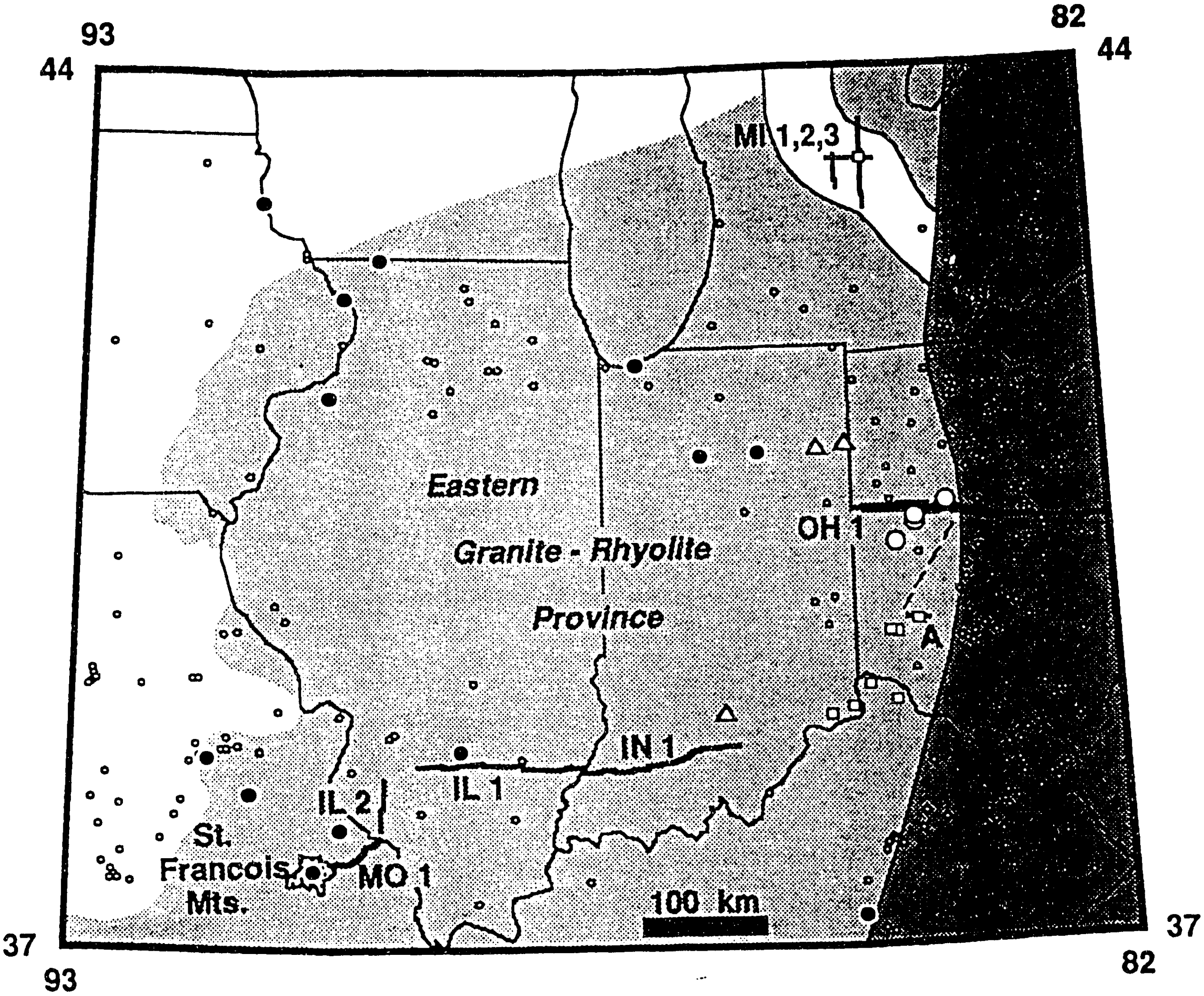

Figure 4. Map of Basement Provinces in Eastern U.S. Midcontinent (Hauser, 1993) Showing: Eastern Granite-Rhyolite Province (Light Gray) (after Bickford and others, 1986); Grenville Province (Dark Gray); Grenville Front (GF); COCORP Profiles (Bold Black Lines); Seismic Line in SW Ohio of Figure 10 ('A'); Drill Holes with Precambrian Sedimentary Rocks (White Squares) (from Shrake et al., 1990, 1991); Drill Holes in Granite-Rhyolite Province with Zircon U-Pb Age Determinations (Black-Filled Circles) (Bickford and others, 1986; Van Schmus and others, 1987); Drill Holes with Felsic and Trachytic Volcanic Rocks near COCORP Line (White-Filled Circles) (McCormick, 1961); Mafic Rocks (White Triangles); Other Basement-Penetrating Drill Holes (Small Circles).

information from scattered basement-penetrating drill holes to further map and understand the distribution and nature of these enigmatic stratified rocks beneath the midcontinent.

BACKGROUND

The examples of layered Precambrian rocks on COCORP deep seismic reflection data from the midcontinent occur within the Middle Proterozoic Granite-Rhyolite Province of the central and southern U.S. (Fig. 1), an area of about 10^6 km^2 within which scattered wells to basement commonly encounter 1.3-1.5 Ga undeformed granite or rhyolite (Denison and others, 1984; Bickford and others, 1986; Van Schmus and others, 1987). These apparently undeformed rhyolites and granites have been interpreted to represent substantial remelting of previous lower crust in an anorogenic setting (Anderson, 1983; Emslie, 1978), perhaps a region of widespread continental rifting like that of the present Basin and Range Province of the western U.S. (Bickford and others, 1986). Because of the veneer of Paleozoic rocks across most of the U.S. midcontinent, however, very little is known in detail about the 'basement' rocks beneath this vast region.

Drill-hole samples provide some information about the nature of the Precambrian basement beneath the Phanerozoic platform cover. However, basement-penetrating drill holes are sparce over large regions (Fig. 4) and rarely penetrate and sample more than a few meters or tens of meters of basement rock, leaving important questions about the nature of the Precambrian 'basement'. Not only are basement-penetrating drill holes relatively sparse over large regions, but they commonly are biased samples of basement. Many basement drill holes in the midcontinent sample anomalous basement highs or were sited at strong local gravity/magnetic anomalies (i.e., Fig. 5). These factors, together with a common lack of clear or accessible (i.e., published) petrographic or petrologic documentation of the Precambrian rocks encountered in many drill holes limit understanding of the basement geology of the U.S. midcontinent.

A continuation of the COCORP lines of southern Indiana and Illinois into southeast Missouri (Pratt and others, 1989) attempted to connect these layered rocks to basement outcrop in the St. Francois mountains (Figs. 1 and 4), the only significant basement exposure in this region (Kisvarsanyi, 1981; Sides and others, 1981). However, this layered assemblage becomes less distinct and disappears in that

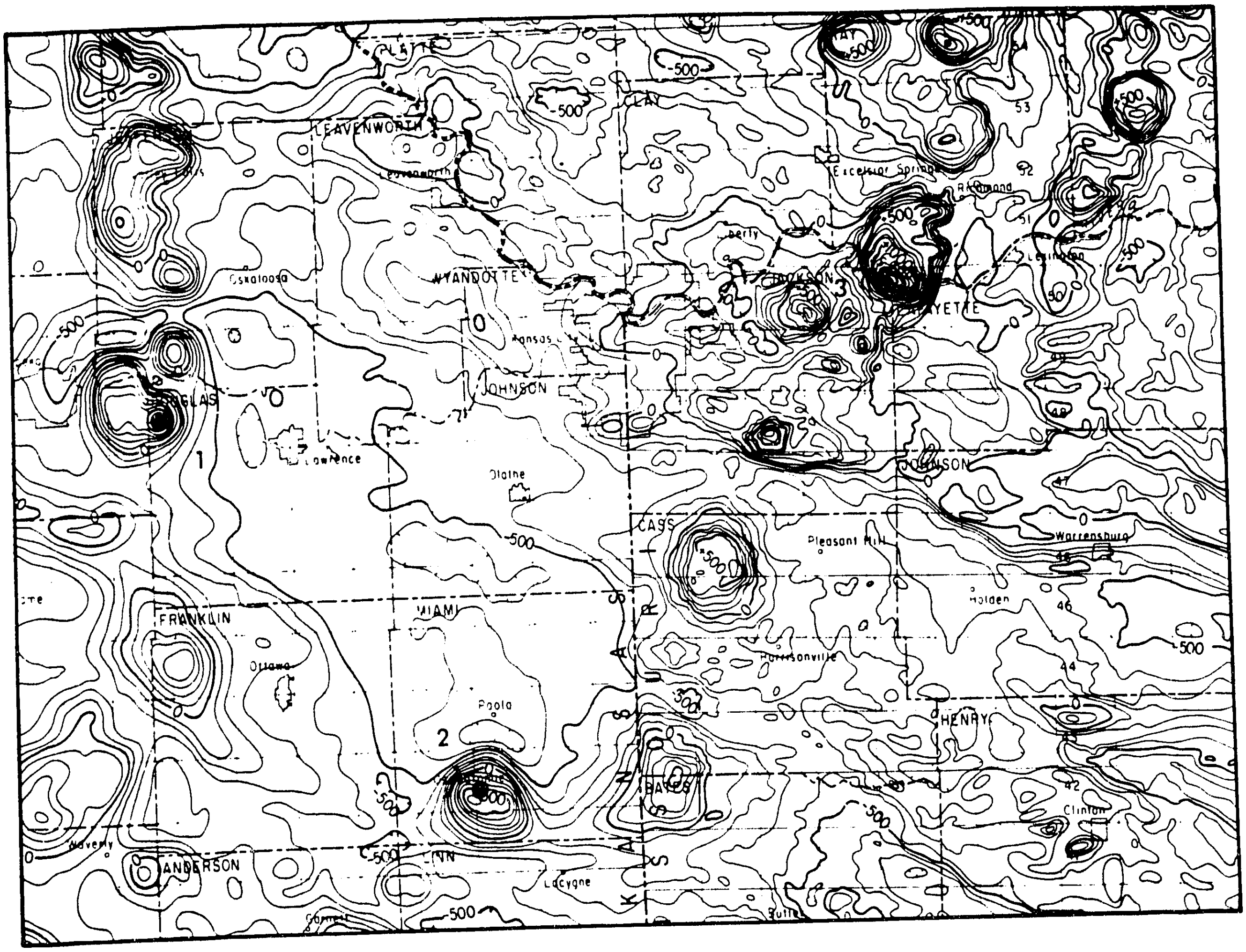

Figure 5. Portion of Aeromagnetic Map of Eastern Kansas and Western Missouri Emphasizing the Common Sampling Bias of Basement-Penetrating Drill Holes of the Midcontinent (From Van Schmus et al., 1987)

direction (Pratt and others, 1989). Therefore, the well-layered Precambrian sequence observed on the COCORP profiles does not apparently crop out there. Either the exposures of the Granite-Rhyolite province in the St. Francois Mountains, which represent a caldera complex, are not typical of the basement rocks throughout the Granite-Rhyolite province and an important facies change occurs, or the Precambrian layered rocks observed throughout the region on the COCORP data are an unrelated sequence of rocks. On the one hand, based upon the U-Pb date on zircon extracted from granite recovered from a drill hole near the COCORP line in southern Illinois (Fig. 4) (Van Schmus et al., 1987) and the granitic rock reportedly recovered from the Cisne Community well within a mile of the COCORP profile (Figs. 2 and 4) the layered sequence observed on the reflection data is apparently either intruded by or overlain by granitic rock of the Granite-Rhyolite province. Thus the sequence of layered Precambrian rocks beneath southern Illinois and Indiana are either part of or older than the 1.4-1.5 Ga rocks of the Granite-Rhyolite Province. This inference is also consistent with the observation that the examples of layered Precambrian rocks on the COCORP deep seismic data from the midcontinent occur so far within the broader Middle Proterozoic Granite-Rhyolite Province of the midcontinent (Fig. 1). This may suggest that these layered rocks represent a thick pile of silicic volcanic and volcanic clastic rocks, locally intruded by granitic stocks and perhaps mafic sills. On the other hand, much of the layering observed might represent a Precambrian sedimentary basin covered by a relatively thin veneer of silicic volcanic material and only locally intruded by granite plutons. Since basement-penetrating drill holes have thus far not penetrated deeply into basement it is possible that a sequence of largely sedimentary material could lie beneath a thin veneer of silicic igneous material. Indeed, the general reflection character and lateral continuity of these layers on the available reflection data is suggestive of a sedimentary sequence.

These possibilities suggest quite different relationships between these layered rocks and the Granite-Rhyolite province and have different tectonic ramifications and resource potential. One possibility suggests that these stratified sequences represent major middle Proterozoic basins formed between scattered silicic volcanic centers, such as that cropping out in the St. Francois Mountains of SE Missouri. In this model these layers might represent some admixture of volcanic flows, volcaniclastic, and other sedimentary strata, all perhaps injected by mafic sills and local granite plutons. However, the occurrence of the Tillman Greywacke (Ham and others,

1964) encountered in drill holes in southwest Oklahoma and adjacent Texas, southwest of the Wichita uplift, and Precambrian sedimentary rocks recovered from drill holes in southwest Ohio and adjacent states (Fig. 4) (Shrake and others, 1991), give clear evidence that at least some sedimentary material does occur within the broader Granite-Rhyolite province. Preservation of thick and extensive stratified sequences, in turn, might suggest that the whole probably formed within a broadly extensional regime, perhaps analogous to the Basin and Range Province (e.g., Bickford and others, 1986). If these layered rocks are sedimentary, at least in part, these differing hypotheses suggest very different lithologic composition, age, and provenance for these layered rocks with very different implications for resource (hydrocarbon?) potential.

Precambrian Hydrocarbon Potential

Does any part of this layered sequence have hydrocarbon potential (i.e., deep gas)? If some portion of this layered sequence is sedimentary in origin, the sheer volume of this sequence requires that this possibility be considered. However, in considering this point it is important to first recognize that a Precambrian age does *not* in itself preclude the occurrence of hydrocarbons.

Elsewhere in the world Precambrian strata are known to contain hydrocarbons, and in several places major resources have been discovered in Precambrian rocks. For example, in the Lena-Tunguska petroleum province of the Irkutsk Basin on the eastern Siberian platform (Meyerhoff, 1980; Murray and others, 1980) the reservoirs are in Vendian (latest Proterozoic) sandstones as well as the overlying Vendian and Lower Cambrian carbonate strata. The oil is apparently not derived from younger overlying sediments, but indigenous to the Riphean (Upper Proterozoic) and Vendian (uppermost Proterozoic) sequence (Murray and others, 1980). Although estimates vary, the proven and probable reserves in the Lena-Tunguska petroleum province exceed 6.5 Tcf of gas, 270 million bbl of condensate, and 220 million bbl oil (Meyerhoff, 1980). Interestingly, only a fraction of prospective 1,737,000 km^2 area of that basin has been explored, and it has been optimistically suggested that the potential ultimate recovery might reach 100 billion bbl of oil and 200 Tcf of gas and condensate (Meyerhoff, 1980). Oil and gas discoveries have also been reported in Precambrian strata in the Persian Gulf region -- the Birba field of Oman occurs in the Upper Precambrian-Lower Cambrian Ara Salt of the Hupf Group (Alsharhan and Kendall, 1986). Gas has also been discovered in the late Proterozoic Amadeus Basin in Central Australia (Ozimic and others, 1976). Precambrian strata elsewhere in the world also are known to contain viable source rocks (Murray and others, 1980). One familiar example is the 1.0-1.1 Ga Upper Keweenawan Nonesuch Shale on the south shore of Lake Superior where crude oil, as well as optically active alkanes and porphyrins have been found (Barghoorn and others, 1965). Clearly, Proterozoic rocks can contain organic-rich deposits.

Most of the above examples range from Vendian (uppermost Precambrian) to Upper Keweenawan (1.1 Ga), younger than the likely age of any sedimentary sequence associated with or buried beneath the 1.3-1.5 Ga Granite-Rhyolite province of the U.S. midcontinent. However, studies to evaluate the hydrocarbon potential of the McArthur Basin of north-central Australia indicate excellent and laterally extensive source and reservoir facies. Maturation levels in these strata reportedly fall within the oil window throughout the region studied and "live" oil has been observed in a shallow stratigraphic test (Jackson and others, 1986; Fritz, 1987; Jackson and others, 1988).

These oil-bearing and organic rich strata of the McArthur Basin are of particular importance to the issue of hydrocarbon potential of stratified sequences in the Granite-Rhyolite province of the U.S. midcontinent. This is because the strata of the McArthur Basin are *Middle Proterozoic* (1.4-1.8 Ga) in age, the same age as the rocks of the Granite-Rhyolite province of the U.S. midcontinent. Therefore, the mere age of any buried Proterozoic sedimentary sequence in the U.S. midcontinent does *not* in itself preclude hydrocarbon potential. If organic rich sedimentary material is present in the Precambrian layered sequences observed beneath the U.S. midcontinent and unmetamorphosed by local granite intrusions of the Granite-Rhyolite province, its age alone does not preclude hydrocarbon (deep gas) potential.

PROJECT DESCRIPTION

A key goal of this project was to seek and reprocess available industrial seismic reflection data in the U.S. midcontinent; and together with the COCORP profiles, potential field and drill hole data, to further evaluate the distribution, structure, and origin of these enigmatic Precambrian layered rocks.

In the course of oil and gas exploration in the Phanerozoic intracratonic basins of the U.S. midcontinent a vast amount of industrial seismic reflection data has been collected. Although most industrial seismic reflection data sets are proprietary, this effort provided a mechanism and impetus to seek the release some of these data to study the basement rocks of the region.

Industrial seismic reflection data of the region were originally collected with shallow targets in the Paleozoic strata in mind. However, these industrial data were commonly collected to travel times of 2 seconds or more (6+ km) and potentially contain significant information about the Precambrian 'basement' of the region. The original industrial processing of these data mainly concentrated on economic targets within the Phanerozoic section; therefore, dedicated reprocessing of the deeper part of these industry data is likely to significantly improve the image of basement structures and can potentially reveal much about the distribution and structure of the Precambrian layered assemblage beneath the Paleozoic cover. Moreover, most of the industrial data available from this region are vibroseis. Consequently, for those vibroseis industrial data sets available in a pre-correlation format the reprocessing can include extended vibroseis correlation which can extract even longer records and deeper information.

Extended-Correlation Reprocessing of Industry Data

Extended vibroseis correlation is a modification of the usual correlation process and extracts additional information from the latter part of the originally recorded data (i.e., Okaya and Jarchow, 1989). This is possible because the frequencies which were put into the ground at the beginning of the vibroseis sweep can be received and recorded as reflected energy for up to the total listening time, whereas the frequencies of the latter part of the sweep have a shorter part of the total listening time over which they can be received as reflection energy. The normally used correlation process only extracts the travel time for which all frequencies (full bandwidth) are potentially present (Fig. 6). Although there is a progressive narrowing of frequency bandwidth with the extended correlation (Fig. 6), accompanied by a progressive decrease in resolution, additional and considerably deeper usable information can be extracted from the original data by this method. How much deeper depends upon a number of factors such as the original sweep length, total listening time and sweep frequencies, but in many cases

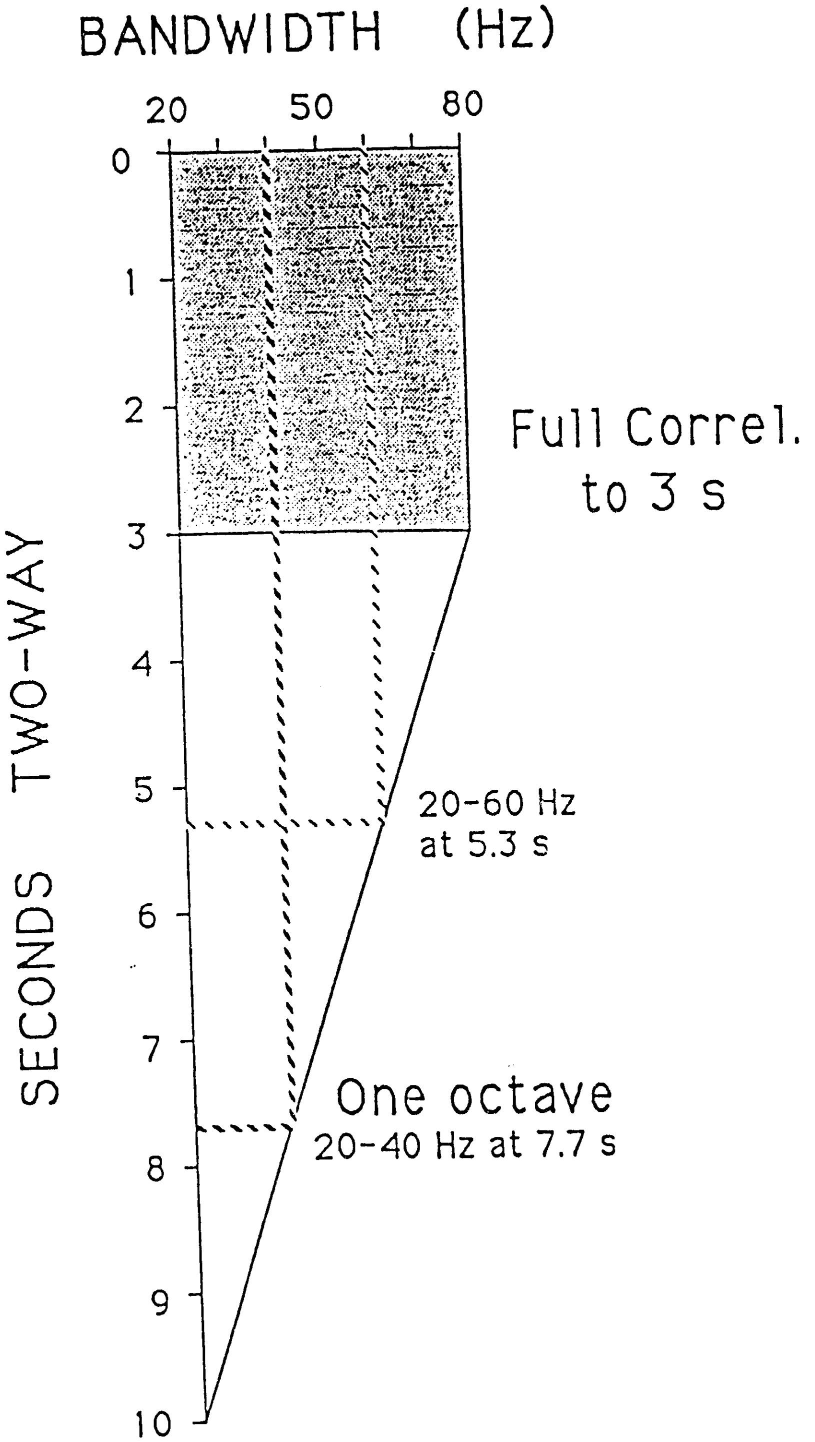

Figure 6. Example Bandwidth Diagram for Extended Vibroseis Correlation of 20-80 Hz Data with 10 Second Listening Time and 7 Second Sweep.

nearly twice the original full-correlation time is possible (in places to depths as great as 20 km).

This kind of reprocessing of existing vibroseis reflection data provided by industry is clearly a cost-effective way to greatly expand the knowledge of the distribution and nature of deeper crustal structure and these Precambrian layered rocks in particular.

The reflection data provided Cornell courtesy of the donor companies (see Acknowledgments) represent millions of dollars of original acquisition costs. Therefore, this project exemplifies an important role of government-sponsored academic research and technology transfer between industry and academic research. By providing data, industry can foster the study of a sequence of strata that is too unknown and risky for industry to consider as a viable economic target at present. However, the mere presence of a sequence of supracrustal rocks of this thickness and volume requires it be addressed in any comprehensive evaluation of U.S. resource potential.

RESULTS

Layered Rocks on COCORP and Industry Data Beneath Illinois and Indiana

As described above, the COCORP deep seismic reflection profiles across southern Illinois and Indiana (Figs. 1 and 2) image a thick sequence of layered rocks which can be traced for close to 200 km in an E-W direction with individual reflections continuing for as much as 80 km (Pratt and others, 1989). This layered sequence thickens from west to east from 1 to 3 times as thick as the overlying Paleozoic cover (Fig. 2).

The Union Oil No. 1 Cisne Community well in Wayne County, Illinois, lying within 1 km of the COCORP profile at about VP 990 (Figs. 2 and 4), reportedly encountered 'granitic' basement at a depth of about 3.5 km. A synthetic seismogram calculated from the sonic log from this well correlates well with the reflections from the Paleozoic sequence and indicates that the Precambrian 'basement' identified was encountered at about 1.5 seconds (Fig. 7) (Pratt et al., 1992). This location, however, is underlain by another 3 km (1+ s) of Precambrian layered rocks (Fig. 2). If granitic Precambrian rock were indeed encountered in this well, then either it intrudes or overlies the layered sequence.

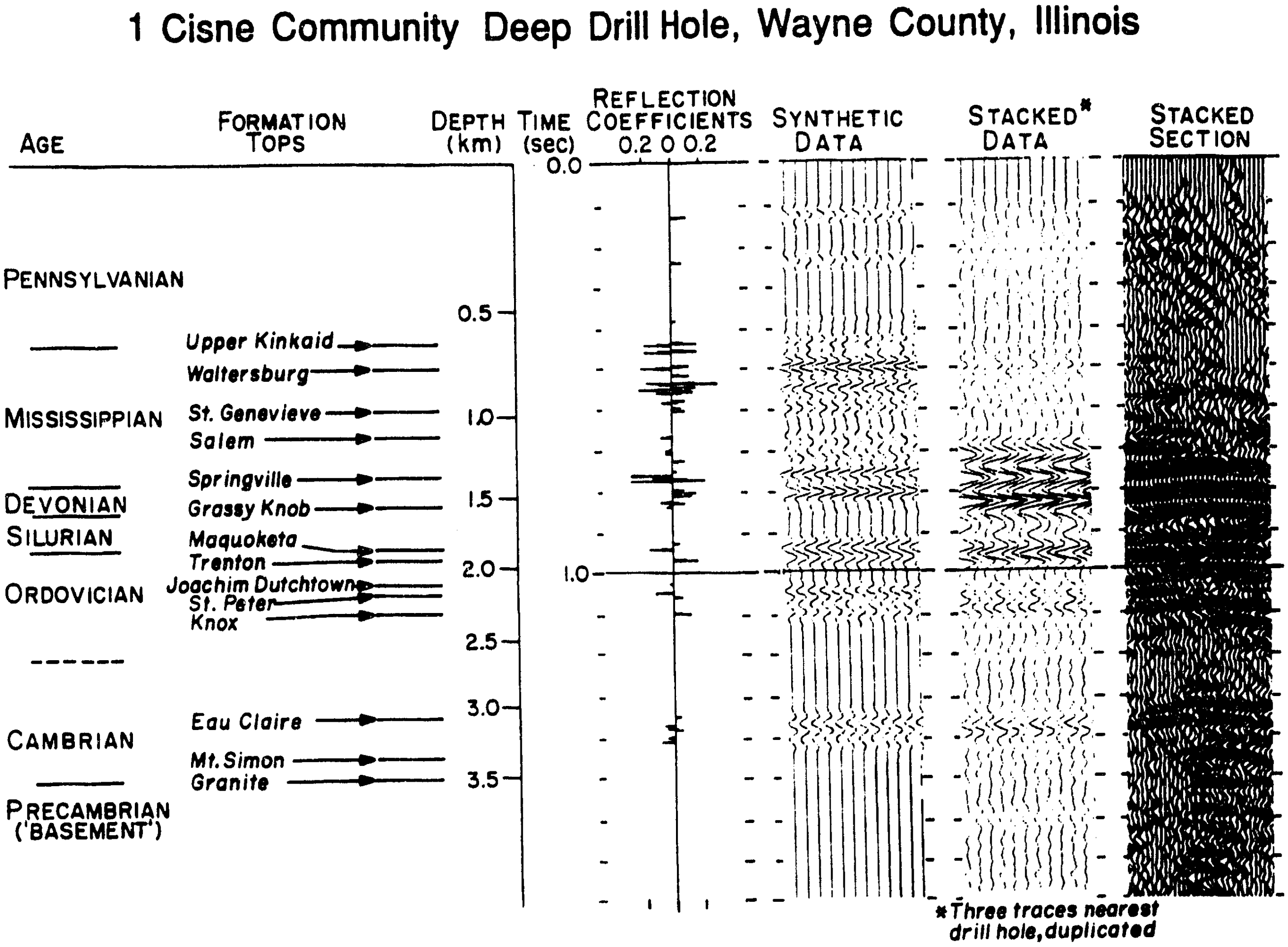

Figure 7. Synthetic Seismogram Calculated from the Sonic Log of the Cisne Community No. 1 Drill Hole in Wayne County, Illinois, Compared With the COCORP Profile about 1 km Away. (From Pratt, Hauser, and Nelson, 1992)

This Precambrian layered sequence is also observed on the reprocessed industry data from the surrounding parts of southwest Indiana and southeastern Illinois (Fig. 8). On a grid of industry lines just north of the COCORP profile in southern Illinois (Figs. 8 and 9) a similar stratigraphy is observed. On these industry profiles (Fig. 9) a Precambrian layered sequence about 1 second thick (2.5-3 km) lies conformable beneath about 3.5 km of Paleozoic rocks of the Illinois Basin. The Paleozoic and Precambrian sequences correlate well with those observed on the COCORP profile (Fig. 10); however, these industry profiles clearly image an angular unconformity at the base of the Precambrian strata at about 3.5 seconds (~10 km depth) (Fig. 9). Sideswipe or out-of-plane geometries for the reflections beneath this angular unconformity can be discounted because they can easily be traced across the 3-D grid of intersecting industry profiles (Fig. 9b). This angular unconformity is expressed on the COCORP profiles across southern Illinois and Indiana as a regionally extensive strong zone of reflections at the base of the horizontally layered Precambrian sequence (Fig 2).

It should be emphasized that this basal angular unconformity is observed on the industry data only as a result of extended vibroseis correlation reprocessing; everything beyond 2 seconds on Figures 9a and 9b result from extended correlation. This example clearly demonstrates the value of this reprocessing technique and its ability to reveal fundamental *new* information from *old* data sets.

Precambrian layered rocks are also seen on industry data from southwestern Indiana (Figs. 8 and 11). However, their base is not as clearly identified as on the profiles in Illinois, perhaps due to a combination of both a thickening of the layered sequence in that direction, as observed on the COCORP data across southern Indiana (Fig. 2a), as well as the progressive loss of energy and resolution with greater travel time related to the extended correlation procedure as described farther above.

A likely equivalent layered sequence and underlying angular unconformity are also observed on industry data in east-central Illinois (Figs. 8 and 12), but these features have not yet been observed on the scattered and sparse industry reflection data from farther north in Illinois (Fig. 8). Although strong basement reflections are imaged on some of these data at greater depth (Figs. 13 and 14), any relationship of these isolated reflections to the layered sequence observed on the seismic profiles farther south, is not yet clear. From this it appears that the layered sequence disappears to the north somewhere in north-central Illinois, perhaps

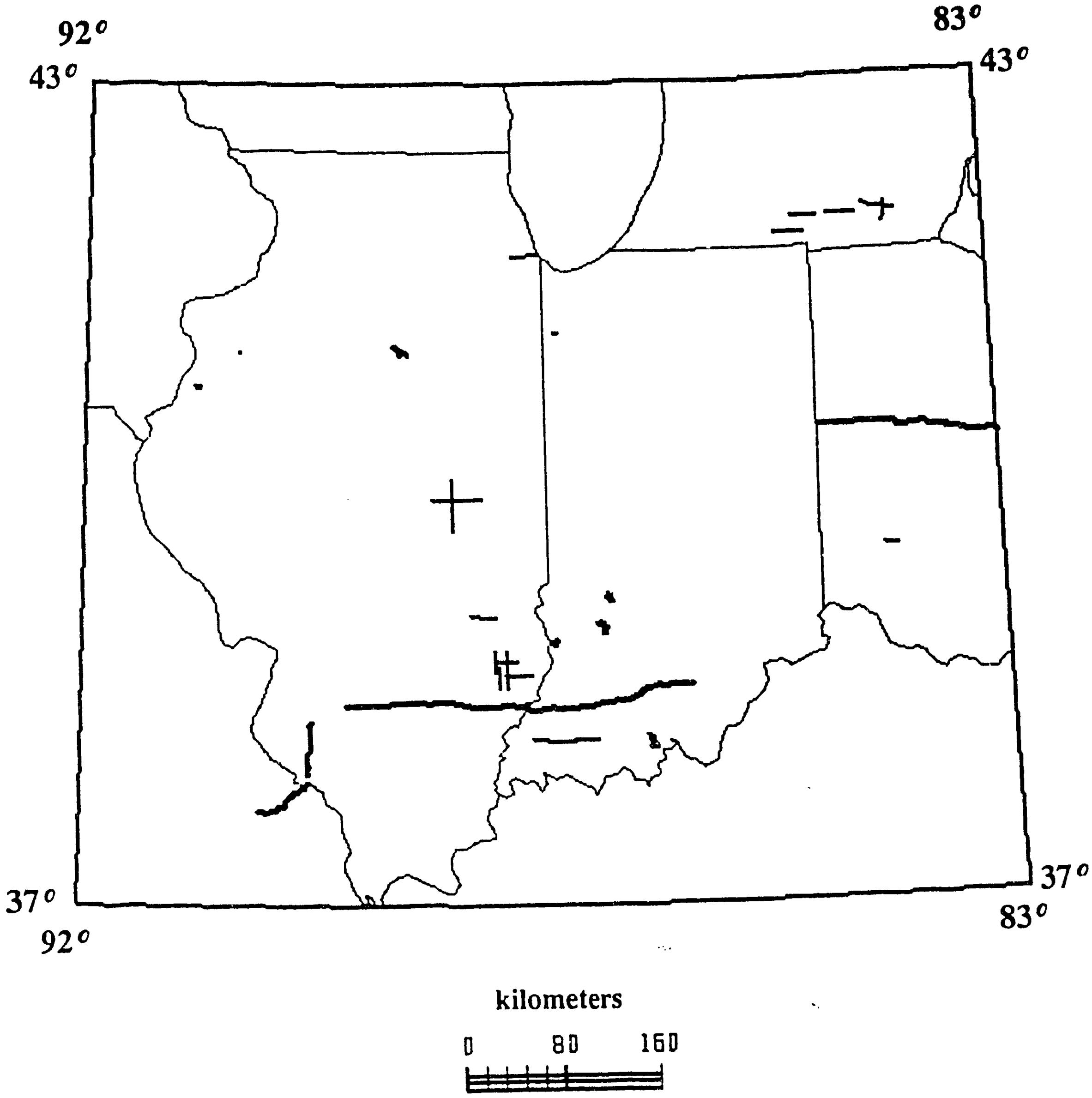

Figure 8. Seismic Data Available for this Project in Illinois Basin Region

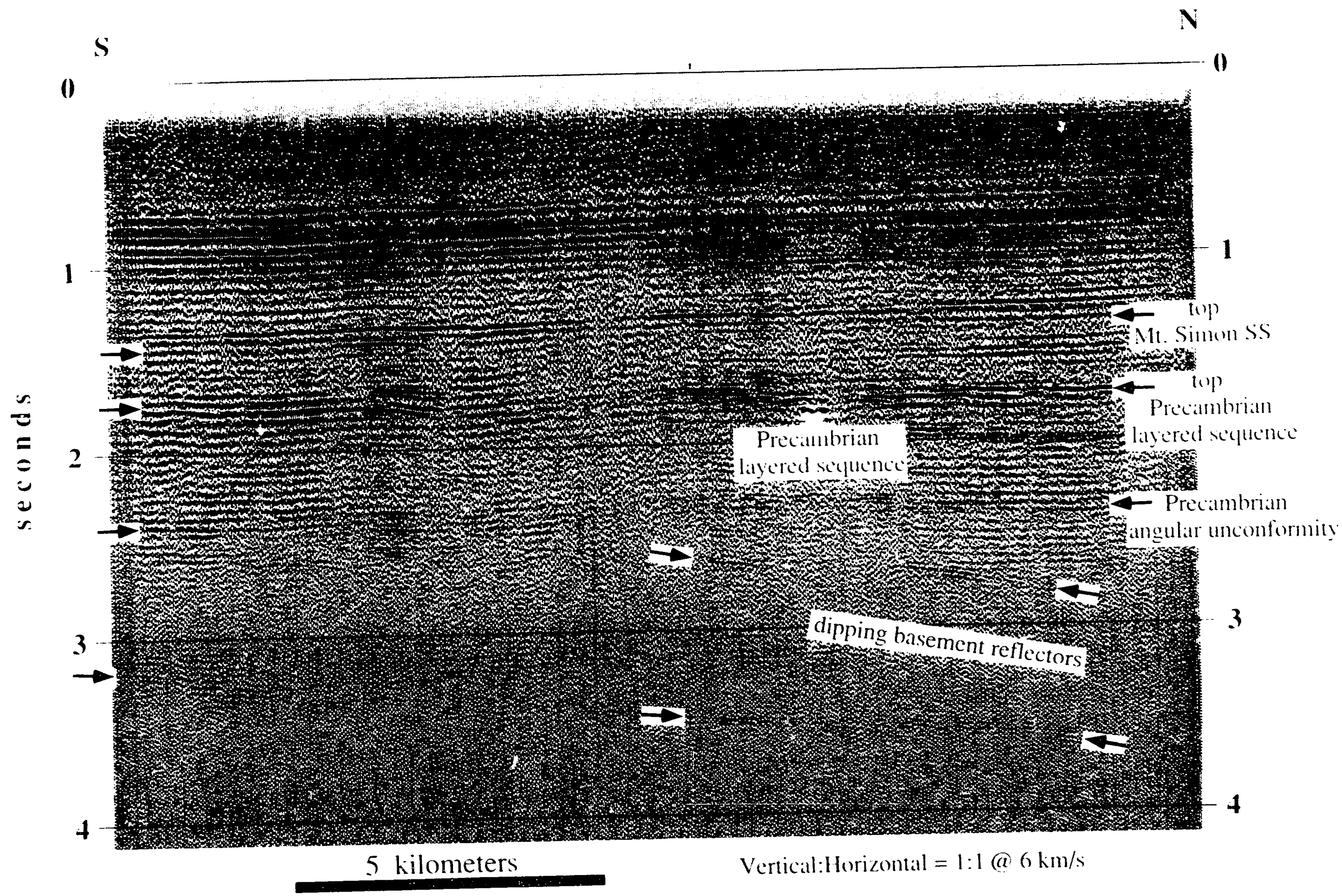

Figure 9a. Sample of the Amoco Data from Southern Illinois Showing the Well-Layered Precambrian Sequence and the Underlying Angular Unconformity. Data Below 2 Seconds is from Extended Vibroseis Correlation.

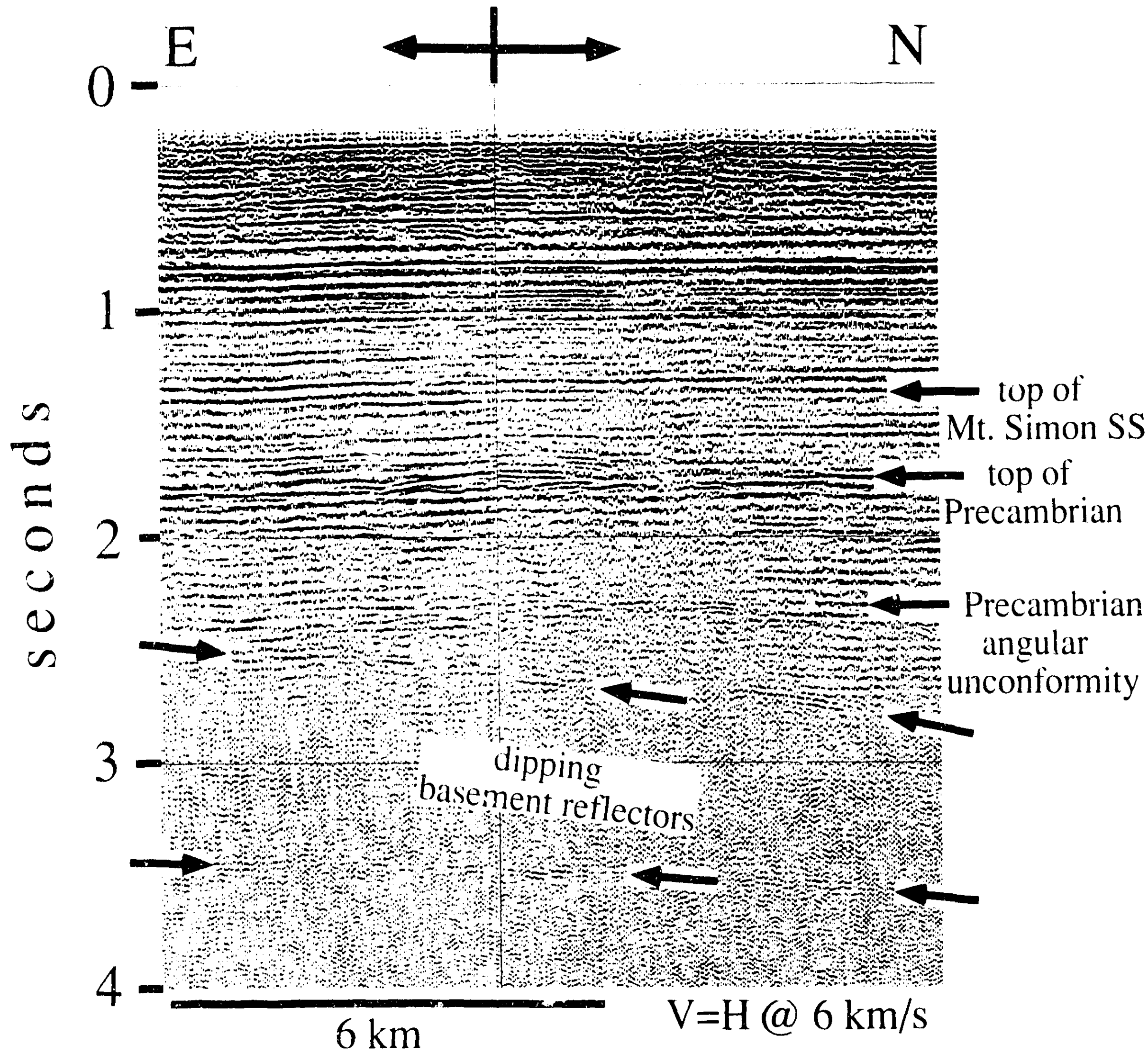

Figure 9b. Sample of Two Intersecting Amoco Profiles from Southern Illinois Showing the Well-Layered Precambrian Sequence and the Underlying Angular Unconformity. Data Below 2 Seconds is from Extended Vibroseis Correlation.

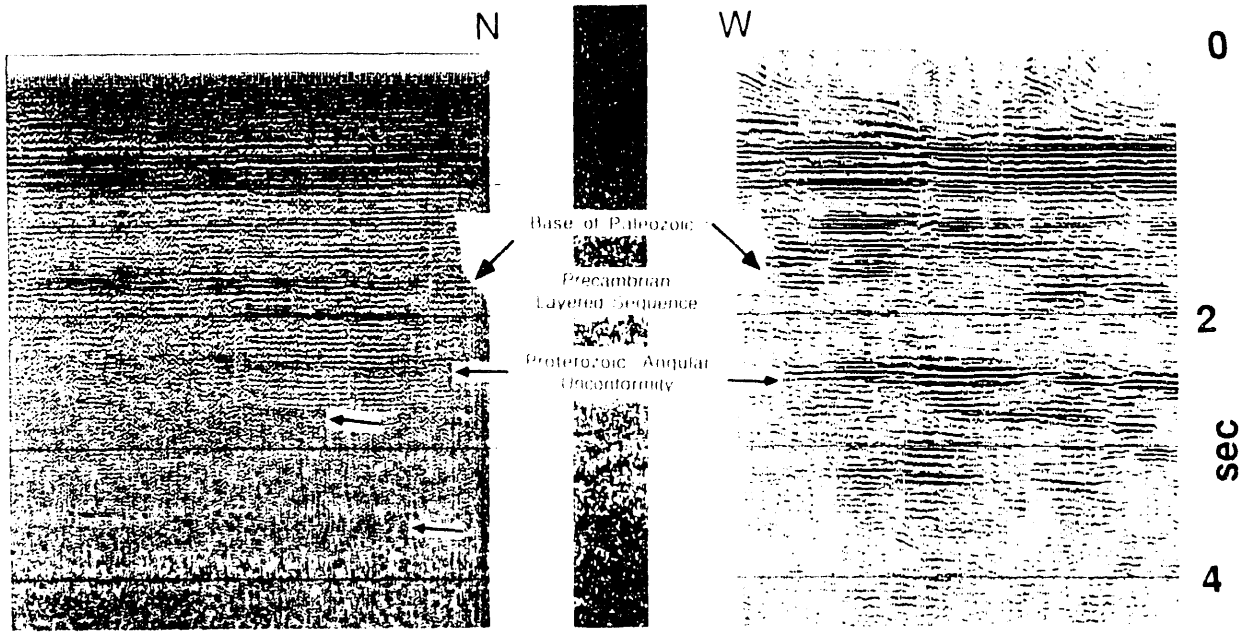

Figure 10. Correlation of the Paleozoic and Precambrian Stratigraphy and Proterozoic Angular Unconformity Correlate between the Industry Data (Fig. 9) and the COCORP Profile in Southern Illinois.

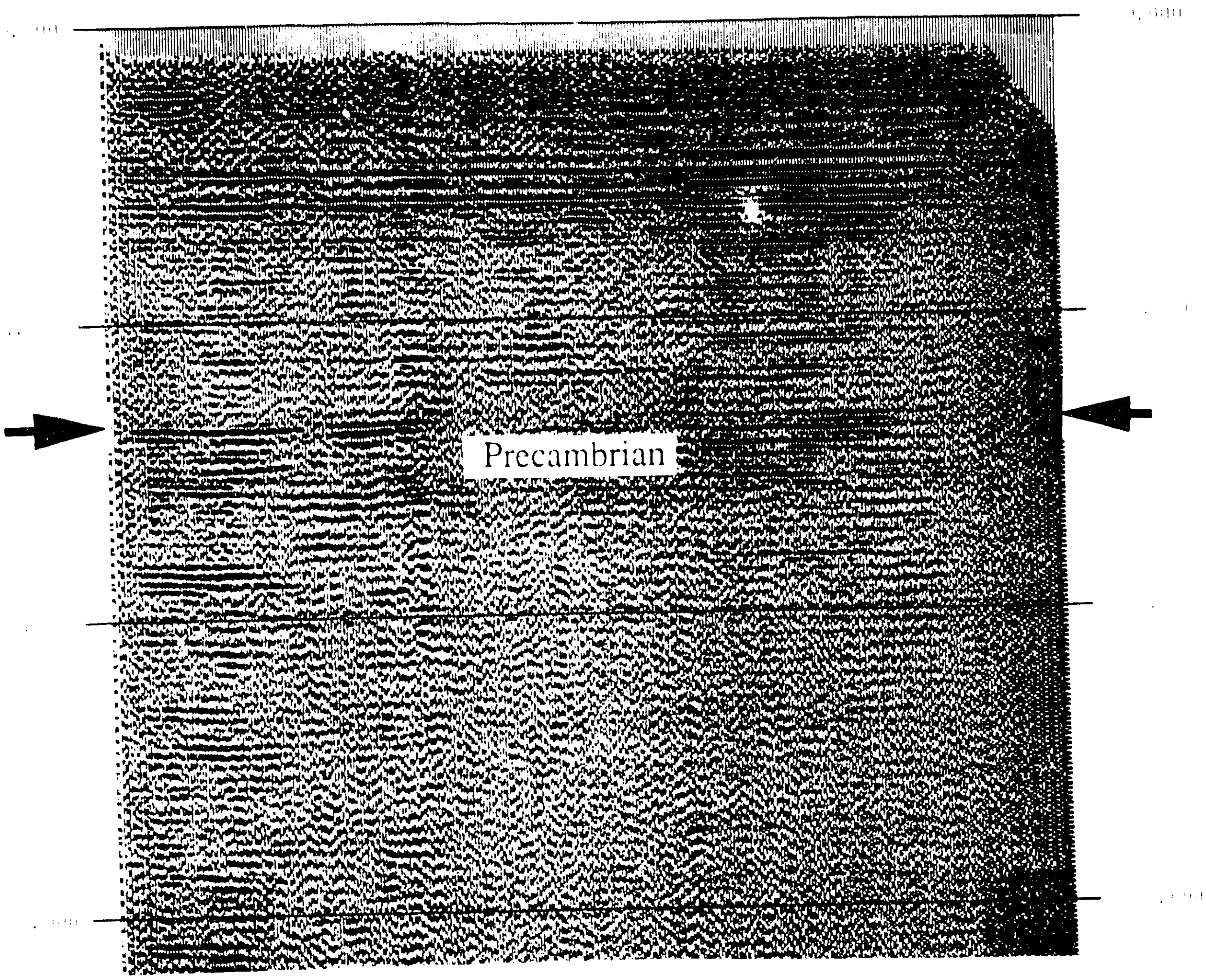

Figure 11. Industry data from Southwestern Indiana Revealing Layered Precambrian Rocks.

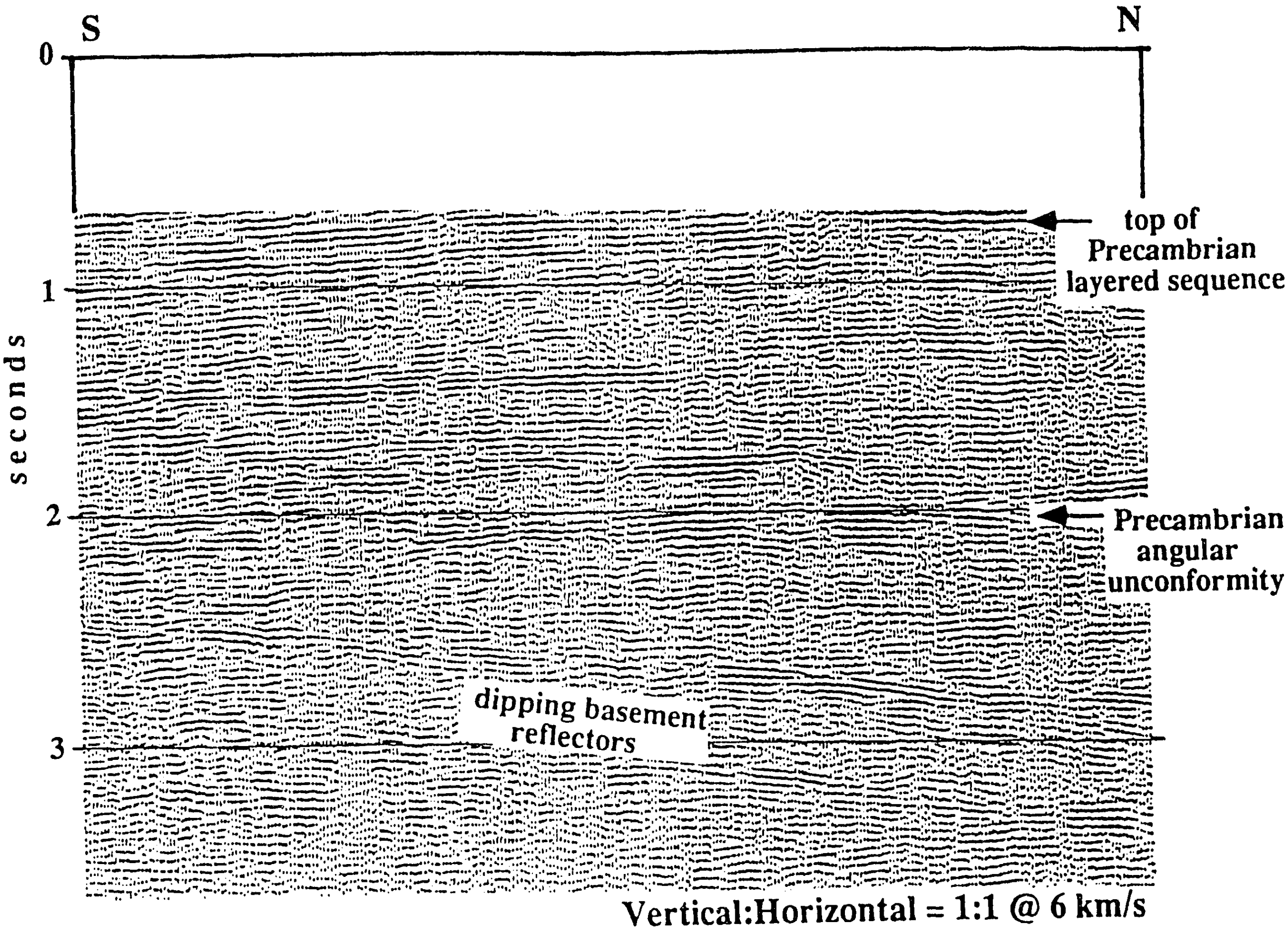

Figure 12. Sample of the EXXON Data from Central Illinois Showing the Well-Layered Precambrian Sequence and the Underlying Angular Unconformity. Publication of Data above).7 Seconds is Restricted.

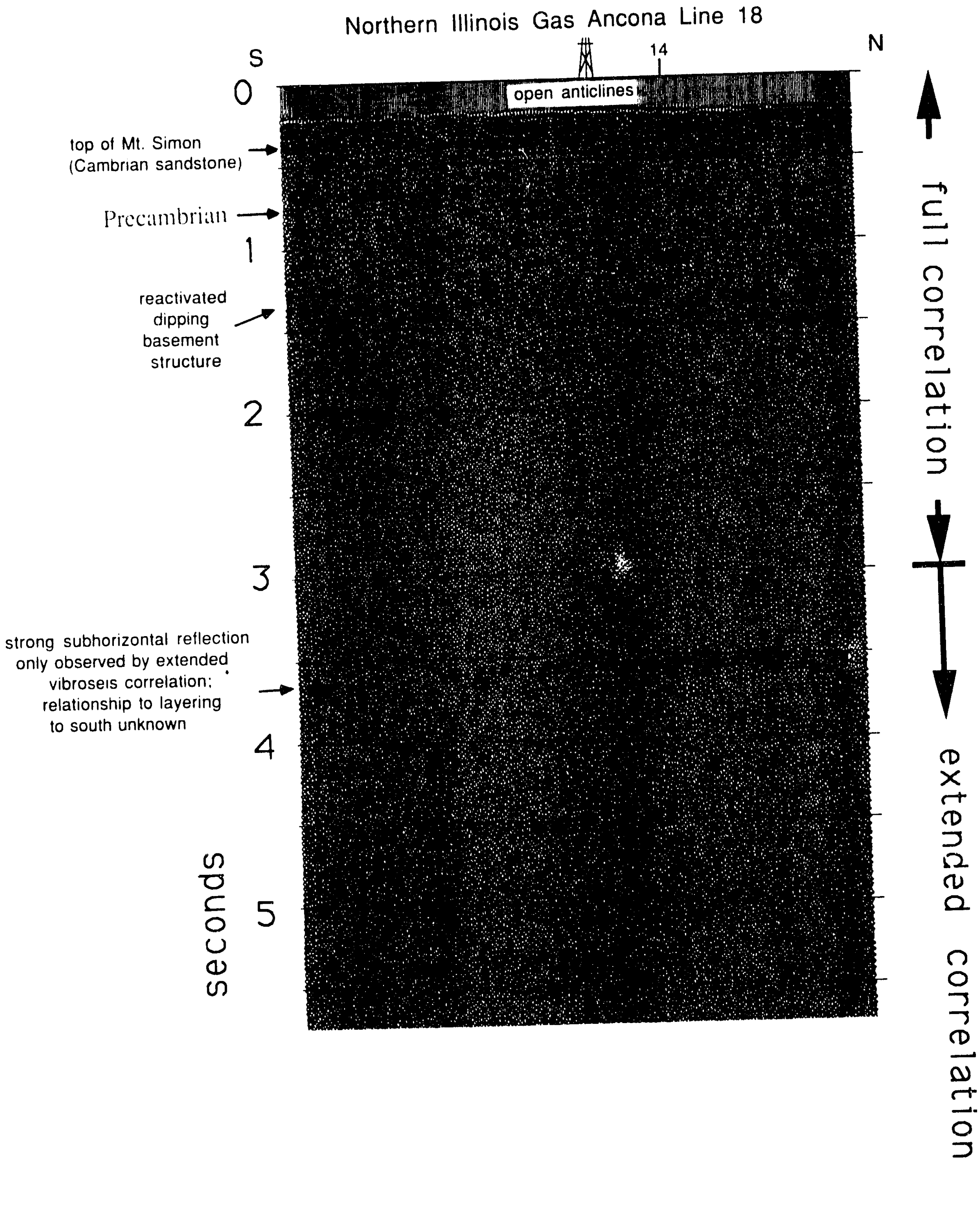

Figure 13. Industry Data from North-Central Illinois near Ancona. Strong Reflection at about 3.5 Seconds is a Completely New Observation because All Data Below 3 Seconds results from Extended Vibroseis Correlation.

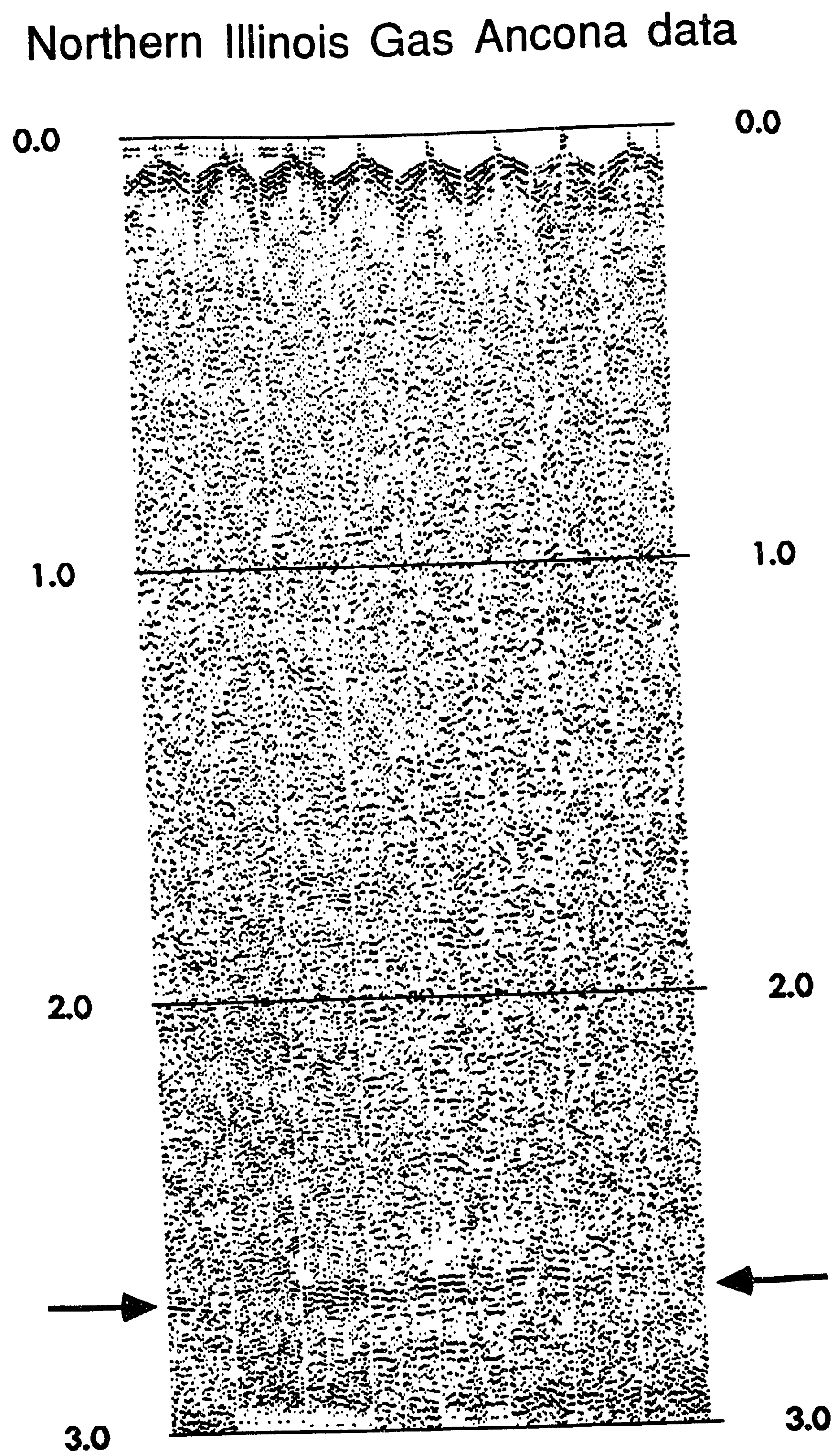

Figure 14. 100% Seismic Data Digitized from Original Analog Recordings of 5-20# Dynamite Shots near Thayer in Northwestern Indiana. Clear Reflection Observed at ~2.6 Seconds.

removed by erosion prior to deposition of the Paleozoic platform cover or experiencing a lateral change like that observed on the COCORP profiles approaching the St. Francois Mts.

The top of the layered assemblage in Illinois and Indiana is commonly conformable with the overlying Paleozoic platform strata (Figs. 2, 9, and 11) which can make identifying the contact between the Paleozoic cover and Precambrian layered sequence difficult. The Paleozoic stratigraphy can be easily identified by correlation with that seen the COCORP profile where it is identified by the Cisne well described above (Fig. 2b). In some places, however, the unconformity between the Paleozoic strata and underlying Precambrian layered sequence is a zone of disrupted reflections (i.e., Fig. 9) irregularities at the base of the Paleozoic sequence, clearly suggesting late Precambrian and/or earliest Paleozoic faulting. The Paleozoic section and the Precambrian 'basement' horizon (Figs. 2 and 4) can also be extrapolated from the Farm Bureau #1 Brown well in Lawrence Co., south-central Indiana (Dawson, 1960) near the east end of the COCORP profile (Fig. 4). The mafic rock encountered in this well suggests that the strong reflection at the top of basement on the COCORP profile in southern Indiana could be a basaltic flow on the Precambrian surface, possibly of Keweenawan(?) age.

Grenville Foreland Structures in Layered Rocks Beneath Western Ohio

Precambrian layered rocks are also observed on COCORP data within the Granite-Rhyolite province beneath western Ohio (Fig. 4); however, there they are apparently deformed in the foreland of the 1.1 Ga Grenville Orogen to the east. On the COCORP profile across western Ohio (Fig. 15) layered rocks are variably imaged but the data suggest a footwall thrust ramp and hanging-wall ramp anticline of a foreland thrust belt (Hauser, 1993). One of the few published petrographic descriptions of basement rocks encountered in drill holes near the COCORP line (white-filled circles on Fig. 4) west of the Grenville Front Tectonic Zone, reports rhyolite (McCormick, 1961), which together with limited isotopic data suggests that these foreland structures are largely developed in rocks of the Granite-Rhyolite province. Published Rb-Sr apparent ages for rhyolite basement samples near the COCORP line in western Ohio are 1.28-1.32 Ga and are comparable to Rb-Sr ages found in the Granite-Rhyolite province elsewhere in Indiana, Illinois and Missouri (Denison and others, 1984; Lidiak and others, 1966; Hoppe and

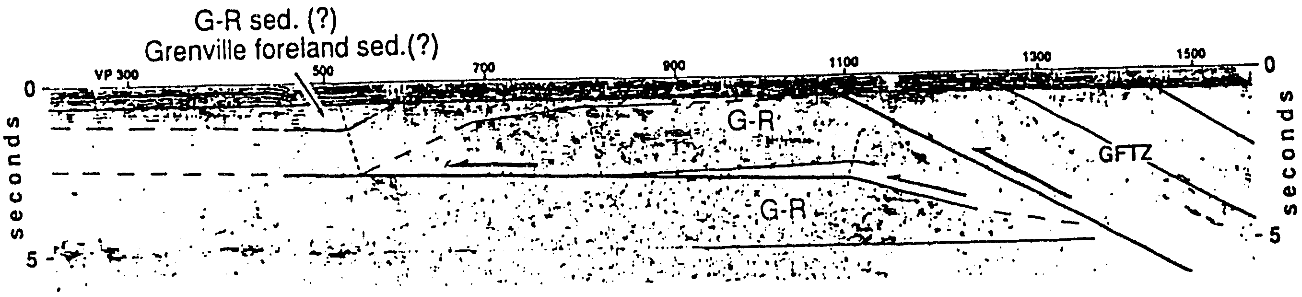

Figure 15. Part of COCORP Line OH-1 Across West-Central Ohio (see Fig. 1, and Bold Line, Fig. 4) Suggesting Foreland Thrust Structures within Granite-Rhyolite Province Rocks. Grenville Front Tectonic Zone (GFTZ); Paleozoic Platform Cover (Pz); Granite-Rhyolite Province Rocks (G-R) (From Hauser, 1993)

others, 1983; Lucius and Von Frese, 1988). These Rb-Sr ages, however, clearly represent only minimum ages since U-Pb ages on zircon from scattered wells throughout the eastern Granite-Rhyolite province cluster within ~30 Ma of 1480 Ma (black-filled circles on Figs. 1 and 4) (Bickford and others, 1986; Van Schmus and others, 1987; Denison and others, 1984).

Precambrian Sedimentary Rocks Beneath SW Ohio: Late Precambrian Rift, Grenville Foreland Basin, or Part of the Regional Layered Sequence?

The structures on the COCORP line in western Ohio are the first evidence of a significant Grenville-age foreland thrust belt in eastern North America, however, a short, shallow seismic line in SW Ohio (Fig. 16 and 'A' on Fig. 4) also reveals an E-dipping sequence of well-layered Precambrian rocks (Shrake and others, 1990, 1991). Moreover, a recent drill hole into the upper part of this dipping sequence encountered unmetamorphosed clastic sedimentary rocks (Shrake and others, 1990, 1991). What is the relationship of the Precambrian layered rocks on this short seismic line, and the sedimentary rocks drilled in its upper part, to the Precambrian layered sequence observed on the COCORP and reprocessed industry data elsewhere across the midcontinent?

The short seismic line in SW Ohio (Fig. 16) reveals a sequence of prominently layered Precambrian rocks dipping ~10° east beneath the Paleozoic cover. In view of the larger-scale Grenville foreland structures observed on the COCORP data to the north and the proximity of the data in SW Ohio to the Grenville Front ~25 km to the east (Fig. 4), the east dip of the *entire* layered Precambrian sequence imaged on this profile may result from its position above a footwall ramp to a deeper Grenville thrust fault (Hauser, 1993).
The dipping layered sequence below the Phanerozoic cover on this short seismic line greatly resembles that imaged on COCORP data in Indiana and Illinois (Fig. 17) in both reflection prominence and continuity. The drill hole which recovered unmetamorphosed clastic sedimentary rocks (termed the Middle Run Formation by Shrake and others, 1990, 1991), penetrated the upper, less reflective part of the dipping Precambrian sequence (Fig. 16 and 17), but did not penetrate the deeper strong reflectors. Similar unmetamorphosed sedimentary rocks are also reported from other nearby drill holes (white squares on Fig. 4), and were originally interpreted as part of a late Precambrian rift (Keweenawan?) (Shrake and others, 1990, 1991).

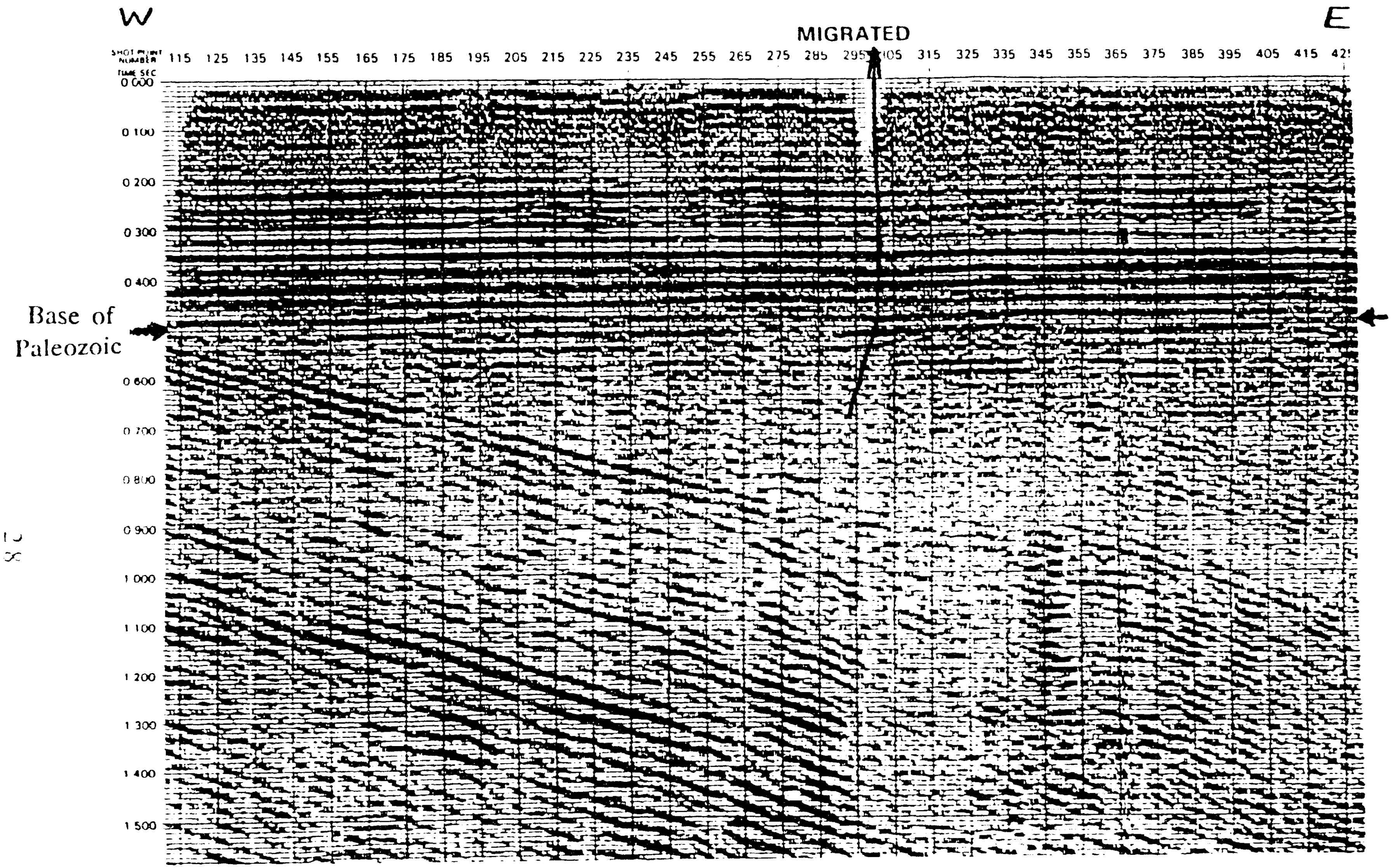

Figure 16. Seismic Data from SW Ohio with Warren County Drill Hole Shown (See Location, Fig. 4) (From Shrake et al., 1990). Well Drilled Several 100 Feet of Precambrian Clastic Rocks.

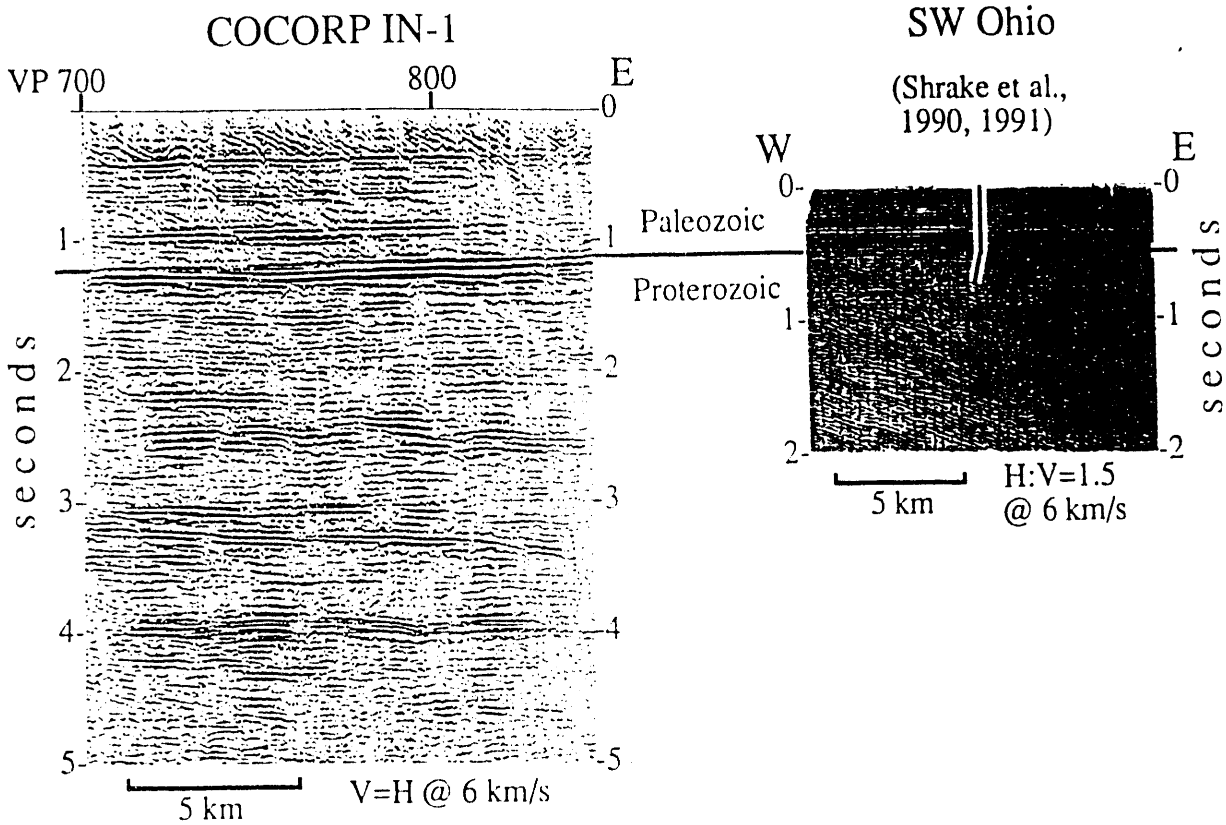

Figure 17. Dipping Layered Rocks on the Short Seismic Line in SW Ohio Compared with the Layered Sequence on COCORP line IN-1 in South-Central Indiana (from Hauser, 1993). Data are at Same Vertical Scale with the Base of the Paleozoic Cover Aligned. Drill Hole Shown on SW Ohio Data Encountered Unmetamorphosed Precambrian Clastic Sedimentary Rocks.

In light of the observation of Grenville thrust structures on COCORP line OH-1 to the north, developed within rocks of the Granite-Rhyolite province, and the similarity of the strongly layered rocks imaged beneath SW Ohio to those on COCORP data in Indiana and Illinois (Fig. 17), two alternative hypotheses must also be considered (Figs. 18 and 19) (Hauser, 1993):

[1] These Precambrian sedimentary rocks may be part of an early Grenville foreland basin deposited upon older layered rocks of the Granite-Rhyolite province (Fig. 18A), or

[2] these Precambrian sedimentary rocks may be older and indicate that unmetamorphosed sedimentary strata are an important constituent of the prominently layered and widespread sequence within the Granite-Rhyolite province (Fig. 19A).

In any case, these sedimentary and underlying layered rocks were apparently deformed within a Grenville foreland thrust belt west of the Grenville Front Tectonic Zone and subsequently eroded and overlain by Phanerozoic platform strata (Figs. 18D and 19D).

Possible Regional Distribution of the Precambrian Layered Sequence

The COCORP data and industry seismic reflection data reprocessed for this project has revealed that Precambrian layered rocks are widespread. These occurrences of well-layered basement rocks also correspond to regions where aeromagnetic data exhibits a subdued and low frequency character of low magnitude (Figs. 20 and 21) (Pratt and others, 1992). Using this aeromagnetic character as a guide, the known occurrences of Precambrian layered rocks may extend beneath much of Illinois and most of Indiana into southern Michigan and Ohio to the Grenville Front, and across large parts of north Texas (Fig. 22). Other regions, such as northern Arkansas (Fig. 22), have a similar aeromagnetic character and might be speculatively underlain by similar layered sequences, but in that region supporting seismic reflection data are absent.

So far, these layered sequences are confined to the region of the Granite-Rhyolite province (Fig. 22), suggesting either a genetic relationship (Fig. 19) or that more than one sequence of stratified

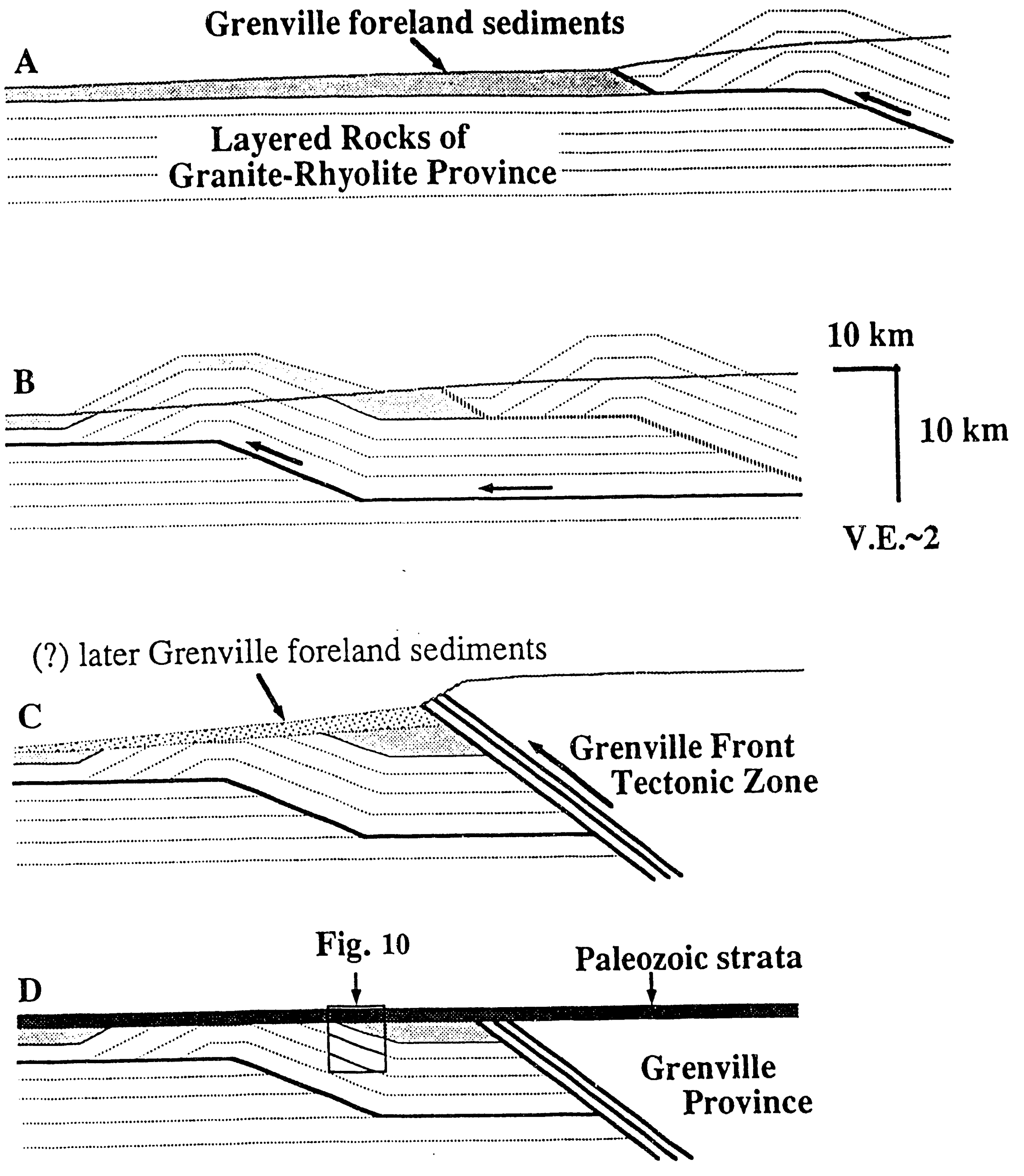

Figure 18. Model Suggesting the Precambrian sedimentary rocks (gray) were Deposited in a Grenville Foreland Basin (from Hauser, 1993). The Interpreted Position of the SW Ohio Seismic Data (Fig. 16) Shown in D. (From Hauser, 1993)

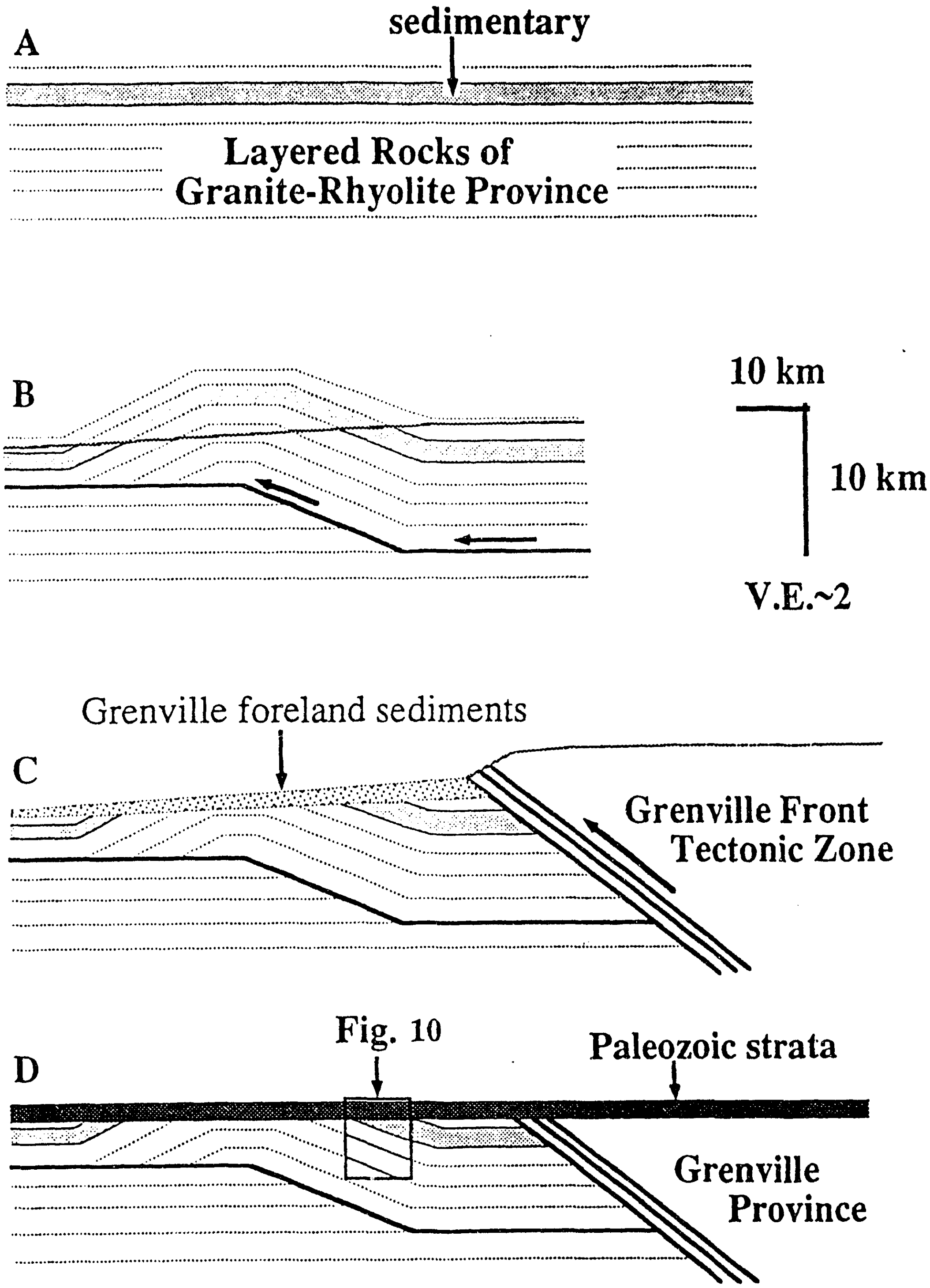

Figure 19. Model Suggesting the Precambrian Sedimentary Rocks as Part of the Granite-Rhyolite Province Layered Sequence (from Hauser, 1993). Interpreted position of SW Ohio seismic data (Fig. 16) shown in D. (From Hauser, 1993)

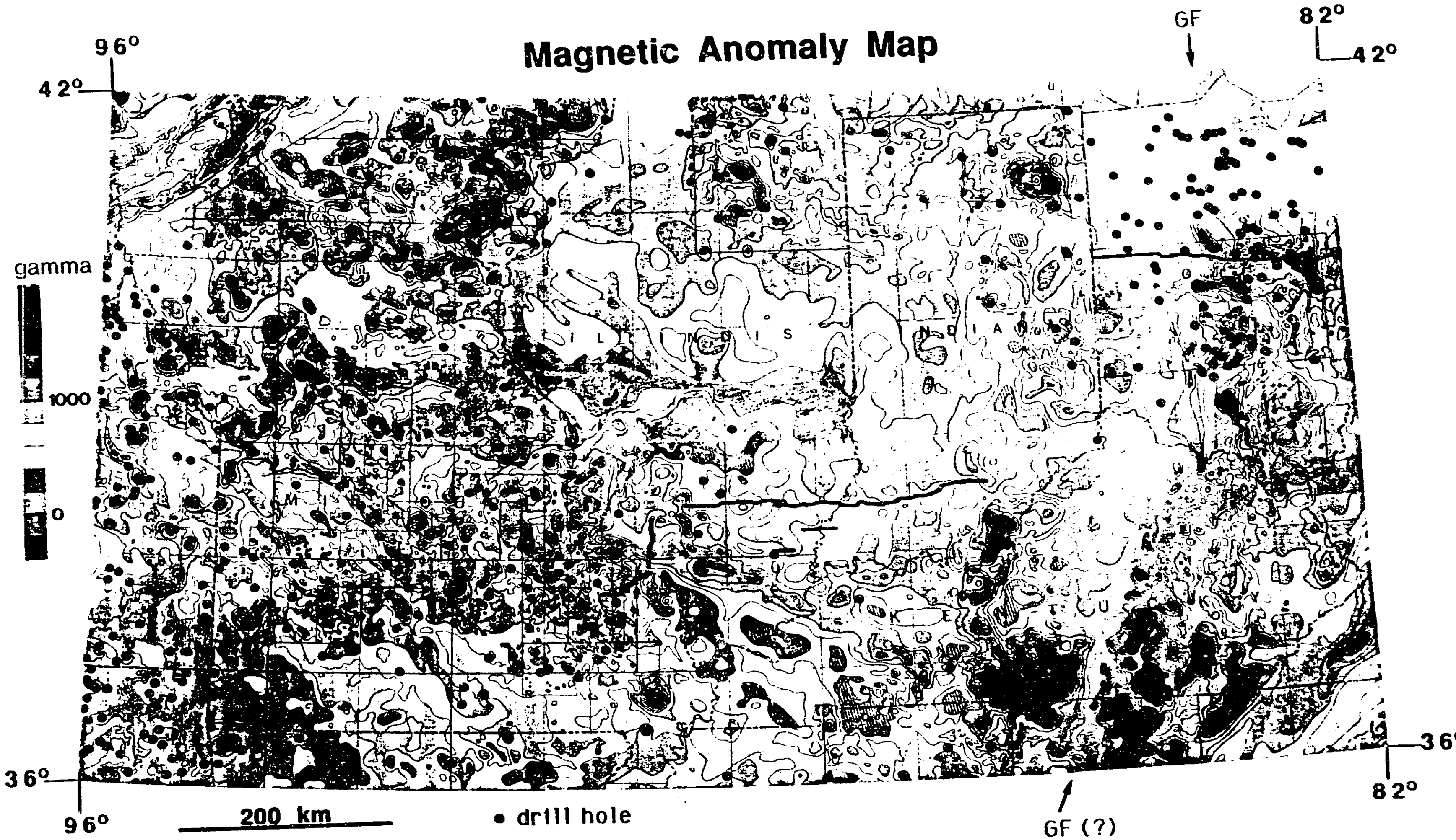

Figure 20. Magnetic Anomaly Map (1982 SEG) of Eastern Midcontinent Region Showing COCORP Profiles as Bold Lines and Basement-Penetrating Drill Holes as Black Dots. (From Pratt, Hauser and Nelson, 1992)

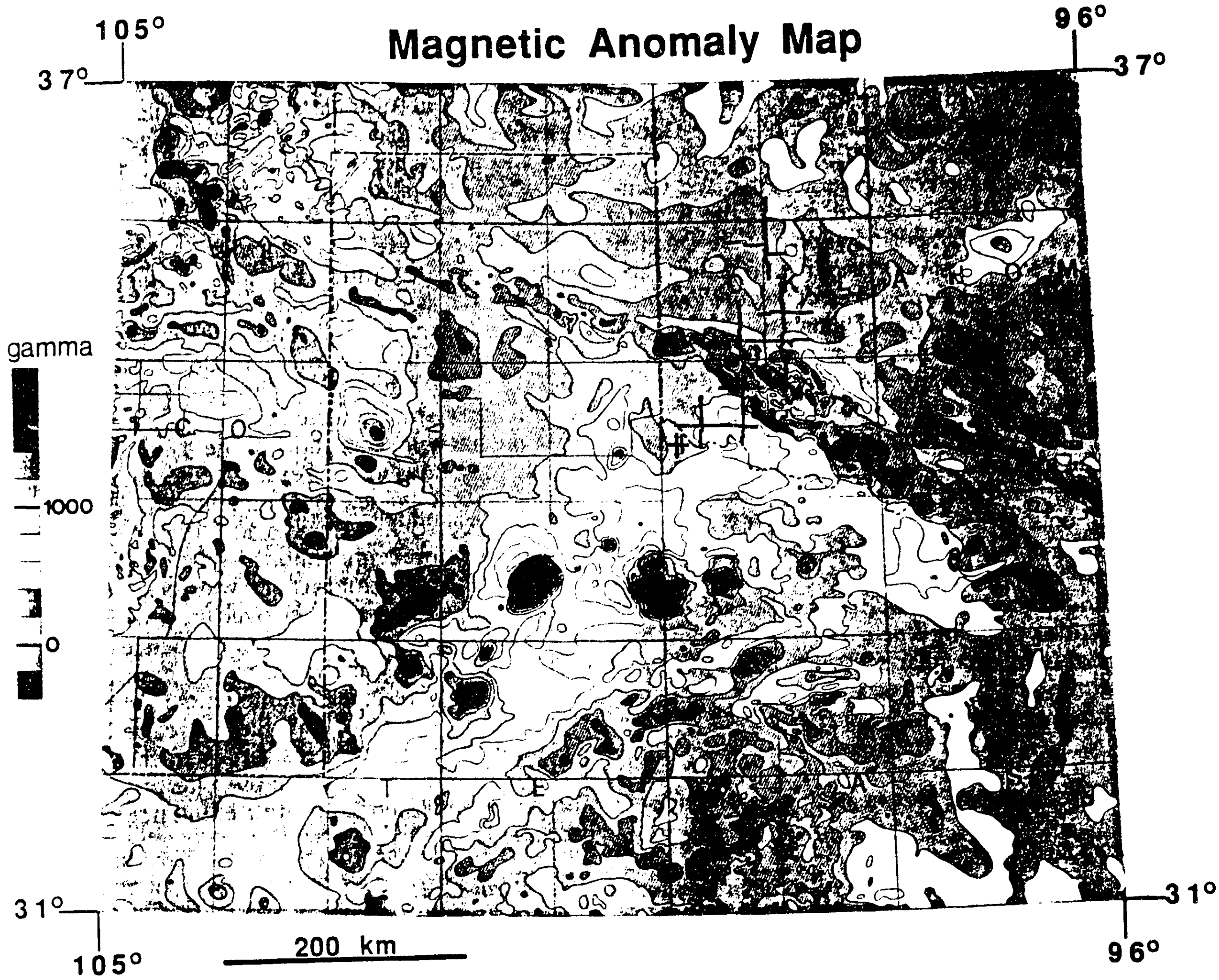

Figure 21. Magnetic Anomaly Map (1982 SEG) of Southern Midcontinent Region Showing COCORP Profiles as Bold Lines (From Pratt, Hauser and Nelson, 1992).

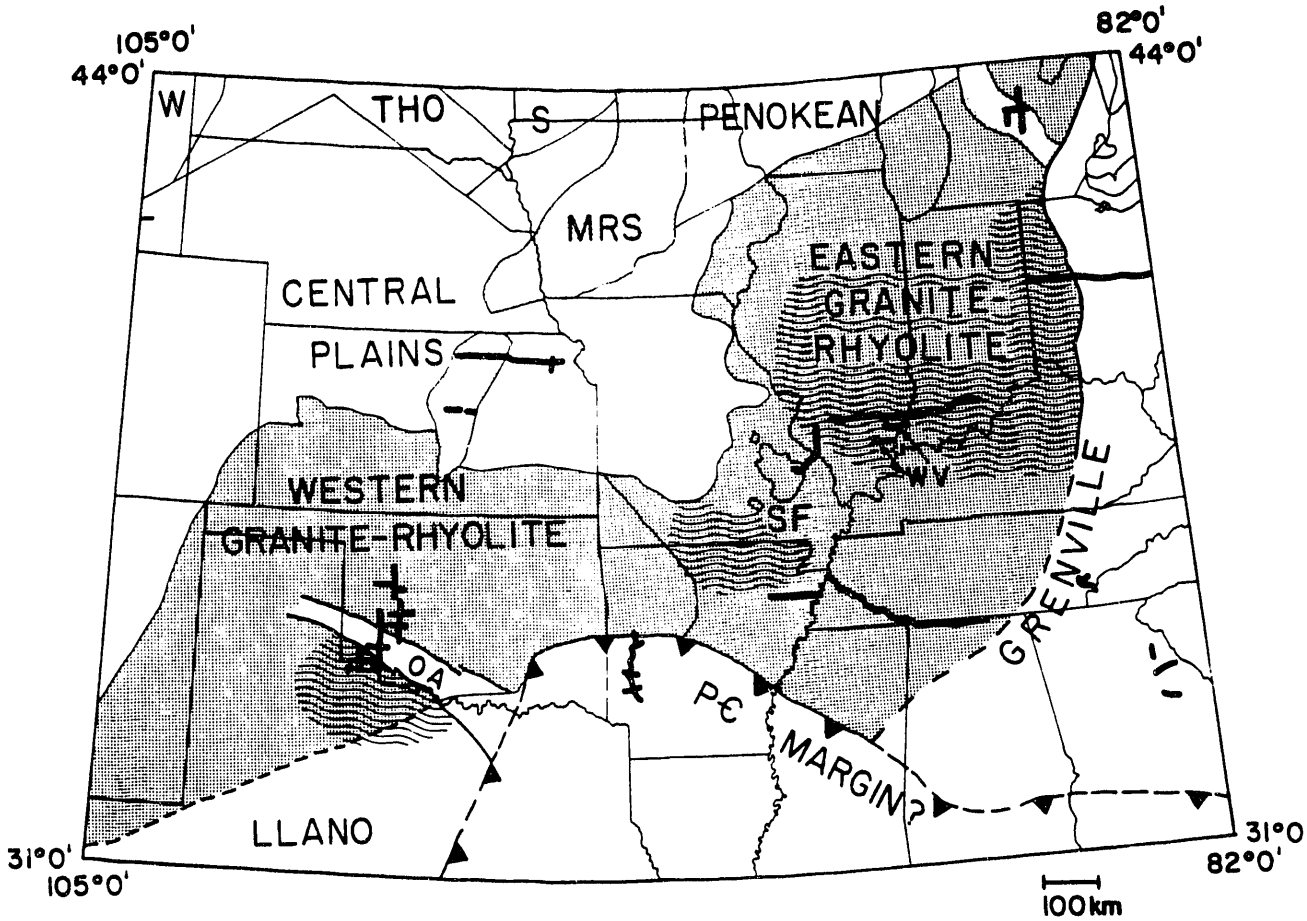

Figure 22. Map of Midcontinent Region Showing Possible Distribution of Precambrian Layered Sequences (Wavy Lines) Suggested by Regions of Low-Frequency, Low Magnitude Aeromagnetic Pattern (from Pratt and others, 1992). COCORP Lines Shown as Bold Lines, Granite-Rhyolite Province as Dark Gray, and Midcontinent Rift (Keweenawan) as Light Gray. St. Francois Mts. (SF)

rocks is present (Fig. 18) and both preserved beneath the southern midcontinent in the foreland of the Grenville orogen.

CONCLUSION

Through the reprocessing of industrial seismic reflection data in conjunction with the COCORP deep reflection lines and information from scattered basement drill holes, this project has begun to outline the distribution, structure, and possible origin of the thick sequences of Precambrian layered rocks beneath the U.S. midcontinent. This project has further outlined the possible setting of unmetamorphosed Precambrian clastic rocks encountered locally in drill holes in southwest Ohio and adjacent Kentucky and Indiana and their possible relationship to the layered sequences observed regionally.

Building upon this beginning, future studies fall into three main categories:

(1) continued and expanded study of existing industrial reflection data from throughout the region,

(2) collection of new seismic reflection data in strategic locations, and

(3) drilling into the layered sequence to directly sample these layered rocks to test if sedimentary material is an important constituent.

Thousands of kilometers of seismic reflection data have been collected during the course of oil and gas exploration in the basins of the midcontinent. Therefore, this study has only scratched the surface of what potentially might be learned through reprocessing and analysis of the existing industrial data of the region for deeper structures. Many of these are older data sets are of limited value to industry for exploration within the Paleozoic platform cover. However, as demonstrated above, these vintage seismic reflection data sets commonly hold basic information on the underlying basement which was not observed or even of interest when first collected and processed. Industry should continue to be encouraged, through projects such as this, to release portions of the huge volume of archived seismic data from the U.S. midcontinent.

Because these existing industrial seismic lines are concentrated in Phanerozoic basins, there are wide intervening regions about which little is known at depth. For example, do the layered Precambrian rocks observed on the industry lines continue beneath the intervening regions? How does the Precambrian layered sequence observed on the industry and COCORP data across southern

Illinois and Indiana relate to layered rocks observed in southwest Ohio? Because of the absence of seismic reflection data in the many regions, questions such as these can only be resolved by acquiring new seismic profiles. Consequently, an important element of future study is the collection of new seismic reflection profiles across strategic regions. Moreover, any attempt to drill into these layered rocks would require new seismic profiling to verify an optimal site.

Eventually a drill hole will probably be necessary to directly sample this sequence of layered rocks to directly test if sedimentary material is an important constituent. Such a drill hole might be a 'hole-of-opportunity' (deepening an existing hole) or a dedicated new site. In either case, however, verification of optimal locations would require analysis of both existing reflection data sets and the collection of new profiles. Through a progressive plan of analyzing existing industrial reflection data and the collection of new seismic lines, a drill hole can be sited to provide the ultimate test of the origin, evolution, and resource potential of this widespread Precambrian layered sequence.

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