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Deep Crustal Sediment Study: Widespread Precambrian Layered Rocks (Sedimentary ?) Beneath the U.S. Midcontinent

CONTRACT INFORMATION

Contract Number	DE-FG21-91MC28136
Contractor	Cornell University Ithaca, NY 14853 (607) 255-4316
Principal Investigator	Ernest C. Hauser
METC Project Manager	Charles W. Byrer
Period of Performance	May 30, 1991 to May 29, 1992

OBJECTIVES

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, its ultimate lateral extent, and resource potential are unknown. The objective of this project is to seek and reprocess seismic reflection data provided by industry from the U.S. midcontinent, and together with the COCORP deep reflection data and information from the scattered basement-penetrating drill holes, to begin to constrain the distribution, origin and evolution of this enigmatic layered sequence, particularly to evaluate if sedimentary material may be an important constituent (i.e., deep gas potential).

BACKGROUND INFORMATION

One of the most exciting new developments in midcontinent geology is the discovery of a thick and extensive sequence of Precambrian layered rocks on the COCORP transect across southern Illinois and Indiana (Figs. 1 and 2) (Pratt and others, 1989). This thick sequence of layered rocks is observed for close to 200 km in an E-W direction on the COCORP data in southern Illinois and Indiana, with individual reflections continuing for as much as 80 km. Proprietary industrial reflection data near the COCORP profile in southern Illinois also are known to image this Precambrian layered assemblage, but the ultimate extent of these layered rocks remains unclear. Also, the composition and origin of this sequence is yet unknown, though the stratified nature of the assemblage suggests a depositional sequence.

A grossly similar layered assemblage was imaged several years ago by COCORP beneath southwest Oklahoma and adjacent Texas (Figs. 1 and 3) (Oliver and others, 1976; Brewer and others, 1981). Based upon the local occurrence of the Precambrian Tillman greywacke in local drill holes in Texas (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 (exclusive of the better-known Keweenawan Rift) demonstrate that thick layered sequences are a major component of the Precambrian 'basement' of the U.S. continental interior, but it is yet unknown how or whether these different occurrences are associated or interconnected, or have a common origin.

Both examples on COCORP data occur within the Middle Proterozoic Granite-Rhyolite

Province of the central and southern U.S. (Fig. 1), an area of about a million square kilometers within which scattered wells to basement commonly encounter 1.3-1.5 Ga undeformed granite or compositionally similar 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.

The drill-hole samples provide information, though sparse, on the nature of the top of the Precambrian basement beneath the Phanerozoic platform cover, but rarely do these drill holes penetrated more than a few tens of meters of basement rock. Therefore, it is unclear whether the layered rocks observed on the COCORP profiles, particularly beneath southern Illinois and Indiana, might represent a thick pile of silicic volcanic rocks and associated sedimentary strata, perhaps intruded by mafic sills, or whether much of the layering might represent a sedimentary basin covered by a relatively thin veneer of volcanic material and only locally intruded by granite plutons. Moreover, basement-penetrating drill holes are relatively sparse, especially in the eastern midcontinent (Fig. 4), and commonly are biased samples, having drilled basement highs or located at gravity/magnetic anomalies. This indicates that the Precambrian layered assemblages observed on the COCORP profiles have probably not been adequately sampled in drill holes.

An extension of the COCORP lines in Indiana and Illinois into the St. Francois mountains of Missouri (Figs. 1 and 4), the only significant basement exposure in the region (Kisvarsanyi, 1981; Sides and others, 1981), indicates that this layered assemblage terminates or changes and becomes less distinct in that direction and does not crop out there (Pratt and others, 1989). The exposures of the Granite-Rhyolite province in the St. Francois Mountains, however, represent a caldera complex and may be atypical of the province as a whole, particularly contrasting with those regions where the COCORP data reveal well-layered Precambrian sequences.

Several possibilities can be imagined for nature of these layered rocks, each of which has different tectonic ramifications and resource potential. One possibility is 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).

Alternatively, these Precambrian layered rocks may be largely sedimentary material underlying a thin veneer of silicic igneous material. The general reflection character and lateral continuity of these layers on the available reflection data is suggestive of a sedimentary sequence. However, if they are, at least in part, sedimentary, what is their lithologic composition, age and provenance? Also, what might be their 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. It is important to recognize, as discussed below, that the Proterozoic age for such a stratal sequence does not in itself preclude the occurrence of hydrocarbons. However, even in the case that these layered rocks are predominantly volcanic rock and lack hydrocarbons, what might the distribution and structure of the layering suggest, for example, about the transport of ore-bearing fluids and non-hydrocarbon mineral deposits or the movement of fluids around deep disposal wells? Clearly much fundamental and valuable information can be gleaned even if hydrocarbons are absent in this layered assemblage. Only a better understanding of the distribution, composition, structure, origin, and evolution of these layered rocks can allow an approach to these assessments.

The mere age of these Precambrian rocks, however, does not preclude the presence of hydrocarbons. Elsewhere in the world Precambrian strata are known to contain hydrocarbons, and in places major resources have been discovered in Precambrian rocks. Perhaps the most striking example is the Lena-Tunguska petroleum province of the Irkutsk Basin on the eastern Siberian platform (Meyerhoff, 1980; Murray and others, 1980). The reservoirs are in both stratigraphic and structural traps largely in Vendian (latest Proterozoic) sandstones, but also in the overlying Vendian and Lower Cambrian carbonate strata. The oil is apparently indigenous to the Riphean (Upper Proterozoic) and Vendian (uppermost Proterozoic) sequence, i.e. not derived from younger overlying sediments (Murray and others, 1980). Estimates vary, but the proven and probable reserves in the few fields presently known exceed 6.5 Tcf of gas, 270 million bbl of condensate, and 220 million bbl oil (Meyerhoff, 1980). Furthermore, 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 even reach 100 billion bbl of oil and 200 Tcf of gas including condensate (Meyerhoff, 1980). Oil and gas discoveries have also been reported in Precambrian strata in the Persian Gulf region where 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). Clearly, Precambrian strata can contain significant hydrocarbon resources. Furthermore, there is abundant evidence for viable source rocks in Proterozoic strata elsewhere in the world (Murray and others, 1980). One such example is the 1.0-1.1 Ga Upper Keweenawan Nonesuch Shale on the south shore of Lake Superior wherein "crude oil, optically active alkanes, porphyrins, and the isoprenoid hydrocarbons pristane and phytane" are present (Barghoorn and others, 1965). Proterozoic time did not suffer the lack of enough simple life forms to produce organic-rich deposits.

Most of the above examples, however, 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 central U.S. This difference in stratal vintage, however, is not a problem, in principle. Recent studies to evaluate the hydrocarbon potential of the McArthur Basin, of north-central Australia indicate excellent source and reservoir facies which are laterally extensive for over 200 km, with maturation levels which "fall within the oil window throughout the study area" (Jackson and others, 1986; Fritz, 1987; Jackson and others, 1988). In particular, "live" oil has been observed there in a shallow stratigraphic test. The strata of the McArthur Basin are *Middle Proterozoic* (1.4-1.8 Ga) in age, as are the rocks of the Granite-Rhyolite province of the U.S. midcontinent, and demonstrate that the mere age of any buried Proterozoic stratal sequence in the U.S. midcontinent does not necessarily preclude hydrocarbon potential. If sedimentary material is present and in places unmetamorphosed by local granite intrusions, deep gas possibilities might exist and are within the range of existing drilling technology.

PROJECT DESCRIPTION

The goal of this project is 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 of the midcontinent.

A vast amount of industrial seismic reflection data has been collected in the course of oil and gas exploration in the Phanerozoic intracratonic basins of the U.S. midcontinent. Although these industrial data are commonly collected to travel times of 2-4 s (~6-12 km depth), 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. Moreover, most of the available industrial data sets from this region are vibroseis; consequently, the reprocessing in this project includes extended vibroseis correlation to extract even longer records and deeper information from the shallow industry data.

Extended vibroseis correlation is a modification of the usual correlation process (i.e., Okaya and Jarchow, 1989) which extracts additional information from the latter part of the originally recorded data. This is possible because the frequencies which were put into the ground at the beginning of the vibroseis sweep can be received 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 (full correlation on Fig. 5). Although there is a progressive narrowing of frequency bandwidth with the extended correlation (Fig. 5), accompanied by a progressive decrease in resolution, additional usable information can be extracted from the original data by this method to considerably greater depths. How much deeper depends upon the original sweep length, total listening time and sweep frequencies, but in many cases nearly twice the original full-correlation time is possible (in places to depths as great as 20 km) revealing much that was heretofore unseen.

Such reprocessing of existing reflection data provided to us by industry, is clearly a cost-effective way to greatly expand the knowledge of the distribution and nature of these layered rocks. The reflection data already made available to us represent millions of dollars of original acquisition costs, but through the courtesy of the donor companies (Table 1; Fig. 6) the important deep information these data contain can be rescued from a slow anonymous magnetic death in the archival vault. This project also exemplifies an important role of government-sponsored academic research and technology transfer. By providing data for this project, 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. The mere presence of a sequence of supracrustal rocks of this thickness and volume requires they be addressed in any comprehensive evaluation of U.S. resource potential.

Table 1. Companies Providing Data to Date

Amoco
Chicago Metropolitan Water District
Citizens Gas & Coke Utility
EXXON
ENRON
Illinois Power
NOMECO
Northern Illinois Gas
Northern Indiana Public Service Company
People's Gas

RESULTS

Reprocessing and analysis of the industry data in conjunction with the COCORP profiles indicate, so far, that the Precambrian layered sequence which underlies southern Illinois and Indiana continues well north into central Illinois and western Indiana, and likely also underlies most of Indiana, continuing into western Ohio. This is only a minimum extent, with its ultimate distribution likely much larger.

In many places the base of the layered Precambrian sequence is defined by an angular unconformity on the seismic reflection data (Figs. 7 and 8). Commonly, such as with the vibroseis Amoco data shown in Figure 7, this basal angular unconformity is only observed as a result of extended vibroseis correlation described above -- demonstrating how this reprocessing technique can reveal fundamental new information from old data sets. This intra-Proterozoic angular unconformity corresponds to the laterally extensive strong reflection observed on the COCORP data at the base of the horizontally layered Precambrian sequence (Fig. 2).

The top of the layered assemblage in Illinois and Indiana is commonly conformable with the overlying Paleozoic platform strata (Figs. 7 and 8), which given the sparsity of basement-penetrating drill holes throughout this region can make choosing the contact between the Paleozoic cover and Precambrian layered sequence difficult. Moreover, the common lack of published petrographic documentation of the basement rocks encountered in these scattered wells contributes greatly to uncertainty about the nature of these layered rocks and basement compositions in general. The Paleozoic section and the Precambrian 'basement' horizon (Figs. 2, 3, 7 and 8) is extrapolated from the better constrained basement drill holes (e.g., the Farm Bureau #1 Brown well in Lawrence Co., south-central Indiana, Fig. 4) (Dawson, 1960) but can be identified on the seismic data in some places by minor irregularities or low-angle truncations of the underlying layered sequence (Fig. 7).

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. 9) layered rocks are variably imaged but the data suggest a footwall thrust ramp and hanging-wall ramp anticline of a foreland thrust belt (Fig. 9) (Hauser, in press). 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 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 Fig. 1) (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. 10 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. 10) reveals a sequence of prominently layered Precambrian rocks dipping ~10° east beneath the Paleozoic cover. In light 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, in press).

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. 10) 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. 10), 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).

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. 10), two alternative hypotheses must also be considered (Figs. 11 and 12) (Hauser, in press). [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. 11A), 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. 12A). 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. 11D and 12D).

Possible Regional Distribution of the Precambrian Layered Sequence

The COCORP data and industry seismic reflection data reprocessed for this project reveals a Precambrian layered sequence which is widespread. Additional industrial seismic data continues to become available from throughout the U.S. midcontinent, and will further provide documentation of its distribution. However, so far this sequence is confined to the region of the Granite-Rhyolite province, suggesting a genetic relationship.

The occurrences of these well-layered basement rocks also seem to correspond to regions where aeromagnetic data exhibits a subdued and low frequency character of low magnitude (Pratt and others, in press). Using this aeromagnetic character as a guide, the known occurrences of the sequence may extend beneath most of Illinois and Indiana, into southern Michigan and Ohio to the Grenville Front, and across most of the Texas panhandle (Fig. 13). Other regions, such as northern Arkansas (Fig. 13), have a similar aeromagnetic character and might be speculatively underlain by similar layered sequences, but supporting seismic reflection data are absent.

FUTURE WORK

Through the use of industrial seismic reflection data in conjunction with the COCORP deep reflection lines and scattered basement drill hole information, we have begun to outline the distribution, structure, and possible origin of the thick sequence of Precambrian layered rocks beneath the U.S. midcontinent. This project has further documented and expanded the known distribution of this layered sequence, and outlined the possible setting and relationship of unmetamorphosed Precambrian clastic rocks encountered locally in drill holes to the regional layered sequence. 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 test if sedimentary rocks are 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, we have only scratched the surface of what potentially might be learned through reprocessing and analysis of these existing industrial data for deeper structures. Many of these are older data sets and of limited value to industry for exploration within the Paleozoic platform cover; as prospects get smaller and more subtle and modern acquisition techniques improve, industry finds it more cost effective to collect newer state-of-the-art data sets. 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. As long as industry continues to be agreeable to release portions of this huge volume of archived seismic data, important information about the distribution of these Precambrian layered rocks and other structures is feasible. This will continue to be an important element of future studies.

Because these existing industrial seismic lines are concentrated in the prospective 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? Questions such as these can only be resolved by acquiring new seismic profiles in regions where none now exists. Consequently, a future element of this study must include the collection of new seismic reflection profiles across strategic regions. Moreover, any attempt to drill into these layered rocks (the third element of future study) should be preceded by new site-specific 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 a hole already being drilled) or a new site. In either case, however, optimal locations would be verified using both existing reflection data sets and dedicated new acquisition. Through such a progressive plan of analyzing existing industrial reflection data and new seismic acquisition, an eventual well-located drill hole can provide an ultimate test of the origin, evolution, and resource potential of this widespread Precambrian layered sequence, which has a volume greater than all of the overlying Phanerozoic sequence.

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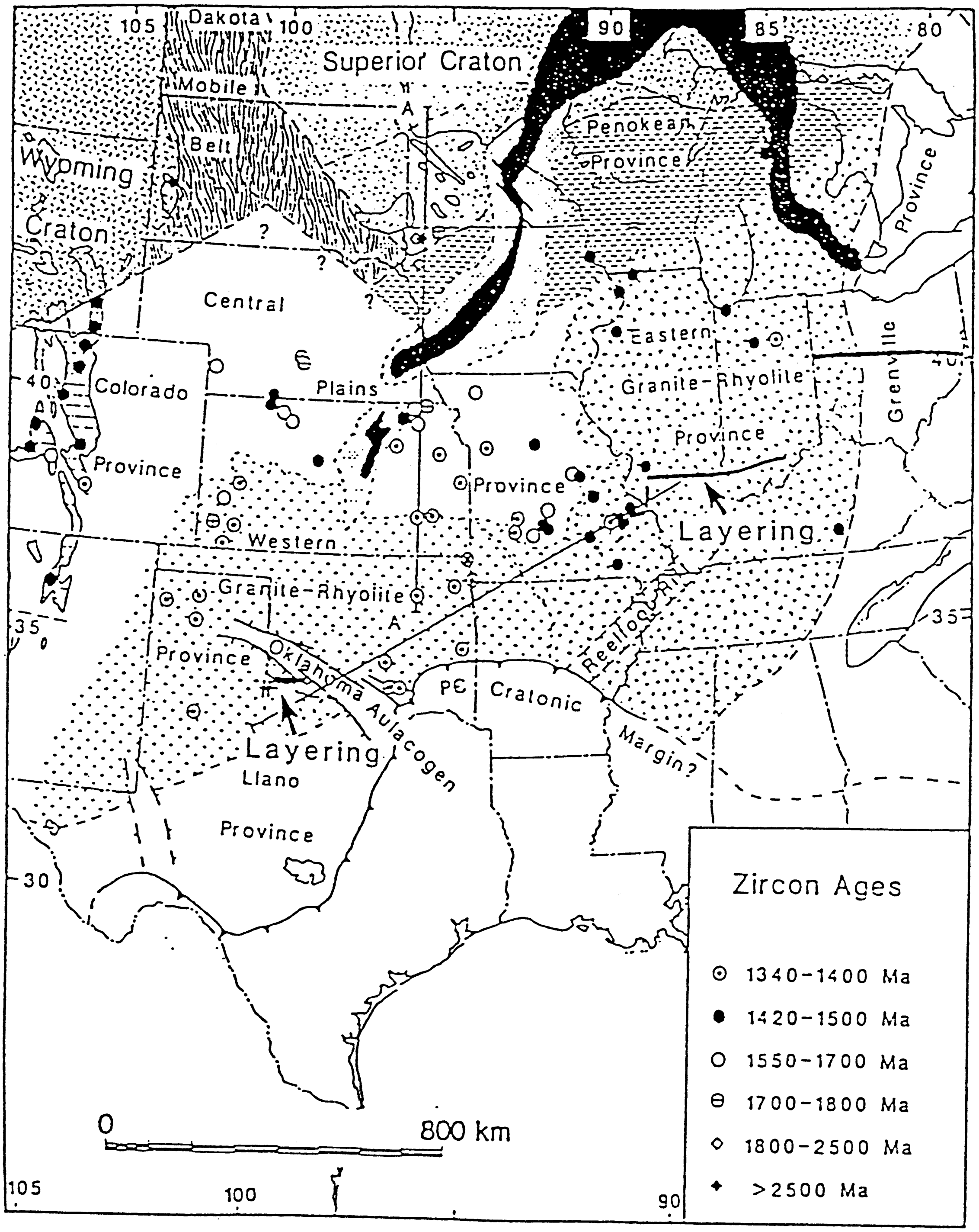

Figure 1. Summary Geologic Map of Precambrian Basement Terranes of the U.S. Midcontinent. Bold Lines Denote COCORP Lines.

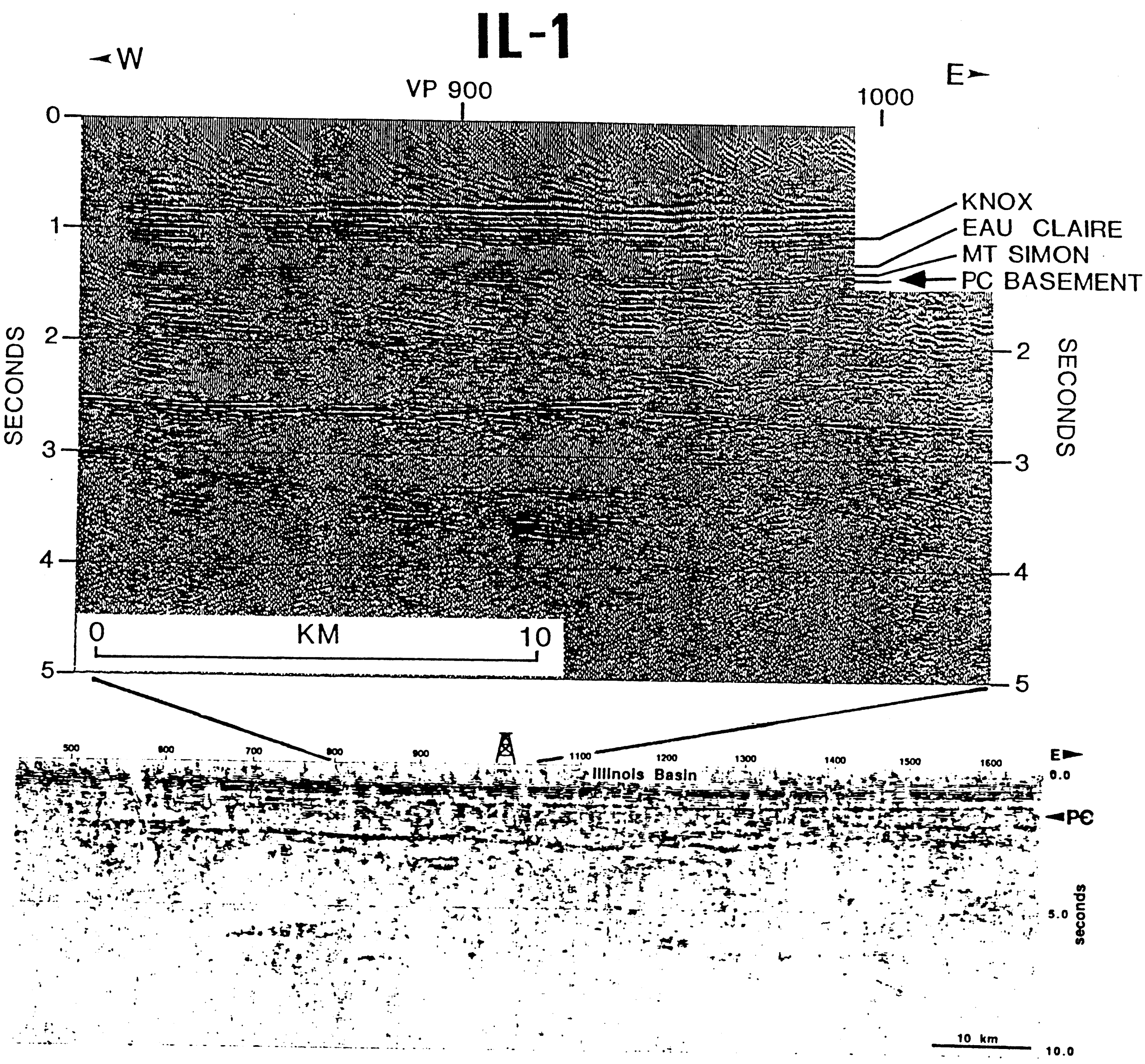

Figure 2. Sample of COCORP Data from Southern Illinois Showing Thick Proterozoic Layered Sequence. Arrows Denote Top of Precambrian.

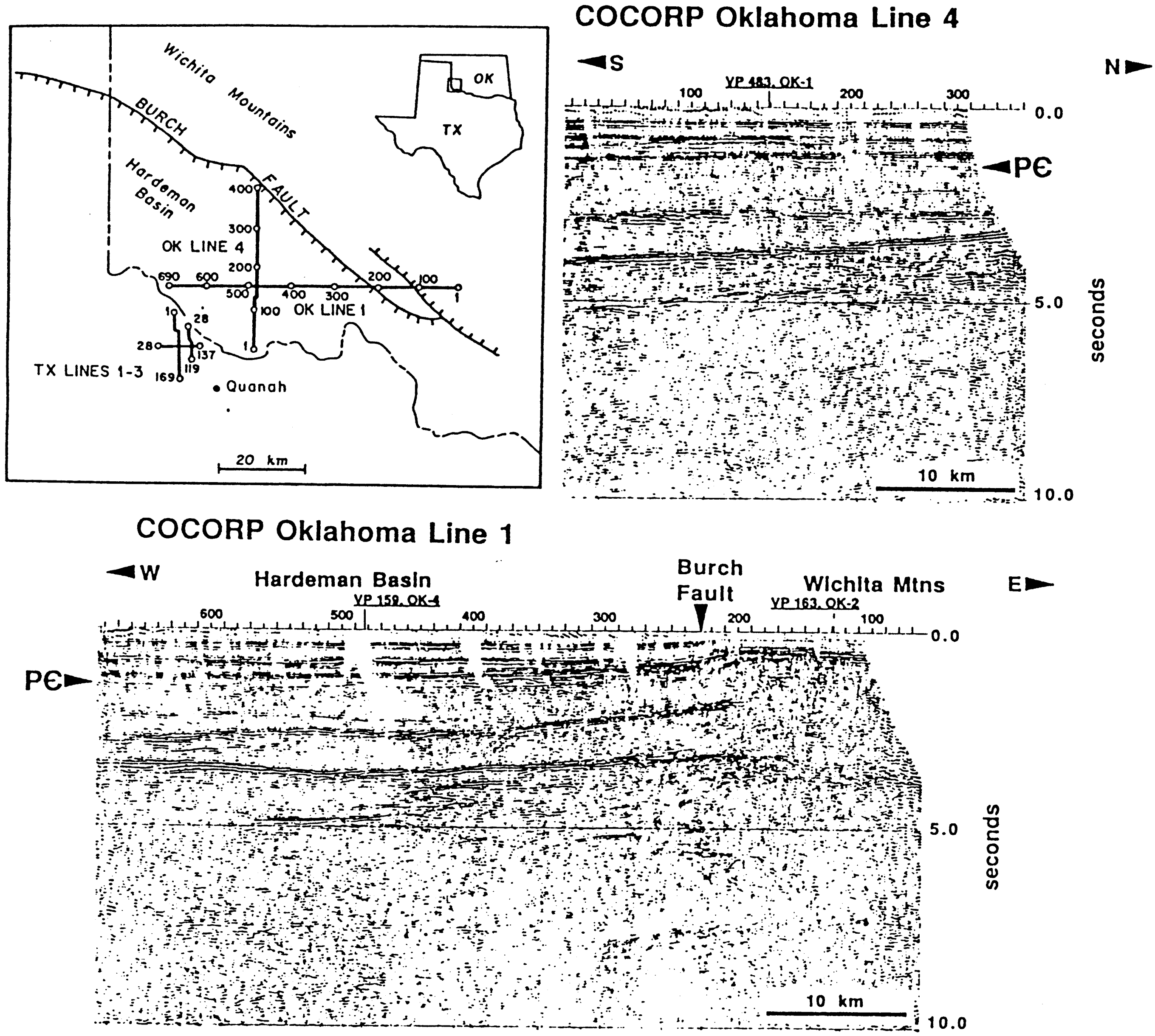

Figure 3. Sample of COCORP Data from SW Oklahoma Showing Proterozoic Layered Sequence. Arrows Denote Top of Precambrian.

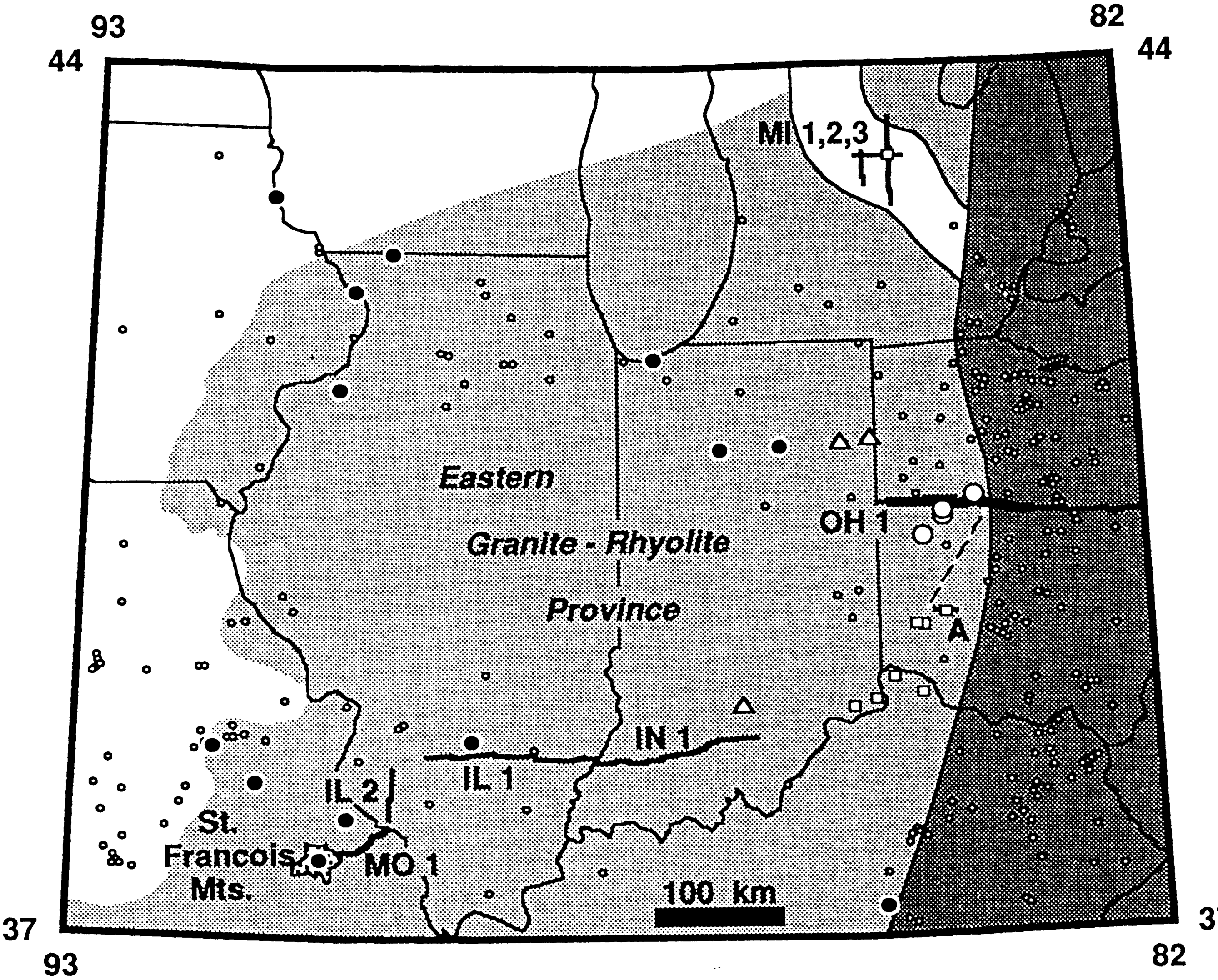

Figure 4. Map of Basement Provinces in Eastern U.S. Midcontinent (Hauser in Press) Showing: Eastern Granite-Rhyolite Province (Light Gray) (after Bickford and others, 1986); Grenville Province (Dark Gray); Grenville Front (GF); COCORP Profiles (Bold Black Lines); Seismic Line in SW Ohio of Figure 10 ('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).

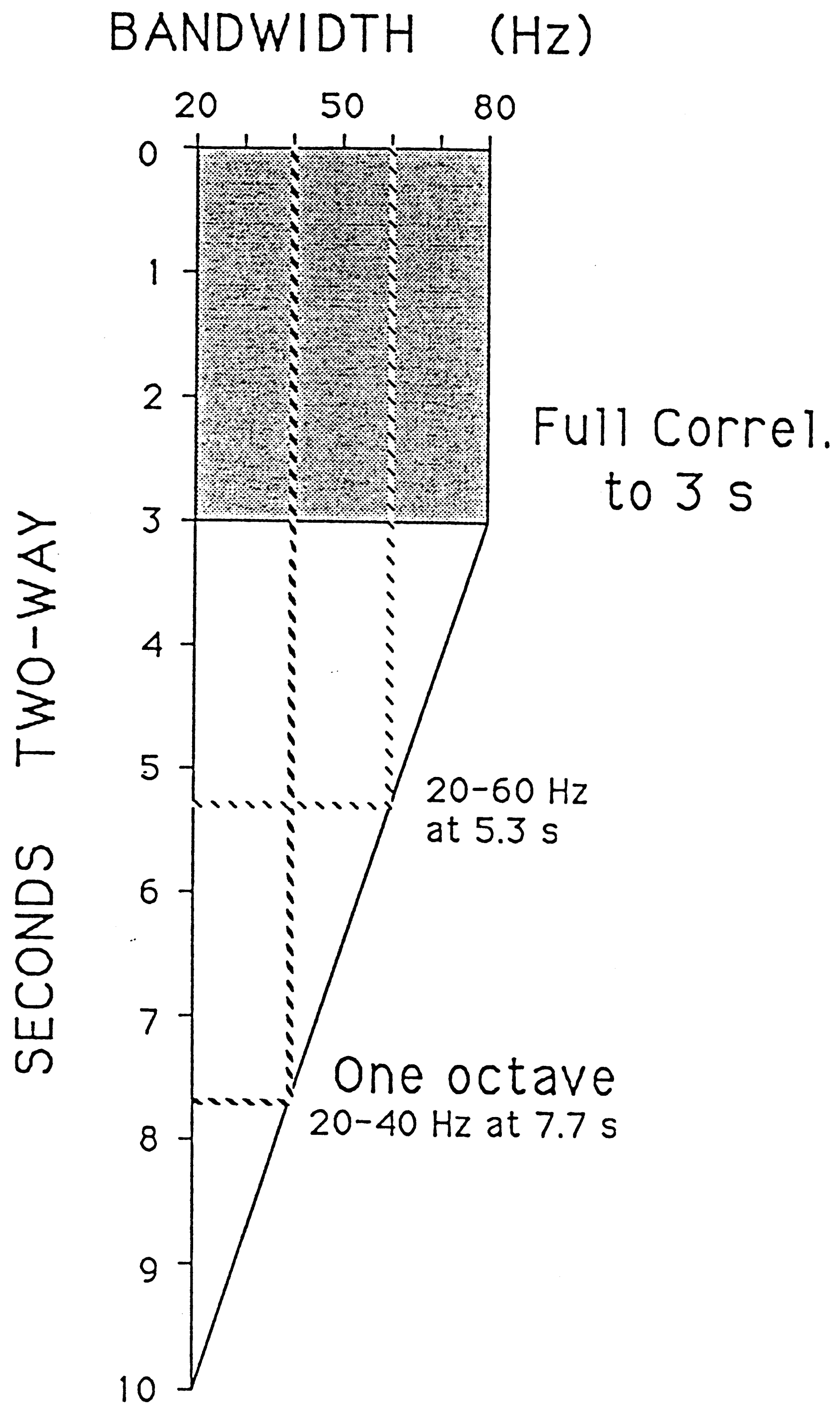

Figure 5. Example Bandwidth Diagram for Extended Vibroseis Correlation of 20-80 Hz Data with 10 Second Listening Time and 7 Second Sweep

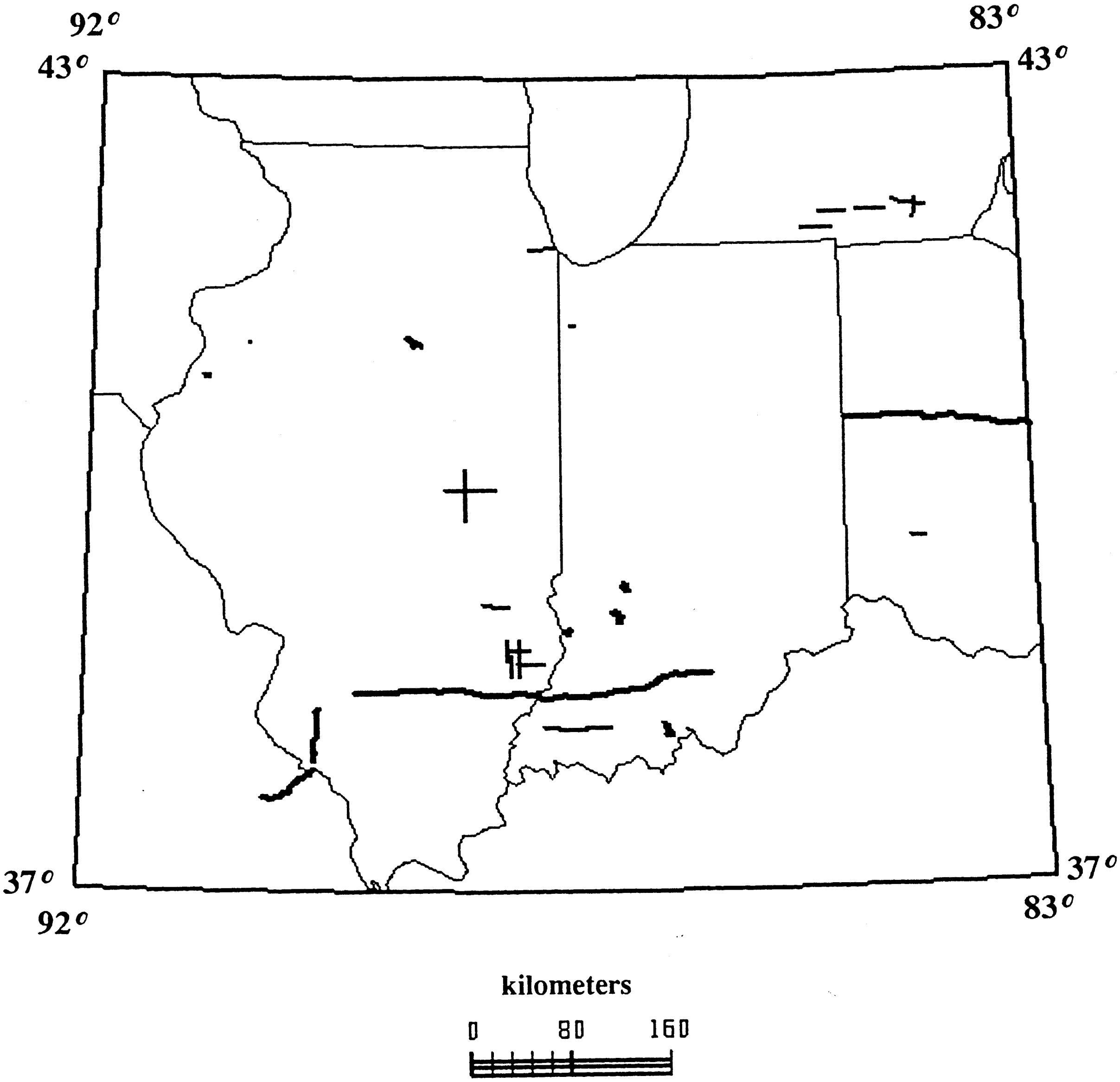

Figure 6. Data Initially Available for this Project

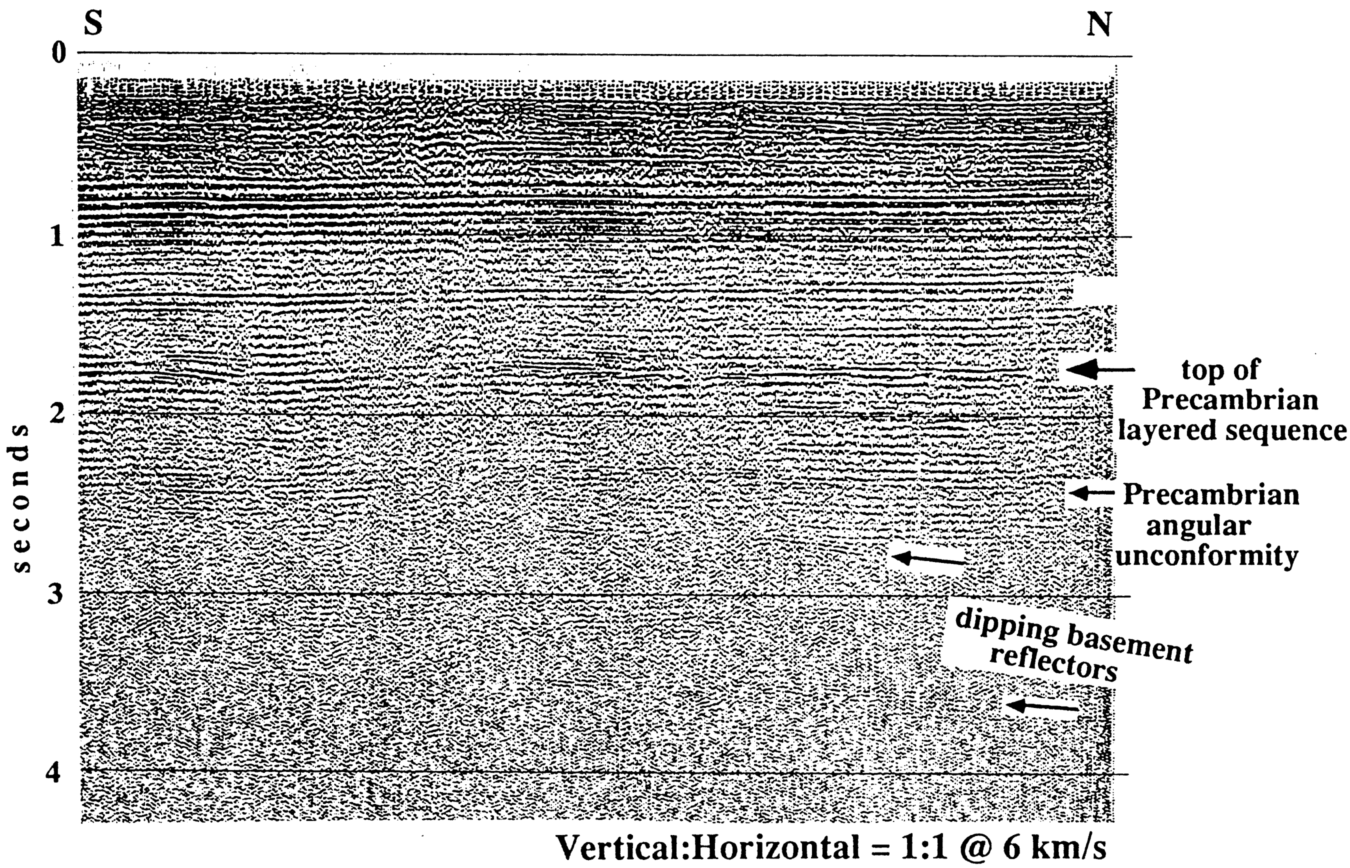

Figure 7. Sample of the Amoco Data from Southern Illinois Showing the Well-Layered Precambrian Sequence and the Underlying Angular Unconformity. Data Below 2 Seconds is from Extended Vibroseis Correlation.

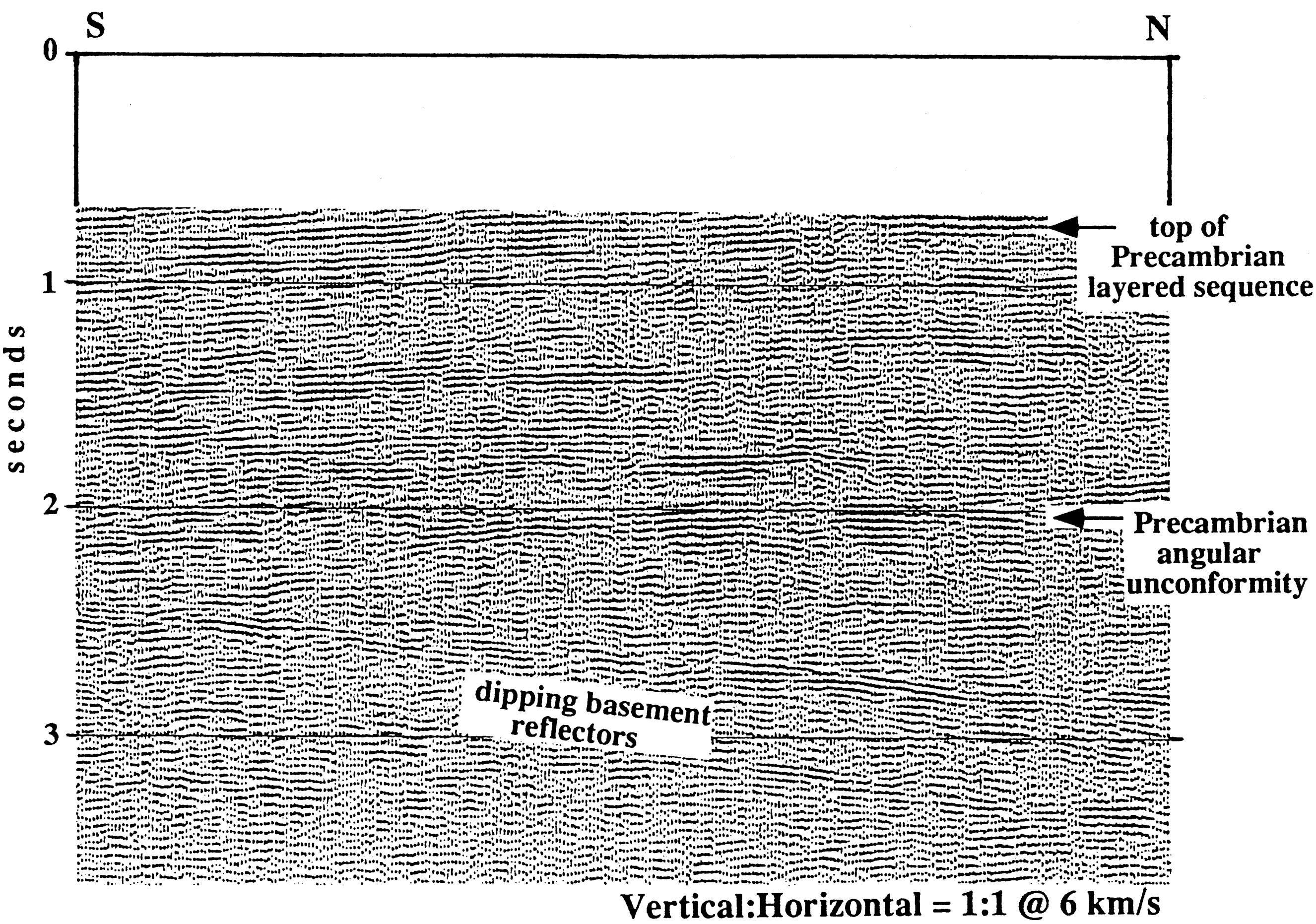

Figure 8. Sample of the EXXON Data from Central Illinois Showing the Well-Layered Precambrian Sequence and the Underlying Angular Unconformity. Publication of Data above 0.7 Seconds is Restricted.

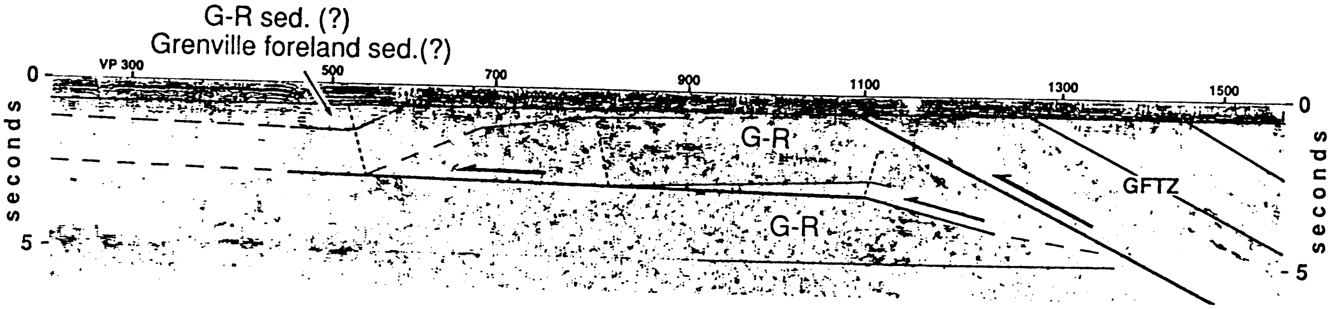

Figure 9. Part of COCORP Line OH-1 Across West-Central Ohio (see Fig. 1, and Bold Line, Fig. 4) Suggesting Foreland Thrust Structures within Granite-Rhyolite Province Rocks. Grenville Front Tectonic Zone (GFTZ); Paleozoic Platform Cover (Pz); Granite-Rhyolite Province Rocks (G-R)

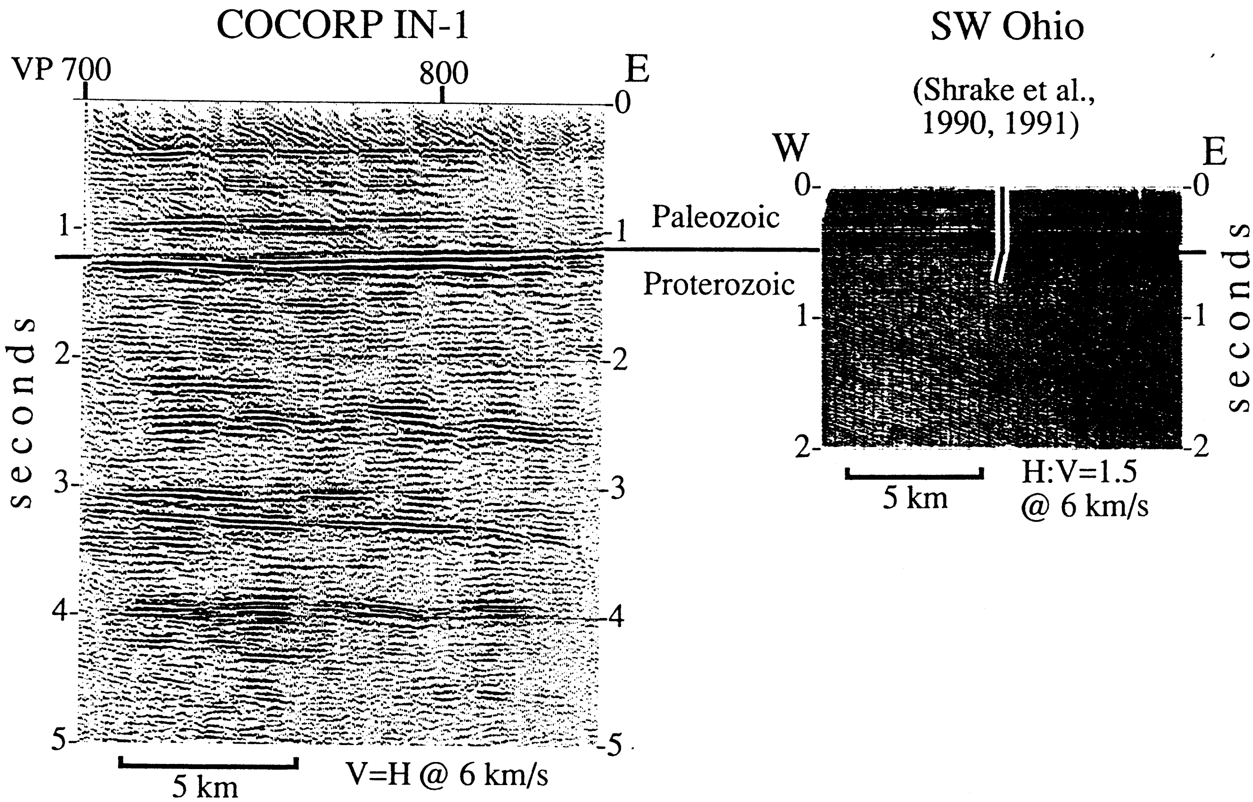

Figure 10. Dipping Layered Rocks on the Short Seismic Line in SW Ohio (see Location in Fig. 4) Compared with the Layered Sequence on COCORP line IN-1 in South-Central Indiana (from Hauser, in Press). Data are at Same Vertical Scale with the Base of the Paleozoic Cover Aligned. Drill Hole Shown on SW Ohio Data Encountered Unmetamorphosed Precambrian Clastic Sedimentary Rocks.

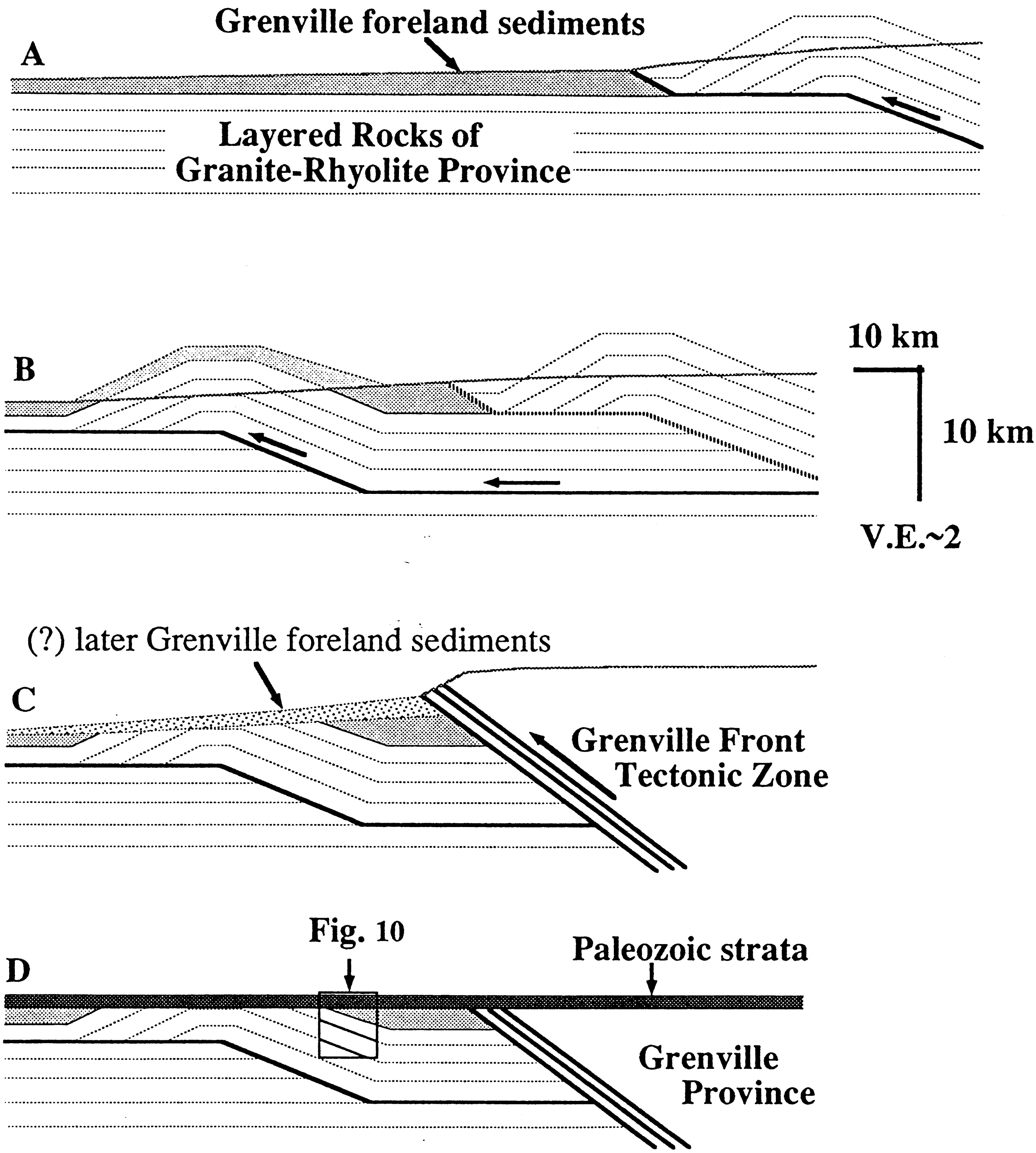

Figure 11. Model Suggesting the Precambrian sedimentary rocks (gray) were Deposited in a Grenville Foreland Basin (from Hauser, in Press). Interpreted Position of SW Ohio Seismic Data (Fig. 10) Shown in D.

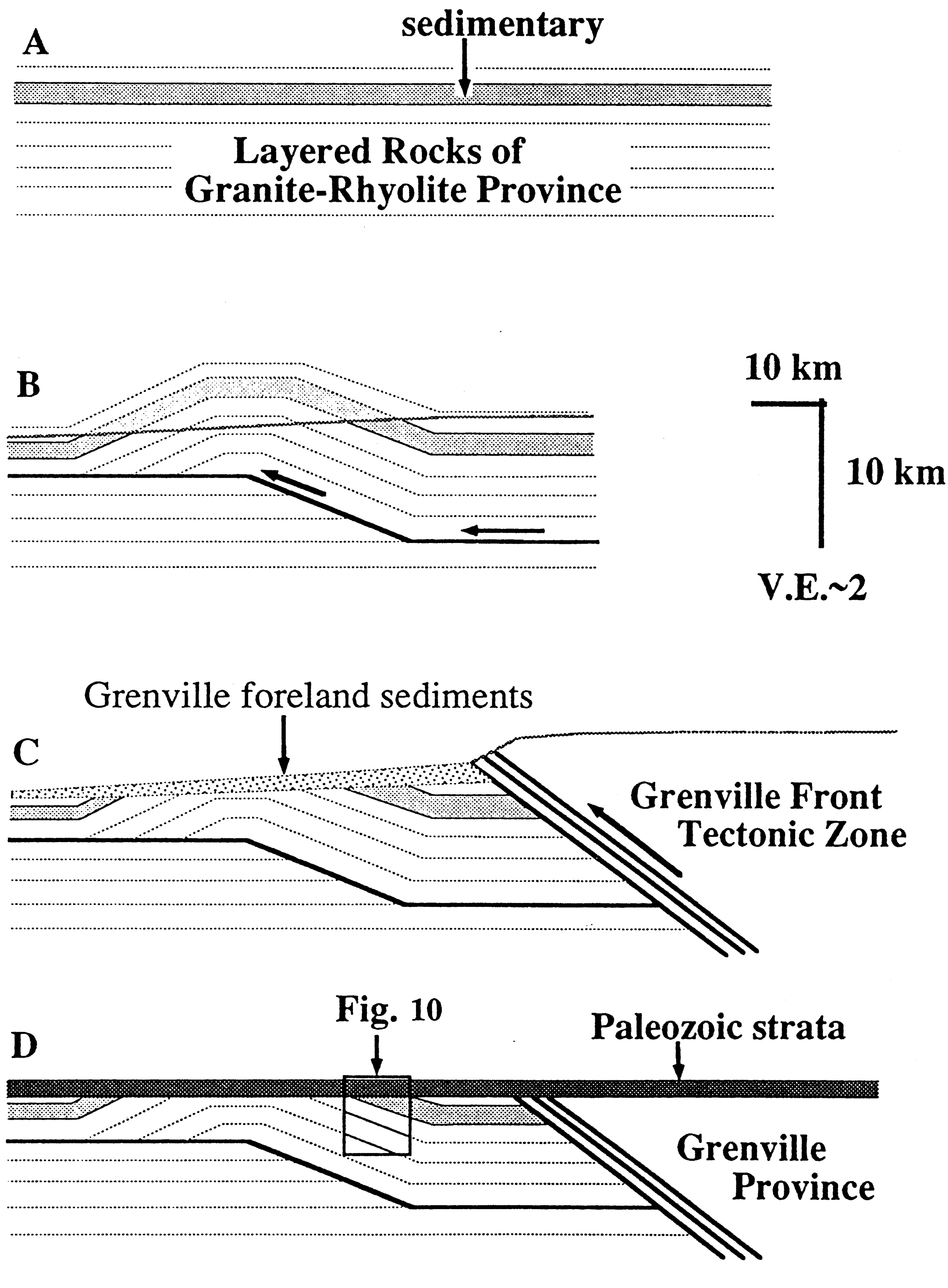

Figure 12. Model Suggesting the Precambrian Sedimentary Rocks as Part of the Granite-Rhyolite Province Layered Sequence (from Hauser, in Press). Interpreted position of SW Ohio seismic data (Fig. 10) shown in D.

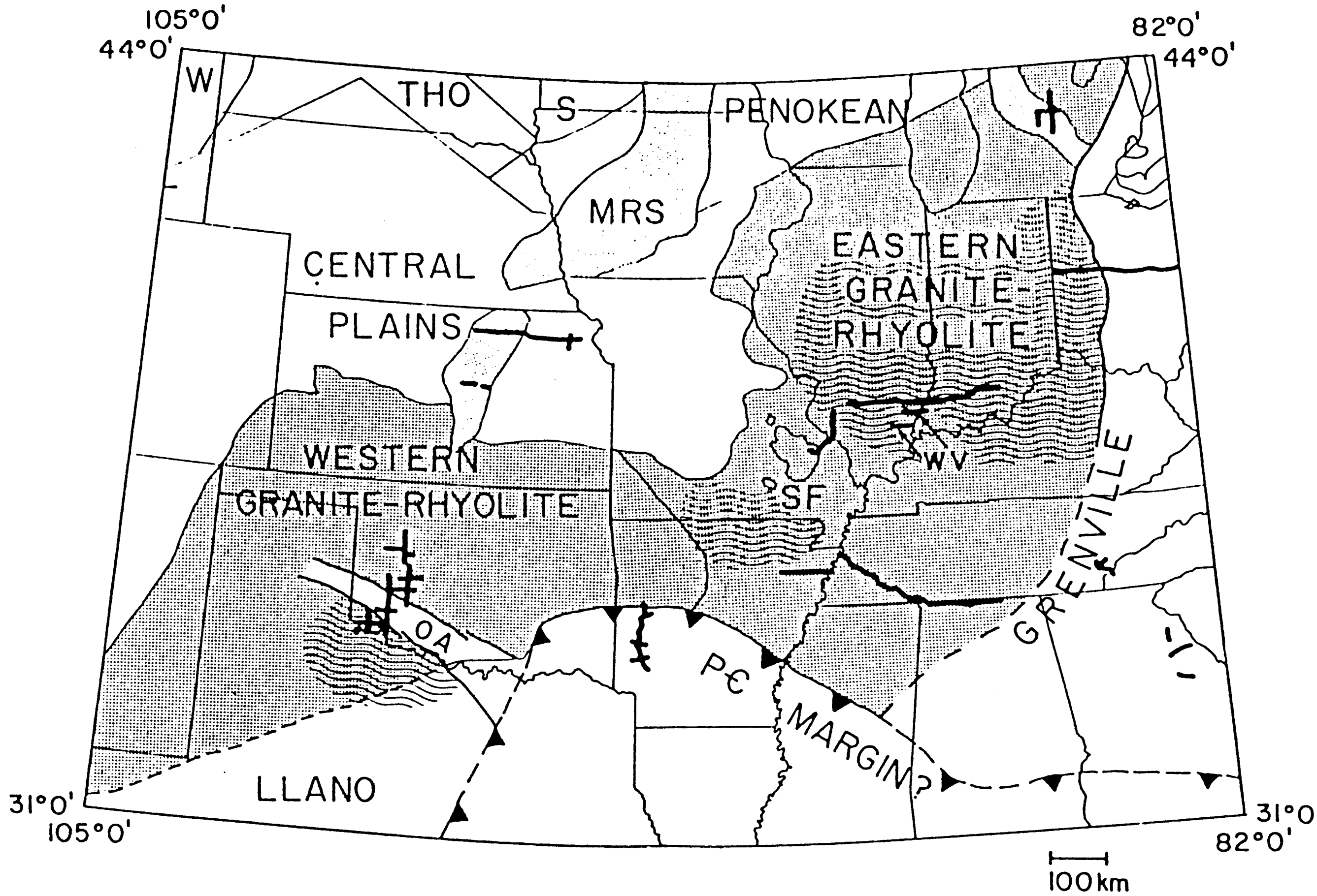

Figure 13. Map of Midcontinent Region Showing Possible Distribution of Precambrian Layered Sequences (Wavy Lines) Suggested by Regions of Low-Frequency, Low Magnitude Aeromagnetic Pattern (from Pratt and others, in Press). COCORP Lines Shown as Bold Lines, Granite-Rhyolite Province as Dark Gray, and Midcontinent Rift (Keweenawan) as Light Gray. St. Franscois Mts. (SF)