The American Association of Petroleum Geologists Bulletin
V. 76, No. 9 (September 1992), P. 1384-1401, 12 Figs.

Widespread Buried Precambrian Layered Sequences in the U.S. Mid-Continent: Evidence for Large Proterozoic Depositional Basins[1]

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ABSTRACT

Large regions of the North American mid-continent are underlain by Precambrian layered rocks buried beneath Phanerozoic sedimentary strata. South of the Wichita Mountains, published seismic reflection profiles show a Precambrian layered assemblage extending for at least 40 km in both the north-south and east-west directions, and industry data show that it may continue 150 km to the southeast. Seismic reflection data in the Illinois region show a Precambrian layered assemblage extending 320 km in an east-west direction and 200 km in a north-south direction. In both cases, the layered rocks are as much as 12 km thick. Apparent sequence boundaries (onlap, downlap) within these assemblages suggest they are parts of large depositional basins with diffractions and dipping strata due to faulting. The layered sequences correlate with regions of relatively long-wavelength and low-amplitude magnetic anomalies; the extent of this magnetic signature suggests that about 200,000 km^2 of Illinois, Indiana, and western Ohio, about 50,000 km^2 of southernmost Oklahoma and north-central Texas, and about 32,000 km^2 of southern Missouri and northern Arkansas may be underlain by similar Precambrian strata.

Drill holes indicate that the top of the mid-continent Precambrian "basement" is composed largely of silicic igneous rocks. Such material may comprise a large part of the layered sequences. Alternatively, these igneous rocks could be intermixed with, or underlain by, nonvolcanic (meta?)sedimentary strata. The strong reflectivity of some layers suggest that minor mafic flows and/or sills may also be present. Analysis of U/Pb and Nd/Sm isotopes within the granites and rhyolites imply that the layered sequences postdate crustal formation at 1.7–2.0 Ga and predate or are contemporaneous with the 1.3–1.5 Ga crystallization ages of the granites and rhyolites. Though these layered rocks have a spatial association with igneous rocks and thus have likely been metamorphosed, the possibility that they contain Precambrian hydrocarbons that escaped heating is as yet untested.

INTRODUCTION

On the basis of scattered drill hole data, it has been inferred that the buried Precambrian interior of the United States, exclusive of the Mid-continent rift system, consists largely of Proterozoic metamorphic and igneous rocks (Muehlberger et al., 1967; Denison et al., 1984; Bickford et al., 1986; Van Schmus et al., 1987) (Figure 1). Our paper summarizes COCORP and other seismic reflection data that image stratified rocks suggestive of substantial depositional assemblages of Middle Proterozoic age (Brewer et al., 1981; Pratt et al., 1989) (Figures 1, 2). Two such assemblages have so far been recognized. The first is about 12 km thick and covers an area of more than 5000 km^2 (42 × 150 km) south of the Wichita uplift. The second lies beneath the Illinois basin and adjacent regions, is also about 12 km thick, and is seen on seismic reflection data scattered over an area of about 50,000 km^2 (320 × 200 km). The

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[1] Manuscript received January 23, 1991; revised manuscript received January 29, 1992; final acceptance March 4, 1992.

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The COCORP project is supported by National Science Foundation grant EAR-8916129. The mid-continent work has received partial support from U.S. Department of Energy grant DE-FG21-91MC 28136 to E. Hauser, and from American Chemical Society, Petroleum Research Fund grant 22309-AC2 to L. Brown. The COCORP eastern mid-continent data were collected by a crew from Seismograph Services Corporation and the data in the southern mid-continent by a crew from Petty-Ray Geophysical. The field effort benefited from the advice and help of personnel from the state geological surveys of Illinois, Indiana, Missouri, Ohio, Oklahoma, and Texas. Processing was carried out on the COCORP MEGASEIS (Seiscom Delta) seismic computer system, the Cornell Theory Center's IBM 3090 computers at the Cornell National Computer Facility, and by Petty-Ray Geophysical. The synthetic seismogram of the Cisne well was generated by Hope Jacunski. Tom Hildenbrand supplied data to fill in some of the magnetic anomaly map. Many persons participated in useful discussions and exchanged ideas concerning the layered sequences, including Sue Kay, Bill Hinze, Eva Kisvarsanyi, Pat Bickford, Randy Van Schmus, Bob Kay, Larry Brown, Jack Oliver, Mike Mueller, and John Rupp. Institute for the Study of the Continents (INSTOC) contribution number 145.

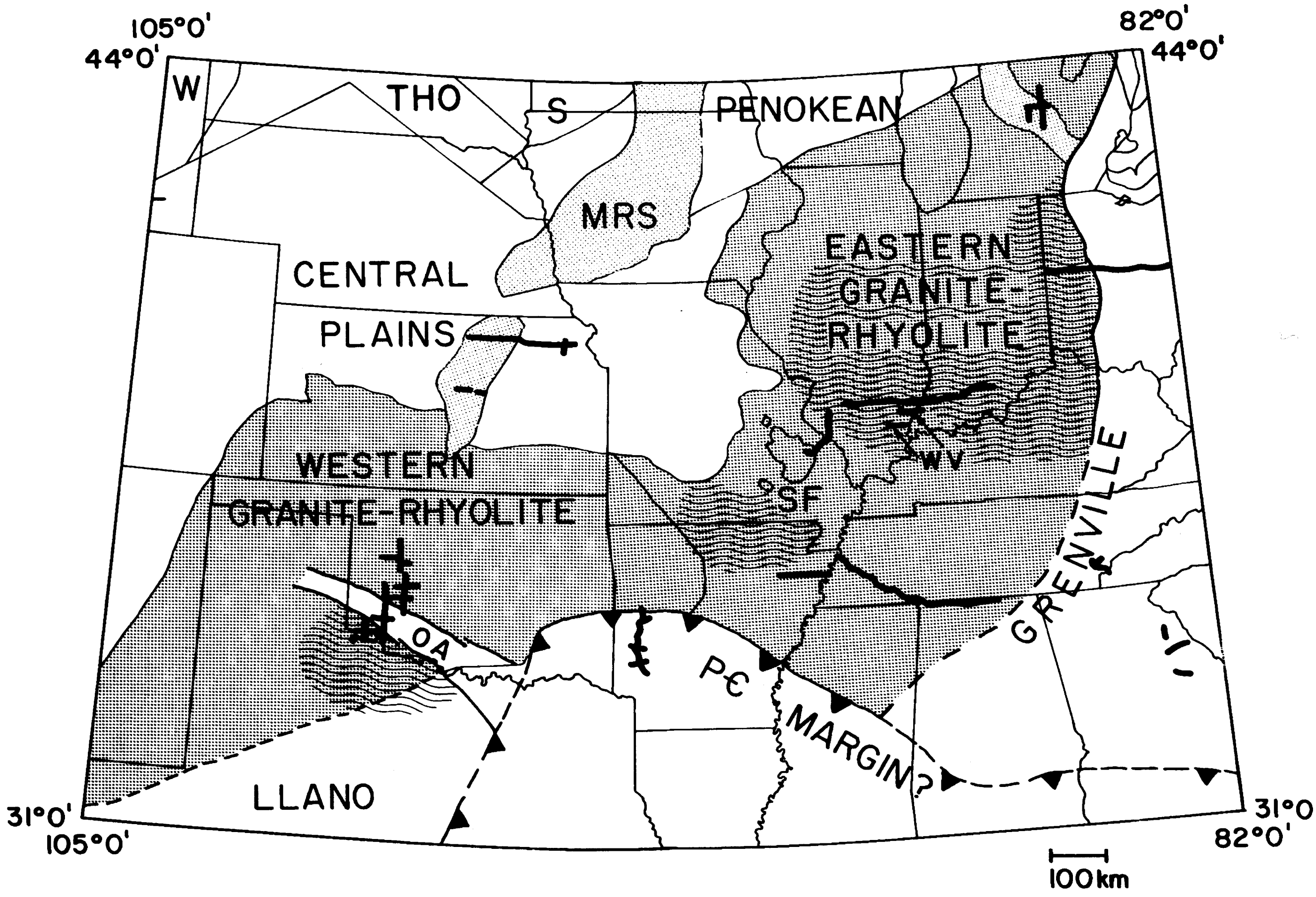

Figure 1—Map of the mid-continent region showing Precambrian geologic provinces as defined from drill hole data (Bickford et al., 1986). COCORP seismic reflection transects are shown as heavy lines; WV are the Wabash Valley data of Sexton et al. (1986). Wave pattern indicates the areas where the upper crust may be dominated by thick sequences of Precambrian rocks seen on the seismic reflection profiles or suspected from analysis of magnetic anomaly data (see text). The line (part dashed) separating the eastern granite-rhyolite and Grenville provinces is the estimated location of the Grenville front. SF = outline of the St. Francois Mountains as defined by the sea-level contour on the Precambrian rocks; OA = Oklahoma aulacogen; W, S, THO = Wyoming and Superior provinces and intervening Trans-Hudson orogen (Dakota mobile belt); MRS = Mid-continent rift system.

ultimate extent of both of these assemblages is unknown; however, magnetic anomaly data indicate they may be far larger than currently demonstrated, and that there may be other as yet unrecognized examples beneath the region.

Both of the known stratified assemblages lie within the Proterozoic granite-rhyolite terranes of the U.S. mid-continent, defined on the basis of scattered drill hole penetrations. The thick assemblages may be largely or entirely Middle Proterozoic silicic volcanic and volcaniclastic strata. If so, they may provide insight into the nature and origin of major anorogenic felsic igneous terranes found on other continents (e.g., Kay et al., 1989). Alternatively these assemblages may consist largely or entirely of nonvolcanic sedimentary strata lying between eruptive centers and/or beneath a veneer of silicic volcanic rocks. Without knowing the lithology of these strata, their resource potential remains unknown. However, Pb-Zn and a variety of other base metal deposits correlate with silicic volcanic terranes (e.g., Sawkins, 1989). Similarly, substantial hydrocarbon resources have been found in Precambrian strata (Meyerhoff, 1980; Murray et al., 1980) and could be present if parts of the assemblages have escaped significant heating. Regardless of economics, the Proterozoic strata are a major addition to the North American crust and are therefore fundamental to understanding the evolution of the continent.

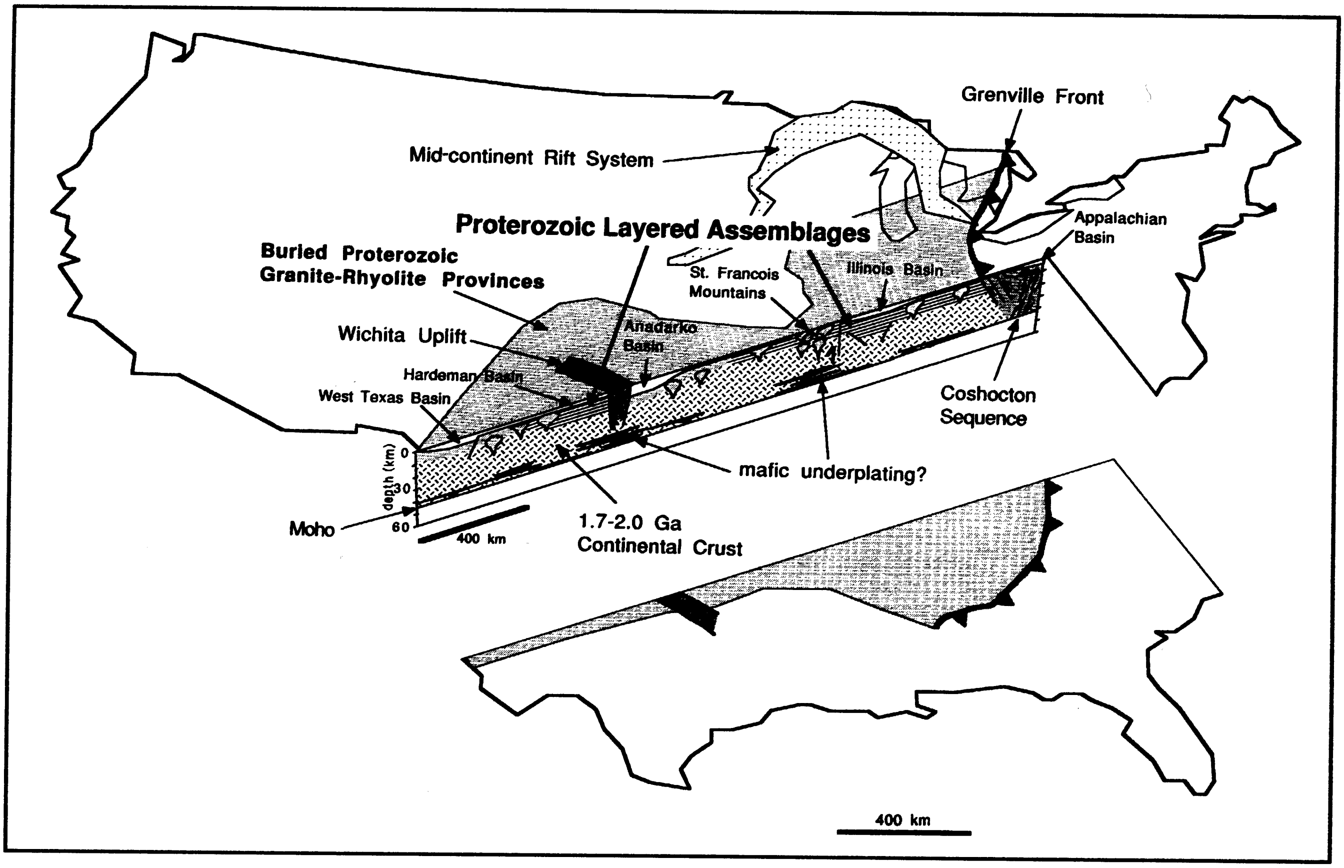

Figure 2—Perspective view of the U.S. with a schematic cross section of the mid-continent region showing the inferred extent of the Precambrian layered sequences. Features of the cross section are explained in the text. Compiled from Brewer et al. (1981, 1983), Van Schmus et al. (1987), Pratt et al. (1989), and Culotta et al. (1990).

PRECAMBRIAN LAYERED ROCKS IN THE MID-CONTINENT

The Quanah Sequence of Texas and Oklahoma

Distribution

Consortium for Continental Reflection Profiling (COCORP) data acquired over the Hardeman basin of Oklahoma and Texas (Oliver et al., 1976; Brewer et al., 1981) reveal a thick sequence of layered Precambrian rocks (Figure 3). Numerous drill holes locate the top of Precambrian rocks at approximately 1.3 s (3 km depth), above an approximately 12-km-thick succession of layered rocks seen on the seismic sections. These Precambrian strata are here referred to as the Quanah sequence after the nearby town of Quanah, Texas. The Quanah sequence is abruptly truncated against the Burch fault at the southern edge of the Wichita Mountains and is traceable 42 km to the southwest where the data end (Brewer et al., 1981). Similar layering on industry data about 150 km southeast of the COCORP data is also truncated by faulting just south of the Wichita Mountains (Brewer et al., 1981). The extent of the Quanah sequence to the northwest is unknown because of a lack of published data. If the same layered assemblage is being imaged on all the data, it covers an area of at least 42 × 150 km (a 5000-km^2 ellipse).

North of the Wichita Mountains, the COCORP transect does not show evidence of thick Precambrian layered rocks beneath the Anadarko basin (Brewer et al., 1983). Up to 4.8-km-thick layering is evident below the Cambrian Reagan sandstone, but this is likely part of the Lower to Middle Cambrian Wichita igneous complex (Widess and Taylor, 1959; Brewer et al., 1983). Though the deeper parts of this layering could correlate with the Quanah sequence, it would nonetheless be quite thin in comparison to that imaged south of the Wichita Mountains. It thus appears that the Wichita Mountains effectively mark the northern edge of the Quanah sequence.

The base of the Quanah sequence is a gradational boundary distinguished by a decrease in the number, amplitude, and length of reflections on the section (Figure 3). The layering is unambiguous to a traveltime of slightly more than 5 s, implying nearly 12 km of Precambrian strata. Relatively weak reflections occur below 6.0 s traveltime, but it is not clear if these are related to the overlying Precambrian strata.

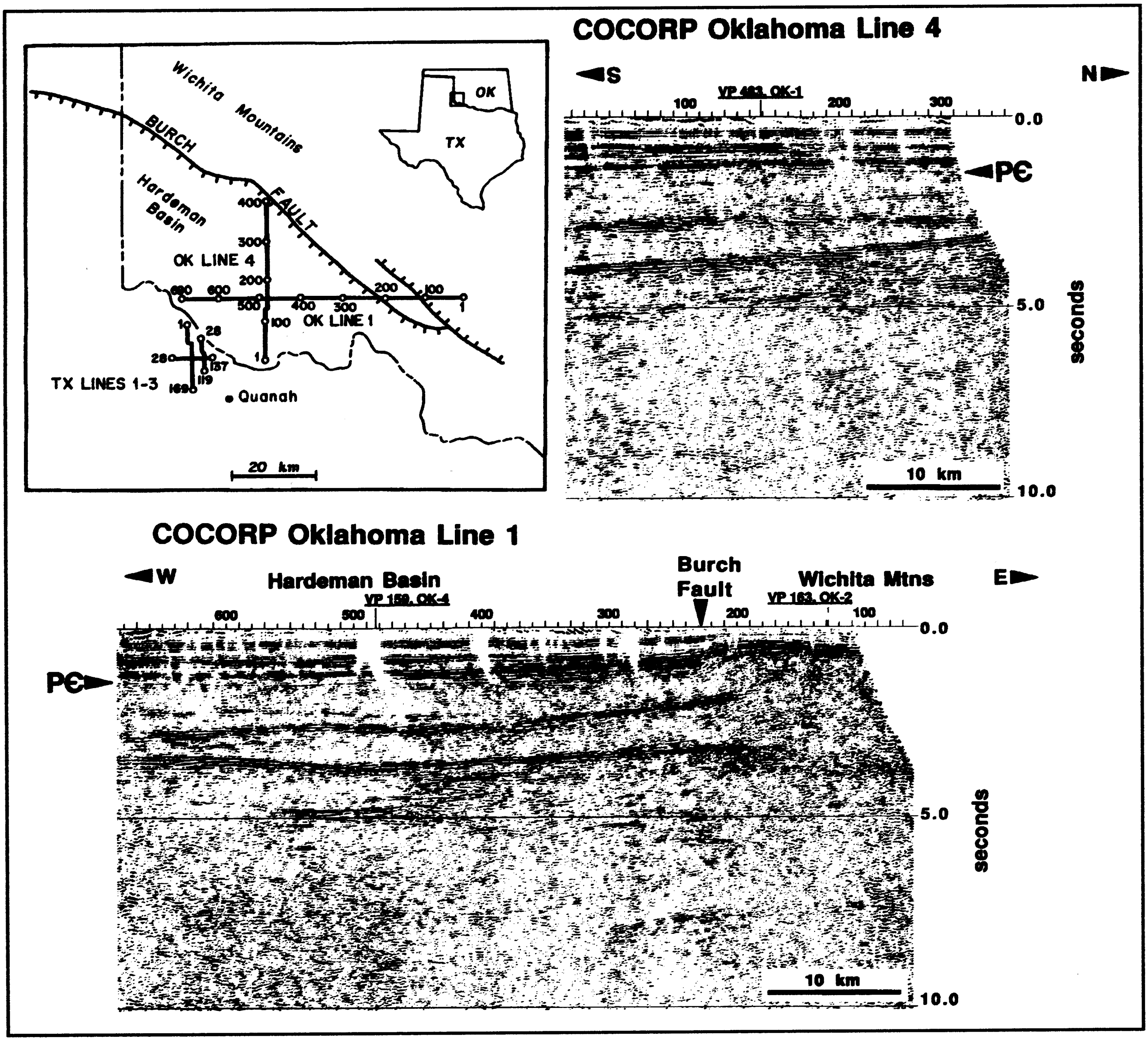

Figure 3—Upper 10 s two-way traveltime of COCORP Oklahoma line 1 and Oklahoma line 4 (Brewer et al., 1981) with the approximate top of Precambrian rocks marked. Note the thick sequences of layered strata that dominate the upper Precambrian crust. Inset map shows the line locations with vibrator point numbers marked, as well as the locations of the COCORP Texas surveys (Oliver et al., 1976). The seismic data are unmigrated, coherency filtered, and plotted with no vertical exaggeration, assuming a conversion velocity of 6.0 km/s.

Internal Features

Two strong reflection packages at traveltimes of about 2.0 and 4.0 s (5–11 km depth) are continuous for approximately 40 km along the COCORP lines (Oliver et al., 1976; Brewer et al., 1981) (Figure 3). Several of the lines cross at right angles and show that these reflectors have only slight dips, and that they are not parallel. A third reflector lying at approximately 5.0 s traveltime (about 14.5 km depth) is not as prominent as the other two, but can be traced for about 10 km (Figure 3).

Between the strong reflectors are strata which appear to discordantly lap or truncate against them, thus defining sequence boundaries suggestive of a depositional origin for the strata. Downlap or onlap is inferred at several locations (Brewer et al., 1981) (Figure 4), and truncations against the base of the strong reflections are inferred to represent erosional unconformities.

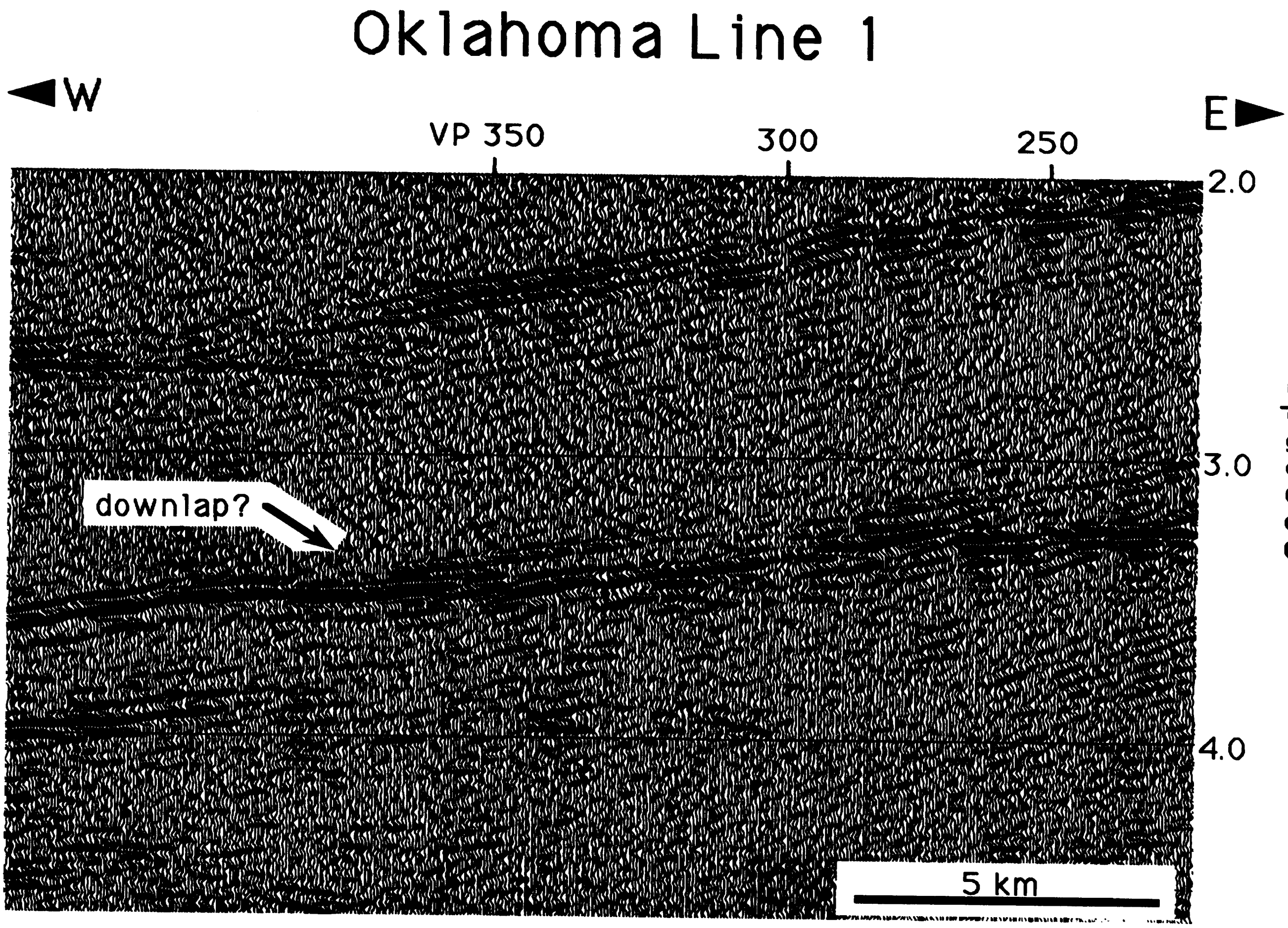

Figure 4—Portion of COCORP line Oklahoma 1 showing apparent downlap within the Precambrian layered sequence. Data are migrated and plotted with no vertical exaggeration, assuming a velocity of 6.0 km/s. Time is two-way traveltime.

Velocity Analyses

Because there are several exceptionally strong, subhorizontal events in the Precambrian section, accurate interval velocities were obtained (Brewer et al., 1981). The velocities increase downward from 6.1 ± 0.3 km/s between the top of the Precambrian and the first reflector to 6.3 ± 0.3 and 6.5 ± 0.2 km/sec between the deeper pairs of reflectors. The ranges on these velocity values indicate the lateral variability of velocities within the layers. These values are characteristic of igneous, metamorphic, or well-indurated sedimentary rocks.

The Centralia Sequence of Illinois and Indiana

Distribution

Layered Precambrian rocks are imaged on the upper 5 s (about 15 km depth) of COCORP lines acquired in southern Illinois and Indiana (Pratt et al., 1989) (Figure 5), and are hereafter referred to as the Centralia sequence after the nearby town of Centralia, Illinois. A synthetic seismogram made from the acoustic log of a nearby drill hole (the Union Oil 1 Cisne Community, Sec. 3, T1S, R7E, Wayne County, Illinois) (Figure 6) shows that a distinctive transparent zone correlates with the Cambrian-Ordovician Knox supergroup, and a reflection triplet correlates with the interbedded clastic and carbonate units of the Cambrian Eau Claire Formation and top of the underlying Mt. Simon Sandstone. There is little, if any, reflection from the Precambrian "basement" surface on the synthetic seismogram or on the seismic line in the immediate vicinity of the drill hole. The top of Precambrian basement lies at 1.5 s two-way traveltime; thus most of the layered rocks imaged on the COCORP lines lie within the Precambrian "basement."

Several exceptionally strong reflectors within the Precambrian sequence occur on the central 170 km of Illinois line 1 and Indiana line 1 (IL-1 and IN-1 in Figure 5). Diffractions and dipping reflections near station 300 on Illinois line 2 mark the western limit of the layered rocks (Figure 5). This apparent truncation corresponds approximately with projected extensions of the Cottage Grove and St. Genevieve fault systems (Nelson

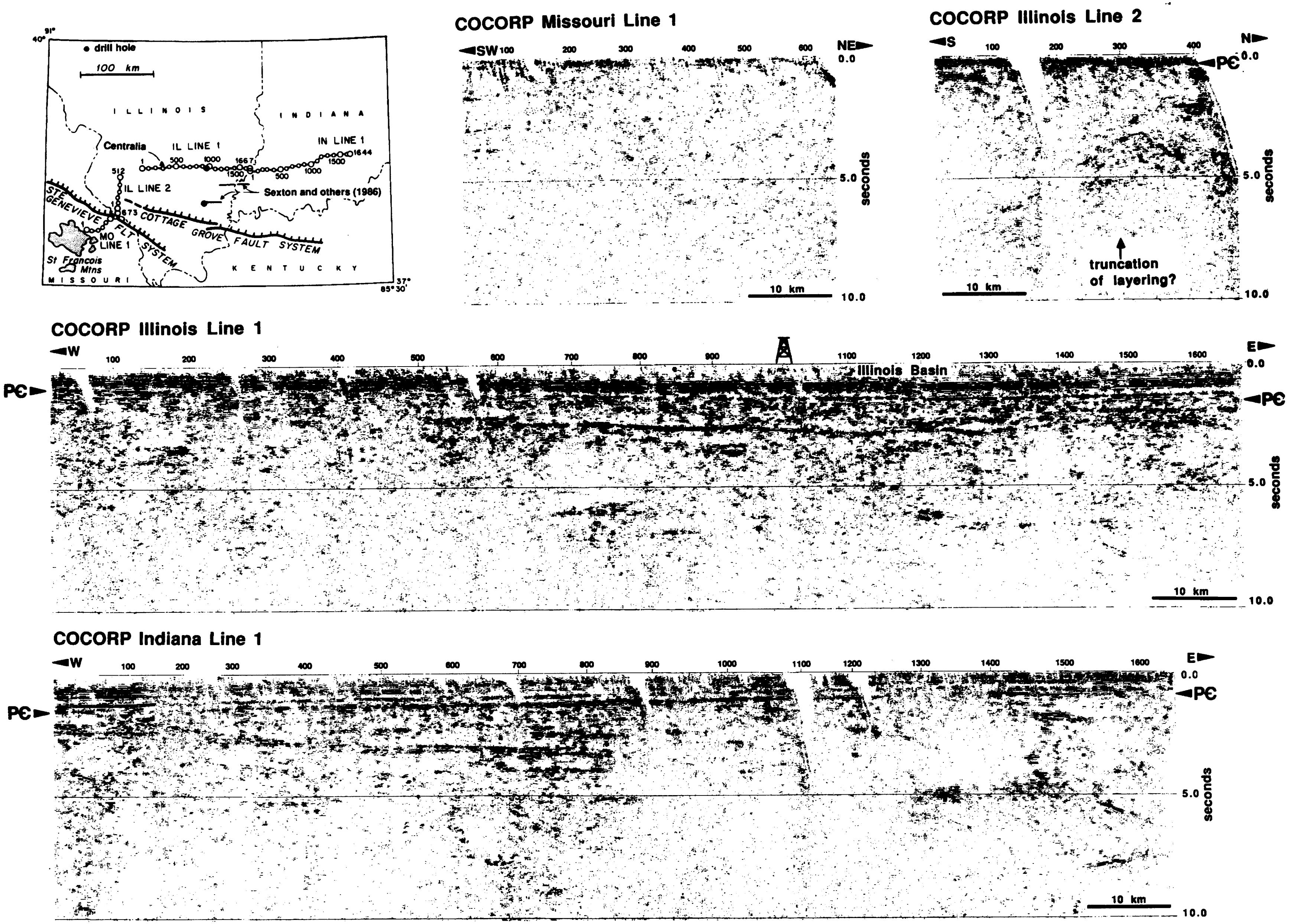

Figure 5—Upper 10 s two-way traveltime of COCORP Illinois line 1, Illinois line 2, Missouri line 1, and Indiana line 1 (Pratt et al., 1989) with the approximate top of Precambrian rocks marked. Note the thick sequences of layered strata which dominate the upper Precambrian crust. Inset map shows the line locations with vibrator point numbers marked, as well as the exposed Precambrian rocks of the St. Francois Mountains; the two black dots are the drill holes discussed in the text. The seismic data are unmigrated, coherency filtered, and plotted with no vertical exaggeration, assuming a conversion velocity of 6.0 km/s.

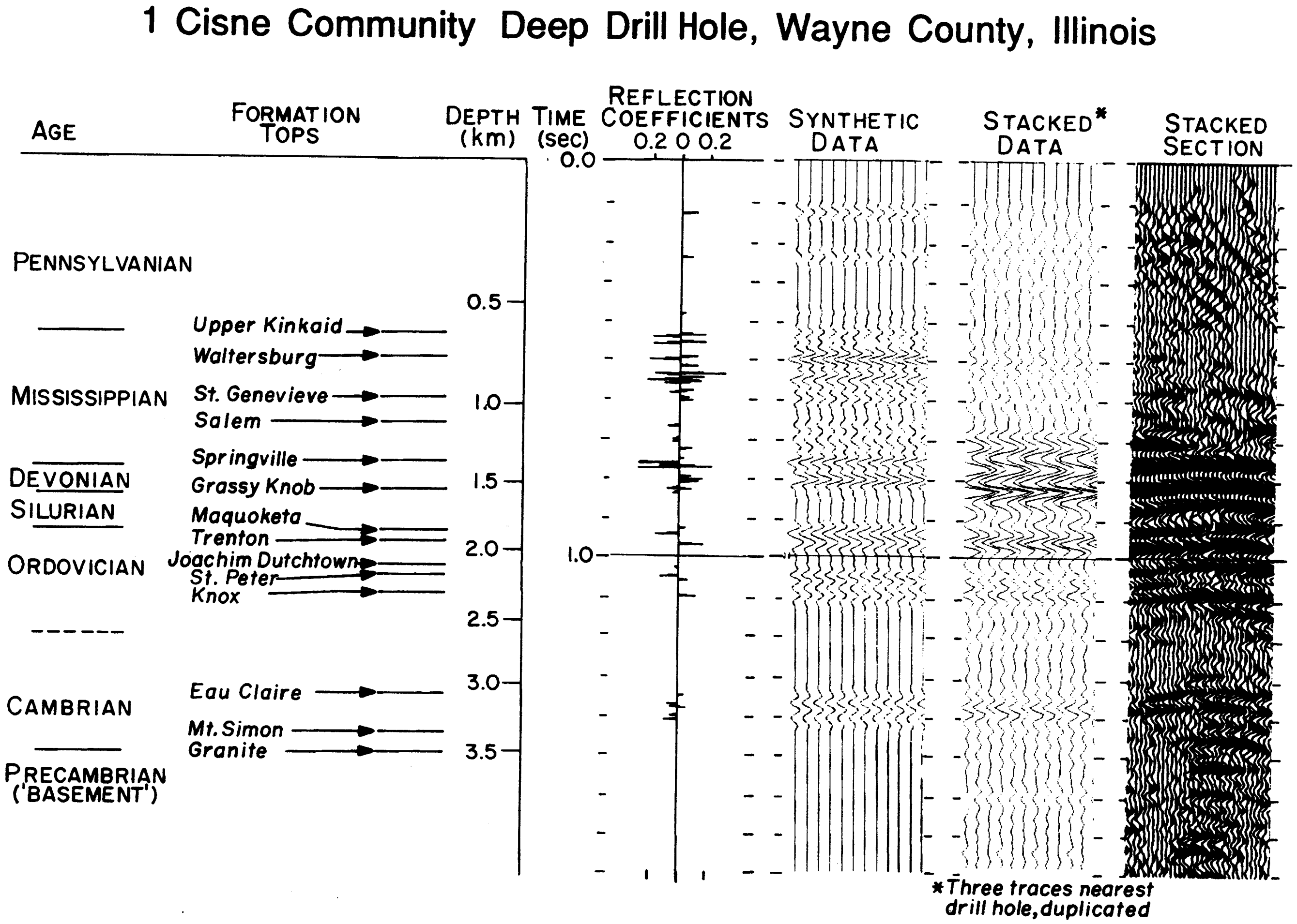

Figure 6—Synthetic seismogram made from the sonic log obtained in the 1 Cisne Community deep drill hole in Wayne County, Illinois. The drill hole is located about 1 km from COCORP Illinois line 1 (black dot near 1000 on map in Figure 5), a portion of which is shown. Vertical dimension is in two-way traveltime (in seconds) after conversion from depth using the sonic log velocities. There is not a strong reflector at the Precambrian boundary, and the Mt. Simon Formation is only 109 m thick in the drill hole.

and Krausse, 1981; Nelson and Lumm, 1984, 1985) (Figure 5) and a strong magnetic anomaly and gradient (Heigold, 1976). These apparently associated structural and magnetic features (part of Heyl's, 1972, "38th parallel lineament") probably mark only a structural disruption within the layered sequence because hints of layering are present further southwest on Missouri line 1 (Figure 5) and magnetic anomaly data (discussed below) suggest the layering continues farther south.

To the east, well-developed Precambrian layered rocks persist across Indiana line 1, for a total documented east-west extent of 320 km. The layering may extend as far as western Ohio, where subhorizontal reflectors between 3.0 and 5.0 s traveltime (9–15 km depth) appear to be truncated by dipping reflectors of the Grenville front tectonic zone (Figures 1, 2, 7). A Precambrian layered sequence with a slight (10–15°) eastward dip is also interpreted from a short seismic reflection profile in southwestern Ohio (Shrake et al., 1991) and may be part of the Centralia sequence. The layering east of VP 1250 on Indiana line 1 differs from that to the west, however, by having diffractions and dipping reflectors at midcrustal depths (4–7 s traveltime) and less continuity (Figure 5).

Industry data (Heigold, 1991) show that the Centralia sequence thickens considerably to the north and thins to the south of COCORP Illinois line 1. Layered Precambrian rocks are seen on gas and petroleum industry data in east-central Illinois nearly 200 km north of COCORP Illinois line 1 (Hauser, 1990), though the continuity of these reflections with the Centralia sequence has yet to be conclusively verified. To the south, Sexton et al. (1986) reported Precambrian stratified rocks on three relatively short (less than 30 km) seismic reflection profiles obtained in the Wabash Valley 15–30 km south of COCORP Illinois line 1 and Indiana line 1 (Figures 1, 8). Though Sexton et al. (1986) interpreted these "pre–Mt. Simon" layered

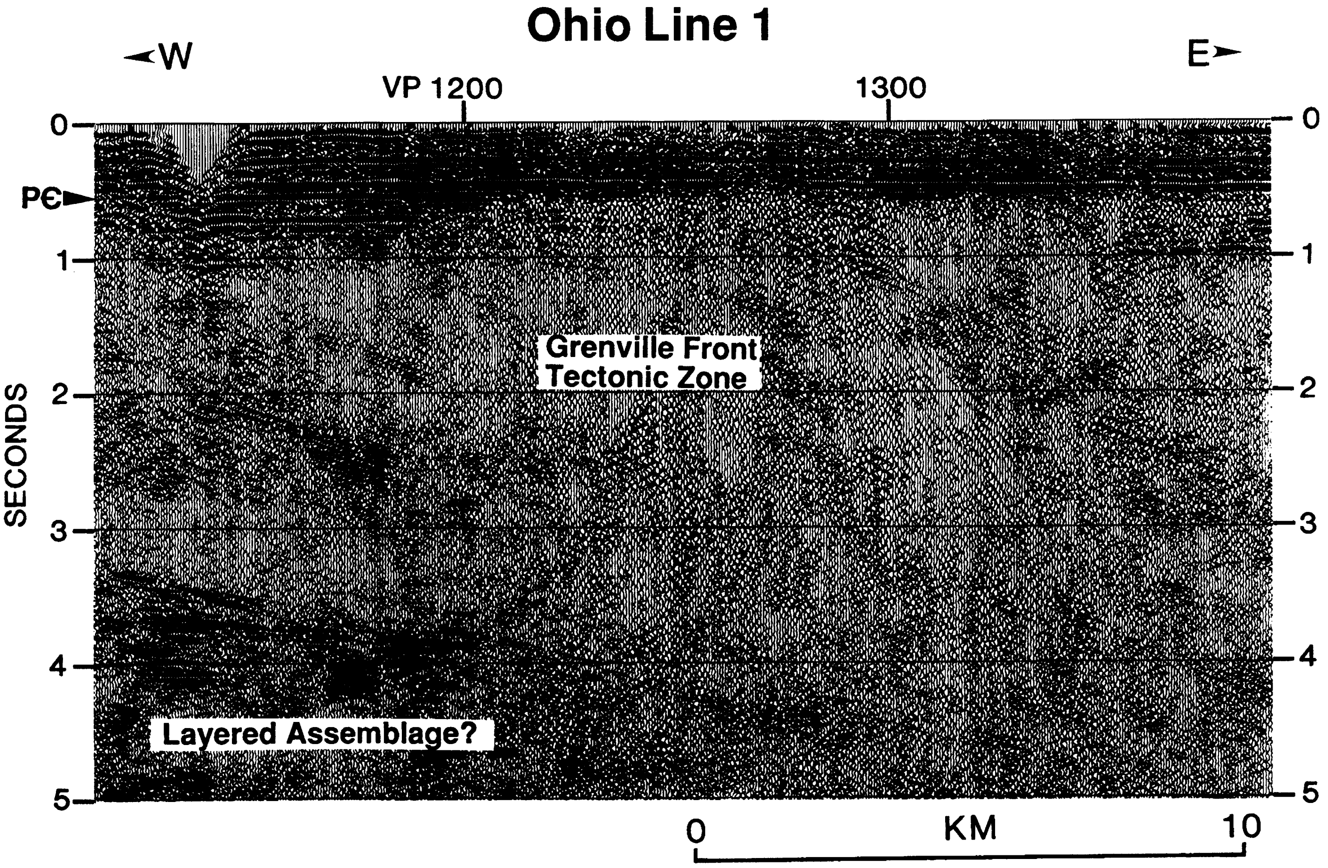

Figure 7—Portion of COCORP Ohio line 1 showing horizontally stratified reflectors on the left side of the figure at 3–5 s two-way traveltime (9–15 km depth) truncated by east-dipping strata interpreted as part of the Grenville front tectonic zone (Green et al., 1988; Pratt et al., 1989). Data are unmigrated, coherency filtered, and plotted with no vertical exaggeration, assuming a conversion velocity of 6.0 km/s.

rocks in part as a northward extension of the upper Precambrian/Lower Cambrian Reelfoot rift and Rough Creek graben (see also Braile et al., 1982, 1986; Nelson, 1990, 1991; Pratt et al., 1990), we believe they imaged part of the older Centralia sequence. Layered Precambrian strata are not imaged outside of or beneath the Reelfoot rift on COCORP (Nelson and Zhang, 1991) and industry data (Howe and Thompson, 1984) 150 km south of the Illinois basin (Figure 1). A total north-south extent of 200 km is thus suggested from the seismic data (Figure 1), giving a total areal extent for the Centralia sequence of more than 50,000 km^2 (assuming a 200 × 320 km elliptical region).

Across most of COCORP Illinois line 1 and Indiana line 1, the Centralia sequence is visible to traveltimes of 4 s, indicating that it is on average 6–8 km thick, or about twice that of the thickest Phanerozoic strata in the region. The lower boundary of the layering is marked by a decrease in the amplitude, number, and length of reflectors rather than by a sharp horizon. The greatest unambiguous thickness of layered rocks imaged on the COCORP data is about 12 km near VP 800 on Indiana line 1 (Figure 5), where strong, subhorizontal reflections occur to traveltimes of more than 5 s. It is not known whether the scattered reflections at traveltimes below 5 s on the line are related to the Centralia sequence.

Internal Features

The prominent reflector between 2.5 and 3.5 s on Illinois line 1 between VP 1000 and 1400 (Figure 5) appears to outline a shallow Precambrian graben underlying the deepest portion of the Illinois basin. Also at several locations on Illinois line 1 and Indiana line 1, the lowermost strata have a fanning geometry (e.g., Figure 9), suggestive of a half graben. A graben has also been interpreted by Sexton et al. (1986) on data in the Wabash Valley just south of the COCORP line, and a normal fault is interpreted within a Precambrian layered sequence on seismic data in southwestern Ohio (Shrake et al., 1991). Taken together, these features are suggestive of an extensional environment during the formation of the layering.

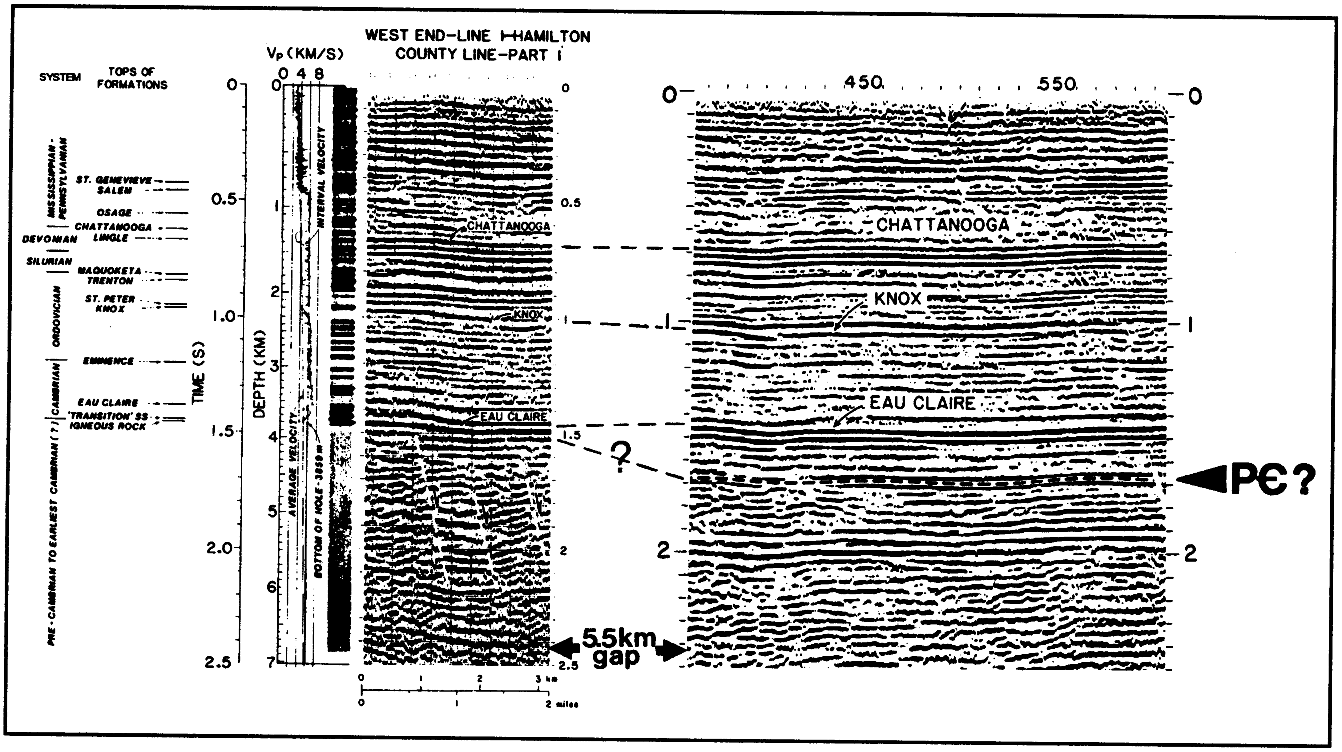

Figure 8—Data from Sexton et al. (1986) with drill hole correlations. Note the absence of the Mt. Simon formation in the drill hole and the presence of about 0.25 s (650 m) of conformable strata below the Eau Claire away from the drill hole. Strata below 1.7 s traveltime are interpreted to be part of the Precambrian layered sequence. Data are unmigrated and are plotted with no vertical exaggeration, assuming a conversion velocity of 2 km/s.

Distinct discordances resembling seismic-stratigraphic sequence boundaries (Mitchum et al., 1977) are apparent between reflectors in the Centralia sequence. Examples of these boundaries are seen between VP 1100 and 1500 on Illinois line 1 (Figure 10), where the uppermost Precambrian rocks have a small (less than 10°) eastward dip and an apparent erosional truncation at their top, and show apparent downlap against a relatively strong, subhorizontal reflection sequence at 2.0 s traveltime. These discordances are most easily related to deposition, such as foreset sequences in an alluvial fan or delta, and erosion.

Velocity Analyses

As expected from analysis of the sonic log from the Cisne drill hole, the portion of the section above the lower Mississippian Springville Shale (Figure 6) is distinctive because of a relatively low bulk velocity of 4.0 ± 0.1 km/s. The lowermost Mississippian through Upper Cambrian section (Springville Shale to the Eau Claire Formation), in contrast, is characterized by high interval velocities (6.3 ± 0.2 km/s) typical of predominantly carbonate strata.

The velocity analyses indicate that a distinct layer of relatively low velocity (5.3 ± 0.4 km/s) material is present beneath the Cambrian Eau Claire across most of Illinois line 1 and Indiana line 1, consistent with a widespread basal clastic sequence about 650 m thick. The inferred total thickness of these strata (650 m) is greater than the 109 m of Mt. Simon formation penetrated in the Cisne drill hole. As discussed below, the Mt. Simon formation is probably abnormally thin at the drill hole locations. The Precambrian layered rocks beneath this clastic unit have bulk velocities between about 5600 and 6200 m/s, with an apparent slight increase (5800 to 6100 m/s) in average velocity eastward across Illinois line 1. Seismic velocities in this range are typical of a wide variety of igneous, indurated sedimentary, and metamorphic rocks. The sizable scatter in the measured velocities may indicate that a variety of rock types compose the layering.

Correlation with Other Data

Drill Hole Data

There are no substantial drill penetrations into Precambrian basement rocks in areas where the basement layered assemblages described here are observed on seismic data. Scattered drill holes do, however, provide direct samples of the Precambrian basement surface (few tens of meters) in the region.

In the Texas-Oklahoma region, predominantly 1.3–1.4 Ga granites and rhyolites assigned to the "west-

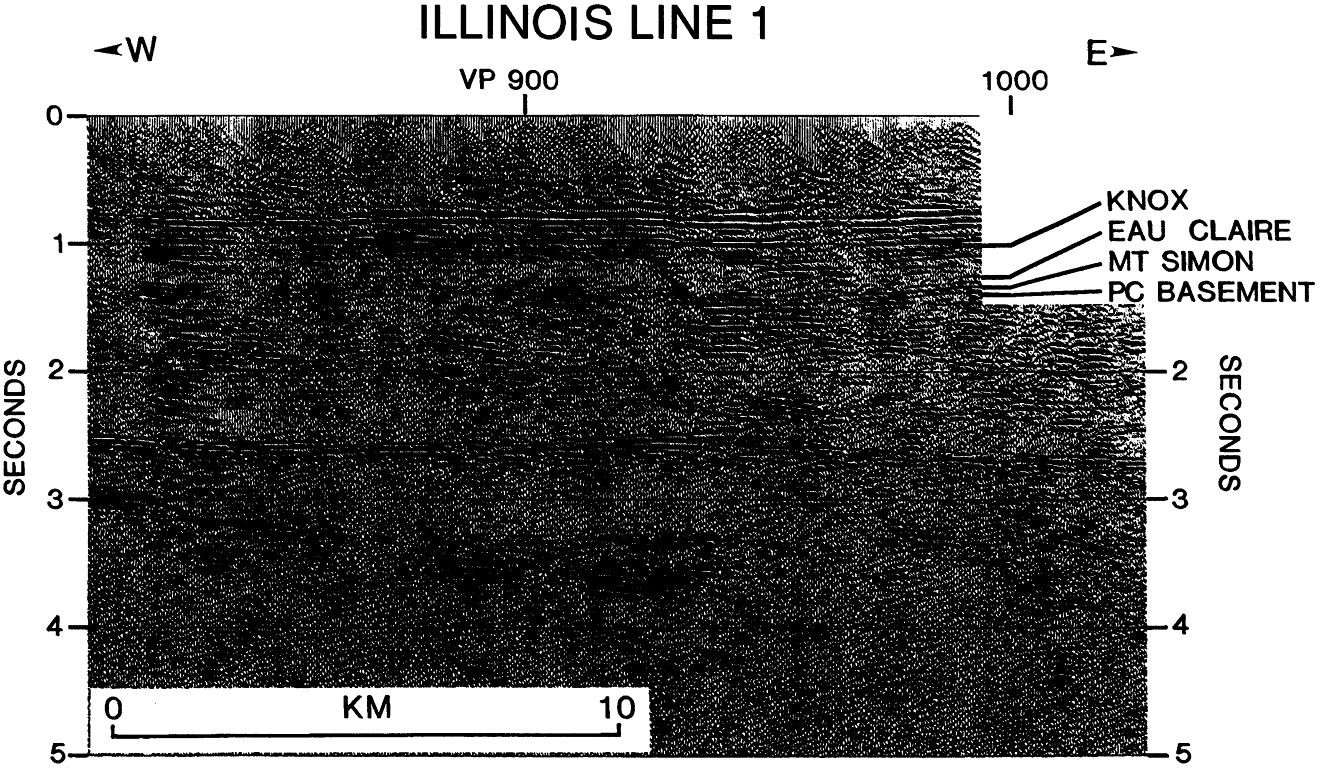

Figure 9—Part of Illinois line 1 near the 1 Cisne Community drill hole in Wayne County, Illinois. The prominent reflector at 2.5–2.8 s two-way traveltime (6.5–7.5 km depth) is continuous for approximately 70 km. The strong reflectors below 3.0 s dip more than the overlying reflectors and suggest the presence of a half graben. Data are unmigrated, coherency filtered, and plotted with no vertical exaggeration, assuming a conversion velocity of 6.0 km/s.

ern granite-rhyolite province" (Bickford et al., 1986) were sampled in basement tests. Substantial sedimentary and metasedimentary rocks also subcrop in the general region (Ham et al., 1964; Muehlberger et al., 1967; Flawn and Muehlberger, 1970), and pieces of metasedimentary rock lie within the 1.35 Ga Arbuckle granites (Flawn and Muehlberger, 1970). These terranes include the Tillman (Red River mobile belt) of southern Oklahoma and northern Texas (Ham et al., 1964), the DeBaca of eastern New Mexico and western Texas (Muehlberger et al., 1967; Denison et al., 1984), and the Fisher of central Texas (Muehlberger et al., 1967).

The Tillman terrane, consisting of graywackes, shales, and minor sandstone and chert, locally metamorphosed to biotite grade, is of particular importance because it comprises the basement surface south of the Wichita Mountains, where COCORP and industry data show prominent layering. The DeBaca terrane is composed primarily of siltstones and carbonate rocks with some rhyolite detritus, and the Fisher terrane is primarily meta-arkose and mica schist. Although uncertainties in the ages of these units make their relationship to the surrounding granites and rhyolites unclear, they are generally believed to be middle to upper Proterozoic (Wasserbug et al., 1962; Ham et al., 1964; Muehlberger et al., 1967; Denison et al., 1984). Their presence, however, suggests that the granites and rhyolites of the region are likely interspersed with, and possibly underlain by, nonvolcanic sedimentary strata.

In the Illinois basin region, drill holes to basement also sampled granites and rhyolites, in this case assigned to the "eastern granite-rhyolite province" (Bickford et al., 1986) (Figure 11). The number of penetrations in the area of the Centralia sequence are few, however, and we argue that they are not representative for several reasons.

(1) The drill holes sampled only the upper few tens of meters of Precambrian rock. The unsampled deeper strata could be of a different composition.

(2) Drill holes for petroleum exploration are sited over anticlinal structures in the Paleozoic cover, which in turn correspond with more resistant rocks composing the paleotopographic highs (monadnocks) on the Precambrian surface (e.g., Atherton, 1971; Schwalb, 1982). It is therefore likely that drill holes have preferentially sampled the more resistant lithologies (granites?) and not the intervening rocks. In better sampled areas nearby, the eroded Precambrian surface has hundreds of feet of local relief, with the lowermost Phanerozoic strata (the Mt. Simon formation) thin or

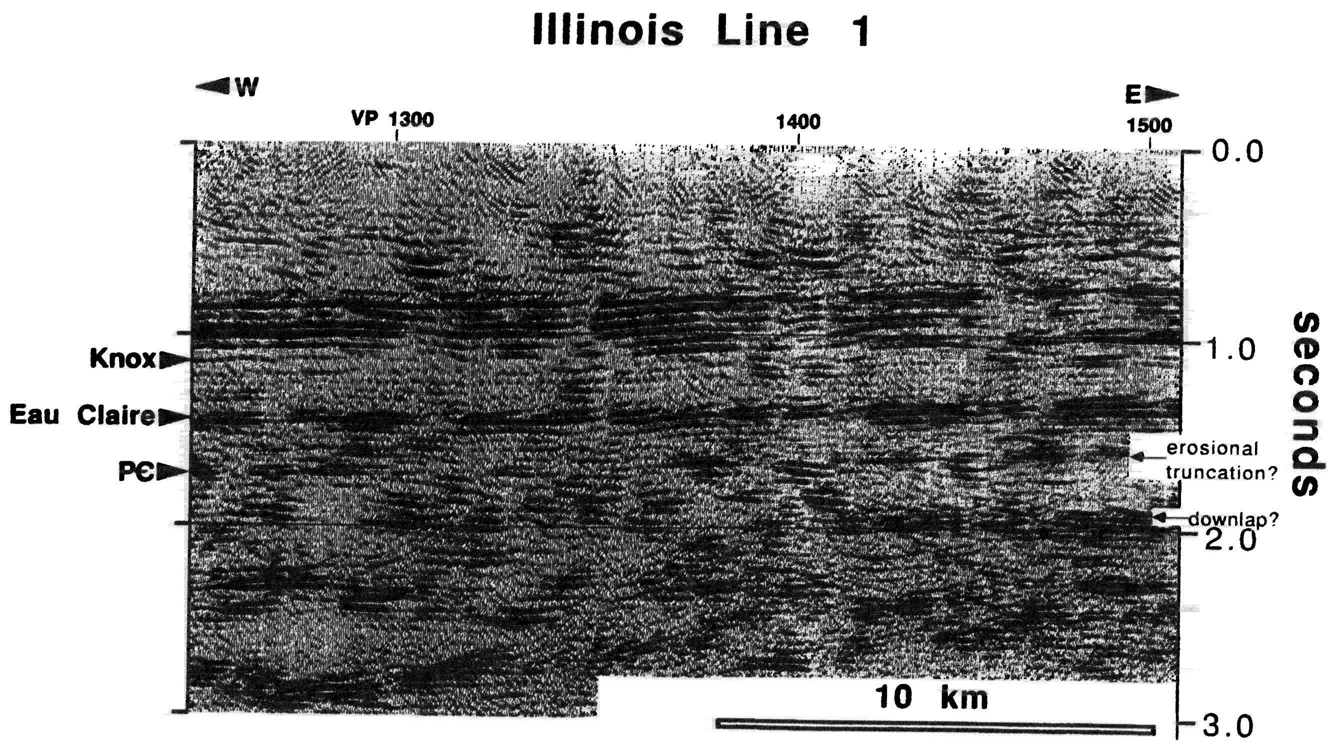

Figure 10—Portion of COCORP Illinois line 1 showing apparent sequence boundaries within the Precambrian layered strata. Note the apparent unconformity labeled "erosional truncation" and interpreted as delineating the top of Precambrian rocks, immediately beneath which the reflectors show a slight eastward dip. The uppermost Precambrian rocks show apparent downlap against the reflector just above 2.0 s two-way traveltime. Data are migrated, coherency filtered, and plotted with no vertical exaggeration, assuming a conversion velocity of 6.0 km/s.

absent on the "hills" (Atherton, 1971, Buschbach, 1975; Schwalb, 1982). This paleotopography causes both differential sedimentation and compaction and thus a correspondence between basement monadnocks and anticlines in the overlying Paleozoic strata. In both the Cisne and the Texaco 1 Cuppy (Sec. 6, T6S, R7E, Hamilton County, Illinois) drill holes, the Mt. Simon formation is thin (109 m in the Cisne hole) or absent (Figures 6, 8), yet across much of the seismic data a strong Precambrian basement reflection approximately 0.25 s below the Eau Claire reflection indicates about 650 m of relatively low-velocity (5.3 km/s) Mt. Simon or pre–Mt. Simon strata (Figures 8, 10). In the two other wells we examined in southern Illinois (the Texaco 1 R. S. Johnson, Sec. 6, T1N, R2E, Marion County, Illinois, and the C. E. Brehm Drilling Company 1 Bochantin Community, Sec. 35, T3S, R2W, Washington County, Illinois), the Mt. Simon Formation also is anomalously thin (219 m) or absent.

(3) The same general argument can be made for drill holes sited for mineral exploration. These holes were drilled primarily in search of rocks of high density or high magnetic susceptibility as delineated by gravity and magnetic data. These potential field anomalies invariably correspond with magnetite-bearing granitic intrusions of the middle Proterozoic granite-rhyolite suite (Van Schmus et al., 1987). It is unlikely that these basement samples are representative of the majority of the rocks corresponding to the magnetically quiescent regions such as those above the Centralia sequence (see below). As an example, of the 128 drill holes to the Precambrian in Missouri and Iowa of which we are aware, about 60% obviously correspond with a gravity or magnetic anomaly visible on 1:2,500,000-scale gravity and magnetic maps (Figure 11), and we suspect the percentage would be much higher if more detailed potential field maps were examined.

(4) There is a real possibility that Precambrian (meta-) sedimentary rocks in the region have gone unrecognized due to misidentification of basement samples in the original drilling reports. This was highlighted by a recent deep drill hole in southwestern Ohio which, rather than Precambrian crystalline basement, cored 580 m of "lithic arenite sandstone" before drilling stopped for financial reasons (Shirley, 1990; Shrake et al., 1991). Subsequent reexamination of reputedly crystalline basement samples obtained in 9 nearby wells in Ohio, Indiana, and Kentucky found that 5 were actually sandstones. A previously unrecognized Precambrian or lowermost Paleozoic sedimentary basin approximately 150 km long has been interpreted from the data (Shrake et al., 1991).

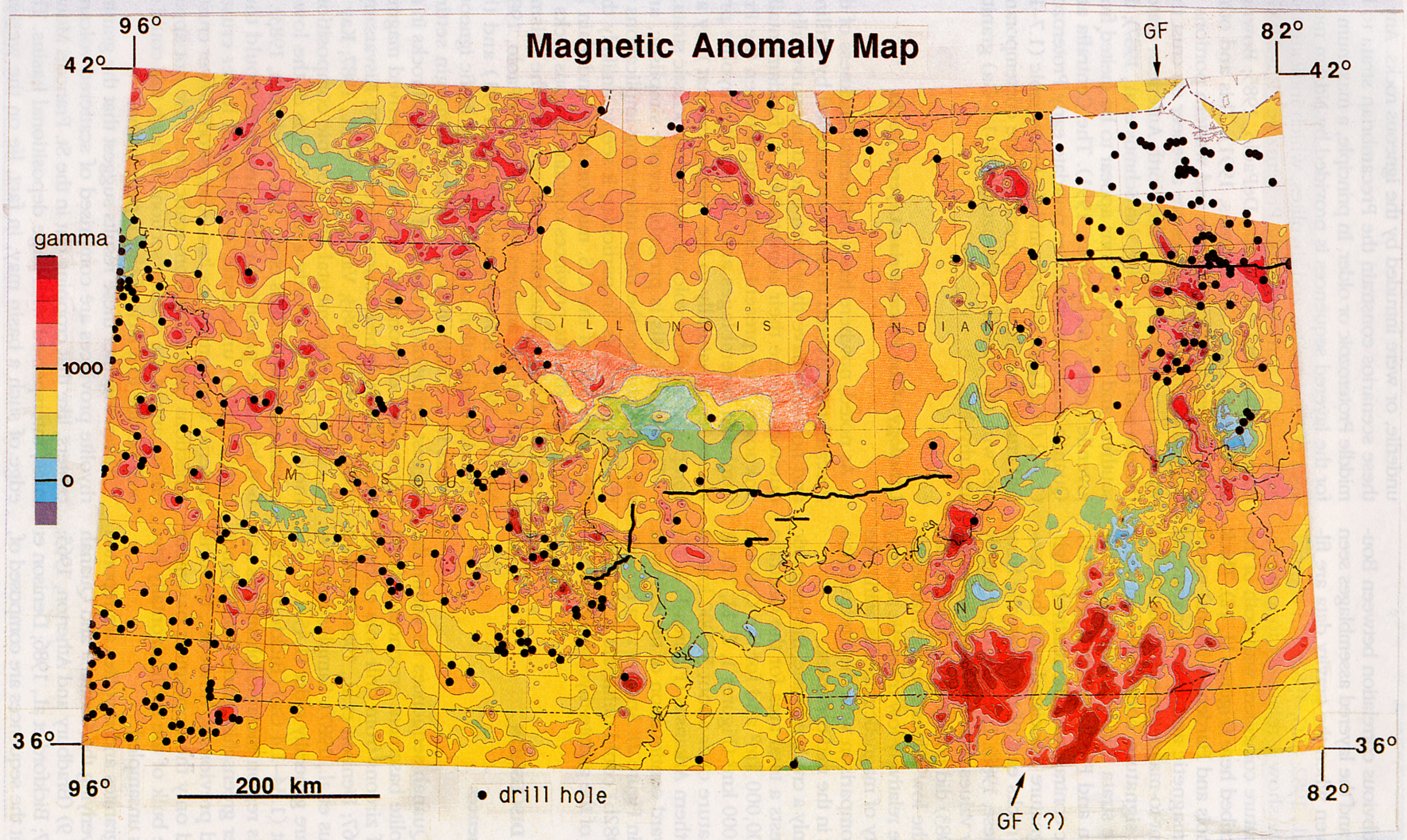

Figure 11—Magnetic anomaly map (SEG, 1982b) of the eastern mid-continent region. Heavy lines mark the approximate location of the COCORP data (Pratt et al., 1989) and the Wabash Valley data (Sexton et al., 1986), and dots mark drill hole locations (Becker et al., 1978; Schwalb, 1982; Mugel, 1986; Lucius and von Frese, 1988). Note the relatively "smooth," low-valued magnetic signature in the southern Illinois and Indiana region. A data gap in central Illinois on the original map (SEG, 1982b) was filled in by hand-contouring data supplied by Thomas Hildenbrand of the U.S. Geological Survey. GF = Grenville front.

Potential Field Data

We have found no obvious correlation between Bouguer gravity anomalies and the layered assemblages seen on the seismic data, even when the gravity data are filtered (Hildenbrand et al., 1982; SEG, 1982a). In contrast, magnetic anomaly data show a relatively long-wavelength, low-valued signature coincident with both of the layered sequences described here (Figures 11, 12). Thick Phanerozoic strata (Illinois and Hardeman basins) would also cause a smooth magnetic anomaly signature by increasing the basement-to-magnetometer distance, but the long-wavelength signature continues eastward, where the Phanerozoic strata thin considerably on the Indiana-Ohio platform and Findlay arch (Figure 11). There is also a dramatic contrast with the relatively high-frequency magnetic signature associated with the metamorphosed basement rocks east of the Grenville front (e.g., Lucius and von Frese, 1988). Likewise, the relatively high magnetic-anomaly values over the Anadarko basin, where Brewer et al. (1983) did not see thick Precambrian layering, contrast with the low values over the Hardeman basin (Figure 12). These relatively low magnetic anomaly values indicate a scarcity of magnetic minerals within the layered sequence in comparison with the Precambrian rocks at other locations in the mid-continent.

Though obviously only a crude estimate, this magnetic anomaly pattern suggests a total area for the Centralia sequence of about 200,000 km^2 and for the Quanah sequence of about 50,000 km^2 (Figures 1, 2, 11, 12). A similar magnetic signature over about 32,000 km^2 in southern Missouri–northern Arkansas (Figures 1, 2, 11) may indicate a southward continuation of the Centralia sequence (as depicted in Figure 2). Another area in western Nebraska (SEG 1982b) could delineate a stratified sequence lying outside of the granite-rhyolite provinces.

INTERPRETATION AND DISCUSSION

Age of the Layered Sequences

The Centralia and Quanah sequences lie within the 1.3–1.5 Ga granite-rhyolite basement provinces defined from U-Pb analyses of zircons from drill hole cuttings (Muehlberger et al., 1967; Denison et al., 1984; Bickford et al., 1986; Van Schmus et al., 1987). Samples from the eastern mid-continent are generally older (1.45–1.51 Ga) than those in the west (1.34–1.4 Ga) (Bickford et al., 1986). Throughout this region metamorphism has not been greater than lower greenschist grade (Van Schmus et al., 1987). As stated previously, however, the drill holes have penetrated only the uppermost basement rocks, thus leaving the bulk of the subhorizontally layered Precambrian rocks unsampled.

Middle Proterozoic granites and rhyolites are reported in drill holes directly overlying the Centralia and Quanah sequences (e.g., Figure 9) (Bradbury and Atherton, 1965; Muehlberger et al., 1967; Bickford et al., 1986; Denison et al., 1984), indicating that the sequences are composed of, underlie, or were intruded by the igneous rocks. Any of these scenarios constrain the Precambrian strata to be middle Proterozoic or older. In principle, a maximum age for the layered sequences is provided by Nd/Sm model ages of the granites and rhyolites, which indicate they melted from early to middle Proterozoic (1.5–2.0 Ga) continental crust (Nelson and DePaolo, 1985; Bowring and Housh, 1991; Van Schmus, 1991). This and other data suggest that the northern and western portions of the granite-rhyolite provinces are a veneer on crust that was previously accreted to the North American craton (Nelson and DePaolo, 1985; Van Schmus et al., 1987); the southern and eastern portions appear to be melted from juvenile crust (Van Schmus, 1991). The Centralia and Quanah sequences therefore postdate early Proterozoic (1.7–2.0 Ga) and perhaps middle Proterozoic (1.7–1.5 Ga) crustal formation, but predate or are contemporaneous with the middle Proterozoic (1.3–1.5 Ga) granites and rhyolites.

Lithology of the Precambrian Layered Rocks

As noted, nowhere has a substantial thickness of the Precambrian layered rocks been sampled by drilling, and nowhere have they been traced unequivocally to outcrop—hence their composition is, fundamentally, unknown. The present correlation between the Precambrian assemblages and the granite-rhyolite provinces leads naturally to the suggestion that they are composed of silicic volcanic and volcanoclastic strata.

This hypothesis is probably overly simplistic, and may well obscure the most interesting implications of the seismic results. In particular, it seems unlikely that the nearly 50% of the U.S. mid-continent underlain by the granite-rhyolite provinces contains igneous rocks as thick as the Precambrian strata seen on the seismic data. Nd isotopic analyses (Nelson and DePaolo, 1985; Nelson, 1990; Bowring and Housh, 1991) and the bimodal distribution of felsic and minor mafic igneous rocks in a continental or continental-margin setting suggest formation by fusion of lower crustal rocks in an extensional environment, with mantle-derived magmas being the likely heat source (Emslie, 1978; Kisvarsanyi, 1981; Anderson, 1983; Van Schmus et al., 1987; Kay et al., 1989). The elemental and isotopic compositions indicate melting of only about 10–30% of the lower crustal material (Cullers et al., 1981; Anderson, 1983). A 6–8 km thick granite rhyolite province would thus imply that an unrealistic 20–80 km of lower crustal material was partially melted. Also, strong lower crustal reflections originating from mafic layers are not apparent on any of the seismic sections, though this could as well be due to a lack of signal penetration.

Taken together these results suggest that the granite-rhyolite provinces are comprised of scattered volcanic centers, like that cropping out in the St. Francois Mountains, interspersed with large depositional basins. The edge of such a basin may, in fact, lie on the western

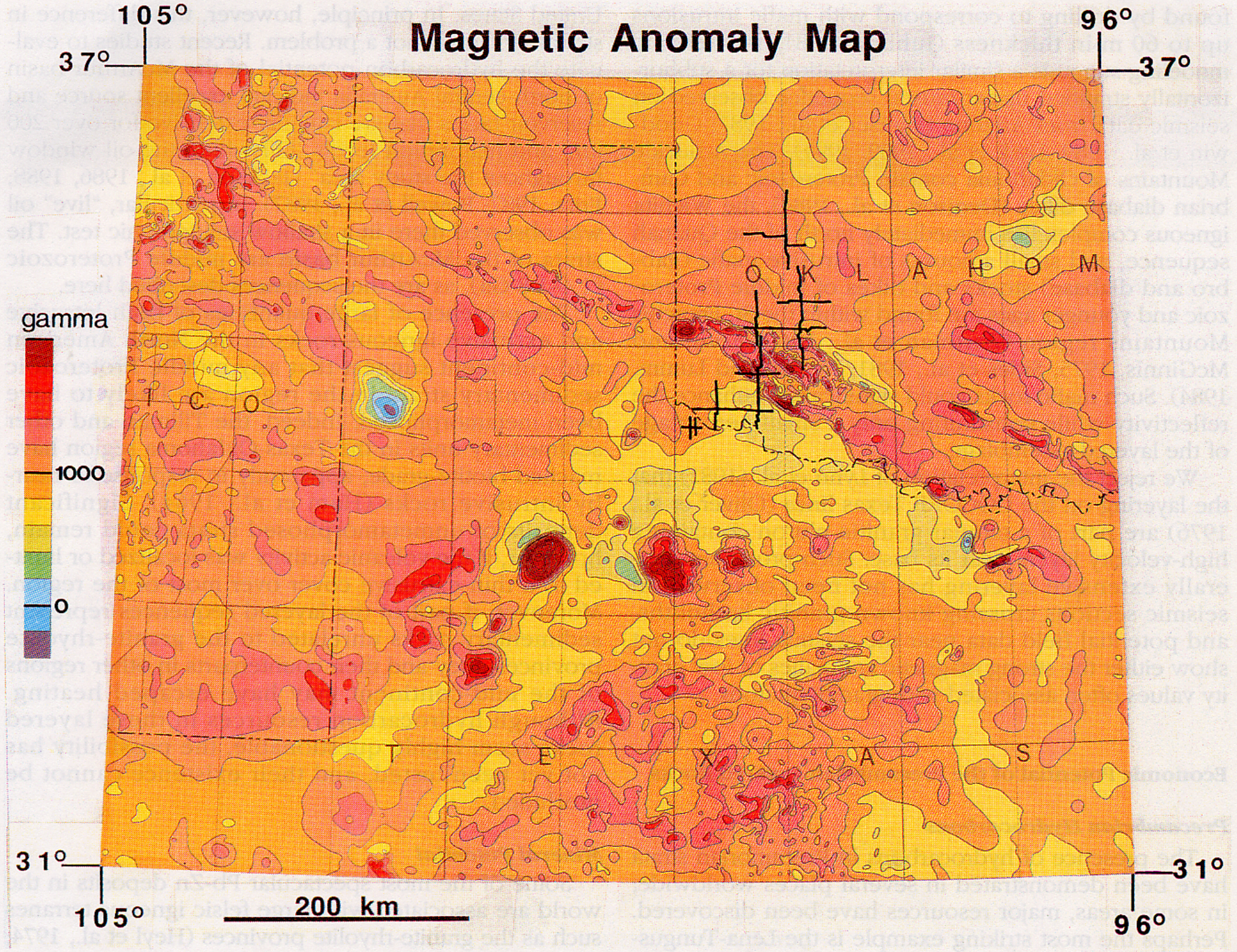

Figure 12—Magnetic anomaly map (SEG, 1982b) of the southern mid-continent (Texas panhandle and southern Oklahoma) region with the COCORP Hardeman County (Texas) and Oklahoma transects plotted as heavy lines (Oliver et al., 1976; Brewer et al., 1981). Note the relatively low magnetic values in the area surrounding the COCORP lines south of the Wichita Mountains.

flank of the St. Francois Mountains, where an erosional unconformity is mapped at the base of about 3 km of volcanic strata (Sides et al., 1981). The lack of strong layering on seismic data acquired near the St. Francois Mountains may be due to the internal complexities of the caldera complex itself, whereas the thick layered sequences are composed of relatively undisturbed outflow and more distal volcanic and sedimentary strata.

The proportion of volcanic versus nonvolcanic sedimentary strata within these interpreted basins is unconstrained. However, given the extent and internal character of the layered sequences, it is entirely possible that nonvolcanic sedimentary strata comprise a significant fraction. For example, the extrusive felsic volcanic rocks may be intermixed with clastic or marine sedimentary rocks. Likewise, older, nonvolcanic sedimentary strata may underlie a thin veneer of felsic volcanic rocks comprising the granite-rhyolite provinces. The relatively high interval velocities of the layered assemblages indicate very well indurated (metamorphosed?) strata, but the variations in interval velocities may indicate that a variety of rock types is present.

The relative paucity of mafic igneous rocks exposed in the St. Francois Mountains and recovered in drill holes sampling the granite-rhyolite terranes, as well as the lack of strong gravity and magnetic anomalies corresponding with the Precambrian layered assemblages, imply that mafic igneous rocks form a relatively minor component of the Centralia and Quanah sequences. We suspect that some of the more prominent reflections, however, have been enhanced by mafic intrusives. Prominent, subhorizontal reflectors in the upper crust at the Siljan impact structure in Sweden (Dahl-Jensen et al., 1987; Juhlin and Pederson, 1987) were found by drilling to correspond with mafic intrusions up to 60 m in thickness (Juhlin, 1988), and seismic modeling suggests a similar interpretation for a subhorizontally stratified upper crustal sequence observed on seismic data from Arizona (Hauser et al., 1987; Goodwin et al., 1989; Litak et al., 1989, 1991). The Arbuckle Mountains of Oklahoma contain Proterozoic and Cambrian diabase dikes (Denison et al., 1984), the Wichita igneous complex lies immediately north of the Quanah sequence, and small amounts of intrusive mafic (gabbro and diabase) stocks and dikes of middle Proterozoic and younger ages are found within the St. Francois Mountains region (Zartman et al., 1967; Ervin and McGinnis, 1975; Sides et al., 1981; Nelson and Lumm, 1984). Such mafic rocks could significantly enhance the reflectivity while constituting only a small percentage of the layered assemblage.

We reject the interpretation of Lynn et al. (1981) that the layering on the COCORP Texas lines (Oliver et al., 1976) are part of a tabular granitic pluton containing high-velocity layers near its base. Such prominent, laterally extensive layering has not been observed on seismic sections crossing known granitic batholiths, and potential field data near the seismic lines do not show either the strong magnetic anomalies or low gravity values often associated with granitic plutons.

Economic Potential of the Precambrian Layered Rocks

Precambrian Hydrocarbons

The presence of hydrocarbons in Precambrian strata have been demonstrated in several places worldwide; in some areas, major resources have been discovered. Perhaps the most striking example is the Lena-Tunguska petroleum province of the Irkutsk basin on the eastern Siberian platform (Meyerhoff, 1980; Murray et al., 1980) in which the oil is apparently indigenous to the upper Proterozoic strata and not derived from younger overlying sedimentary rocks (Murray et al., 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 Huqf Group (Alsharhan and Kendall, 1986), and gas has been discovered in the late Proterozoic Amadeus basin in central Australia (Ozimic et al., 1986). There is abundant evidence for viable but as yet unproductive source rocks in Proterozoic strata elsewhere in the world (Murray et al., 1980). One such example is the 1.0–1.1 Ga upper Keweenawan Nonesuch Shale on the south shore of Lake Superior in which "crude oil, optically active alkanes, porphyrins, and the isoprenoid hydrocarbons pristane and phytane" are present (Barghoorn et al., 1965).

Most of the above examples range from Vendian (uppermost Precambrian) to upper Keweenawan (1.1 Ga) in age, 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 United States. In principle, however, this difference in stratal vintage is not a problem. Recent studies to evaluate the hydrocarbon potential of the McArthur basin of north-central Australia indicate excellent source and reservoir facies that are laterally extensive for over 200 km, and maturation levels "fall within the oil window throughout the study area" (Jackson et al., 1986, 1988; Fritz, 1987; Powell et al., 1987). In particular, "live" oil was observed there in a shallow stratigraphic test. The strata of the McArthur basin are middle Proterozoic (1.4–1.8 Ga), as are the sequences described here.

The presence of large quantities of both intrusive and extrusive igneous rocks in the North American mid-continent suggest that any middle Proterozoic sedimentary strata in the region are likely to have been metamorphosed. Indeed, the Tillman and other sedimentary units in the Texas-Oklahoma region have reached biotite grade, apparently in response to nearby intrusive rocks (Ham et al., 1964). Significant deposits of unmetamorphosed strata could remain, however, if the volcanic activity was localized or limited to a thin extrusive cover over most of the region. Moreover, if part of the layered sequences represent sedimentary rocks unrelated to the granite-rhyolite provinces, they and their counterparts in other regions of the mid-continent may have escaped heating. Although hydrocarbon resources in these layered rocks seem highly questionable, the possibility has not yet been tested, and their existence cannot be precluded.

Mineral Potential

Some of the most spectacular Pb-Zn deposits in the world are associated with large felsic igneous terranes such as the granite-rhyolite provinces (Heyl et al., 1974; Sawkins, 1989). These felsic igneous rocks are often enriched in U, Th, and Pb (Kisvarsanyi, 1977; Doe et al., 1983), though granites within the St. Francois Mountains themselves generally have a low Pb concentration, perhaps because metals were ejected during the early explosive phase of volcanism or later leached from them (Kisvarsanyi, 1981; Sawkins, 1989). The source of the metals in the Pb-Zn deposits of the region is still a subject of debate, but fluids apparently moved Pb and associated minerals from the basement rocks and basement-derived(?) sedimentary rocks (Lamotte Sandstone) into the ore bodies within the overlying strata (Doe and Delevaux, 1972; Kisvarsanyi, 1977; Doe et al., 1983; Sawkins, 1989). The high U and Th concentrations in the volcanic rocks may have aided this concentration process by helping to generate effective hydrothermal systems (Feyn et al., 1978). Regardless of the exact mechanism of ore concentration, the association of major ore bodies with the felsic igneous rocks is striking (e.g., Heyl et al., 1974; Sawkins, 1989). Though the depth of burial is an intimidating barrier to exploration and exploitation of any such deposits, the Precambrian sequences and any associated ore bodies may subcrop at shallower levels in some regions.

Relationship of the Layering to Later Deformation

One of the intriguing aspects of the layering is its correspondence with the Illinois and Hardeman basins. The layering may be related to the Phanerozoic basins in some fundamental manner, with the development of the Phanerozoic basins substantially influenced by structures and lithologies within the underlying Precambrian rocks. The layered rocks may therefore provide important clues to understanding the formation of these Phanerozoic intracratonic basins.

The strong reflectors within the layering can be traced for very large distances and form excellent marker horizons for recording deformation. For example, the eastward dip of the prominent reflector on Indiana line 1 (Figure 5) may indicate crustal downwarp associated with the Grenville front to the east (Green et al., 1988; Pratt et al., 1989; Culotta et al., 1990), perhaps beneath a foreland basin to the Grenville orogen. On a smaller scale, the prominent reflector on Illinois line 1 is broken into distinct segments whose edges sometimes correspond to the near-vertical faults visible in the overlying strata. Often, but not always, these faults appear to break the prominent reflector with displacements opposite to those in the overlying strata. The prominent reflector may therefore be a slightly undulating surface broken by near-vertical faults with strike-slip motion producing an apparently opposite displacement than that in the Phanerozoic strata. Alternatively, the faults visible in the Phanerozoic section could be reactivations of earlier faults, as suggested by Sexton et al. (1986), commonly with an opposite sense of motion. In either case, analyses of basement faulting in the mid-continent could potentially prove useful in studying its deformational history and contemporary earthquakes.

As these examples show, the Precambrian strata could contain significant clues about the structural evolution of the overlying Phanerozoic intracratonic basins, the deformation of the lithosphere, and modern seismicity in the mid-continent. Extracting this information hinges on obtaining a far more detailed picture of the strata, and ultimately understanding the cause of the layering. This eventually will require drilling the layered sequences to determine their composition. Mapping the extent and structure of these layered sequences is obviously a three-dimensional problem, but such mapping, even at a reconnaissance level, has great potential for expanding our understanding of the tectonic history of a major portion of the U.S. mid-continent heretofore largely concealed from view.

SUMMARY

Seismic reflection data show that extensive sequences of layered rocks compose the upper Precambrian basement south of the Wichita Mountains and in the Illinois basin region. These layered sequences are as much as 12 km thick. Seismic data and correlation with relatively smooth, low-valued magnetic anomalies suggest that about 50,000 km^2 of southernmost Oklahoma and northern Texas, 200,000 km^2 of Illinois, Indiana, and Ohio, and about 32,000 km^2 of southern Missouri and northern Arkansas are underlain by these sequences. The internal features of the layered rocks include apparent half graben and sequence boundaries that suggest large depositional basins.

The preponderance of 1.3–1.5 Ga granites and rhyolites found in nearby drill holes imply a middle Proterozoic age for the sequences. They may be composed largely of felsic igneous rocks, but a substantial portion could consist of nonvolcanic sedimentary strata lying beneath, or interbedded with, the felsic igneous rocks. Minor amounts of mafic material within the sequence could cause the extreme reflectivity of some layers. The possibility that Precambrian hydrocarbons lie within the layered assemblage is unlikely given the widespread igneous rocks in the region, but their occurrence has not been tested and cannot be precluded.

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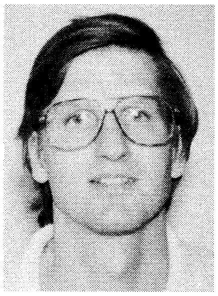

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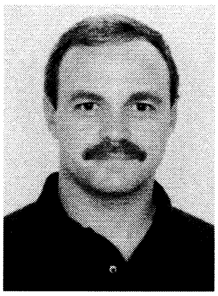

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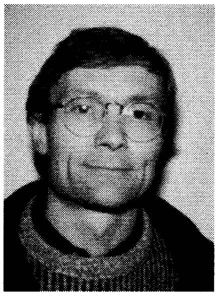

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