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Major Proterozoic basement features of the eastern midcontinent of North America revealed by recent COCORP profiling

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ABSTRACT

COCORP profiling in the eastern midcontinent of North America has (1) traced an extensive sequence of Precambrian layered rocks beneath southern Illinois, Indiana, and western Ohio; (2) detected a broad zone of east-dipping basement reflectors associated with the Grenville front beneath western Ohio; and (3) discovered a wide region of *west*-dipping reflectors penetrating most of the crust beneath eastern Ohio.

The Precambrian layered assemblage may be as much as 11 km thick beneath southern Illinois, extends at least 170 km in an east-west direction, and contains several strong reflectors that have a lateral continuity of 80 km or more. Industry seismic data indicate that the layering is extensive in a north-south direction as well. Possible explanations for the layering include the silicic igneous rocks of the ca. 1.48 Ga eastern granite-rhyolite province, which are penetrated by basement drill holes throughout the region, perhaps intermixed or underlain by mafic igneous or sedimentary rocks.

The 40–50-km-wide zone of strong, east-dipping (25°–30°) reflectors beneath west-central Ohio corresponds to the position of the Grenville front as determined from potential field and drill-hole data. These dipping reflectors in the upper and middle crust are interpreted to result from ductile deformation zones (mylonites) like those exposed at the Grenville front in Canada and imaged on the GLIMPCE seismic reflection lines in Lake Huron. Both the COCORP and GLIMPCE lines show a remarkably similar reflection geometry, despite the more than 500 km separating the two profiles.

Easternmost Ohio appears to be underlain by pronounced west-dipping (<40°) reflectors in the middle and lower crust, which are also interpreted as marking a region of pervasive ductile deformation 80 km or more in width. Analogy with similar reflection packages elsewhere suggests that these reflections may mark a major collision zone. The west-dipping reflectors may be correlative with similar reflectors imaged on another COCORP survey in northern Alabama. The correlations suggested by these new results, though tentative, imply that the eastern midcontinent is composed of a relatively simple assemblage of crustal blocks.

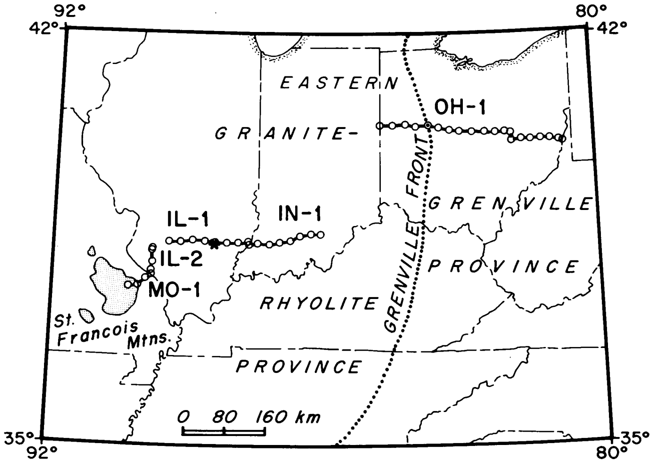

Figure 1. Map of eastern midcontinent region showing general basement provinces and COCORP lines. Every 250th station along line, as well as first and last station, is circled. Grenville front (wide line; Bickford et al., 1986), approximate outline of St. Francois Mountains (shaded above sea level basement contour), and Cisne Community #1 deep drill hole (asterisk) are also shown.

INTRODUCTION

A COCORP transect consisting of 720 km of profiles extending from the St. Francois Mountains of Missouri to eastern Ohio (Figs. 1 and 2[1]) has provided images of major features of the Proterozoic basement rocks of the eastern midcontinent. This survey represents COCORP's (Consortium for Continental Reflection Profiling) most substantive foray into the central U.S. craton, where structures in the Proterozoic crust are masked beneath relatively undeformed Phanerozoic platform sedimentary rocks. The COCORP data were acquired over two widespread basement terranes defined by samples obtained in drill holes: the eastern granite-rhyolite terrane (Bickford et al., 1986; Denison et al., 1984) and the Grenville province (Moore et al., 1986). In the United States, the location of the Grenville front, which separates these basement terranes, has been deduced on the basis of drill-hole and aeromagnetic data (Denison et al., 1984; Lucius and von Frese, 1988; Keller et al., 1982). The front separates relatively large amplitude, high-frequency magnetic anomalies characterizing the high-grade rocks of the Grenville province from the broader, lower amplitude anomalies associated with the igneous rocks to the west (Lucius and von Frese, 1988).

The COCORP reflection data were acquired in the second half of 1987 by using five vibrators as a source and a 120-channel geophone array with 100 m spacing. The nominal source effort was greater than that of earlier COCORP surveys (more and larger vibrators, more sweeps per vibrator point [VP]), although skipped vibrator points and low drive levels were required in some areas because of road conditions and buildings. A 12–52 Hz or 10–48 Hz, 28 s sweep was used. Standard CDP processing (Yilmaz, 1987) was done at Cornell by using the COCORP MEGASEIS computer system and the Cornell National Supercomputer Facility.

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[1] Figure 2 is a loose insert accompanying this issue.

RESULTS

Proterozoic Layered Rocks

The most striking feature on the new profiles is the presence of an extensive sequence of subhorizontal reflectors beneath the Phanerozoic sedimentary rocks of Illinois, Indiana, and western Ohio (e.g., between VP 500 on line IL-1 and VP 1200 on line OH-1 in Fig. 2). These strata have been imaged on smaller surveys (e.g., Sexton et al., 1986) and on unpublished industry data, but their broad lateral extent is only now being recognized.

The reflection from the top of Precambrian basement was identified at 1.4 s traveltime near VP 980 on line IL-1 by means of a synthetic seismogram generated from the acoustic log from a deep drill hole (Union Oil Company Cisne Community #1) that is within a mile of the reflection line (Figs. 1 and 3). Layering is clearly visible beneath the Phanerozoic sedimentary rocks to traveltimes of 4.0 to 5.0 s in some locations, indicating that layered basement rocks are as much as 11 km thick locally. Differences in dip between the basement reflectors and the overlying Phanerozoic section, as well as a lack of repetition on autocorrelograms, rule out multiples as an explanation for most of the deeper reflections.

The layering has the overall appearance of a supracrustal assemblage. In the upper parts of the assemblage, several discrete sets of subparallel reflections suggest distinct, slightly east-dipping (0°–10°) stratigraphic or structural packages (e.g., at 1.8 s beneath and slightly west of VP 900 in Fig. 3). Several strong reflections within the layering (e.g., the event at 2.5 to 2.8 s in Fig. 3) can be clearly traced laterally for up to 80 km, but many of the surrounding reflectors are short (<10 km). The strong reflectors also show evidence of disruption and possibly some large offsets, depending upon how the reflections are correlated on the seismic section. Dipping or fan-shaped reflection sequences at several locations in the lower part of the assemblage have the appearance of half-grabens (e.g., at 3–5 s below VP 500 on Line IL-1), perhaps indicating crustal extension during the early formation of the layered sequence.

Layered reflectors occur below the Phanerozoic sedimentary rocks across all of lines IL-1 and IN-1 and are very pronounced between VP 500 on line IL-1 and VP 900 on line IN-1, a distance of more than 170 km. Traffic and other noise degrade the data near the city of French Lick, Indiana (between VP 900 and 1300 on line IN-1), but east of VP 1200 on line IN-1, dipping reflectors and a ramplike feature indicate deformation within the layering, perhaps indicative of a fundamental lateral change.

The COCORP transect crosses the hypothesized northern arm of the late Precambrian–early Paleozoic Reelfoot rift (Braile et al., 1982; Sexton et al., 1986) between approximately VP 1550 on IL-1 and VP 1200 on IN-1. A distinct graben system is not obvious on the COCORP data at this location, implying that the rift is either very thin or absent in this area; however, the COCORP line lies north of the Sexton et al. (1986) seismic lines on which the rift was interpreted and the Wabash valley fault zone, which they relate to reactivation of Precambrian faulting. Another possibility is that the layering imaged by Sexton et al. (1986) and interpreted as part of the graben fill may actually be part of the stratified assemblage described here, which extends far beyond the hypothesized boundaries of the late Precambrian rift and is, as discussed subsequently, likely to be an older feature of the region.

East of VP 1200 on line IN-1, layering is seen in the shallow basement rocks, and there is a distinct set of strong reflectors at midcrustal depths (3–7 s). On line OH-1, the shallow (<1.7 s) layered reflectors between VP 200 and VP 900 are probably due to a small extension of the Keweenawan rift system previously interpreted from drill-hole data (e.g., Denison et al., 1984; Hinze et al., 1975) (Fig. 2). Midcrustal reflectors show a complex geometry with dipping, subhorizontal and diffracted events and are clearly truncated on line OH-1 below VP 1300 by a set of east-dipping reflections corresponding to the Grenville front. Although a large data gap makes the correlation tentative, strong midcrustal (4–6 s) reflections on the western part of line OH-1 may correspond to similar appearing events at comparable traveltimes on the eastern end of line IN-1.

Most likely, the layered rocks observed on the COCORP data are Middle Proterozoic or older because the uppermost basement rocks recovered in drill holes throughout the eastern and southern midcontinent are predominantly granites and rhyolites whose U-Pb ages consistently fall in the 1340–1510 Ma range (Bickford et al., 1986; Denison et al., 1984; Hoppe et al., 1983). Layered rocks in the upper basement have also been observed on earlier COCORP data from

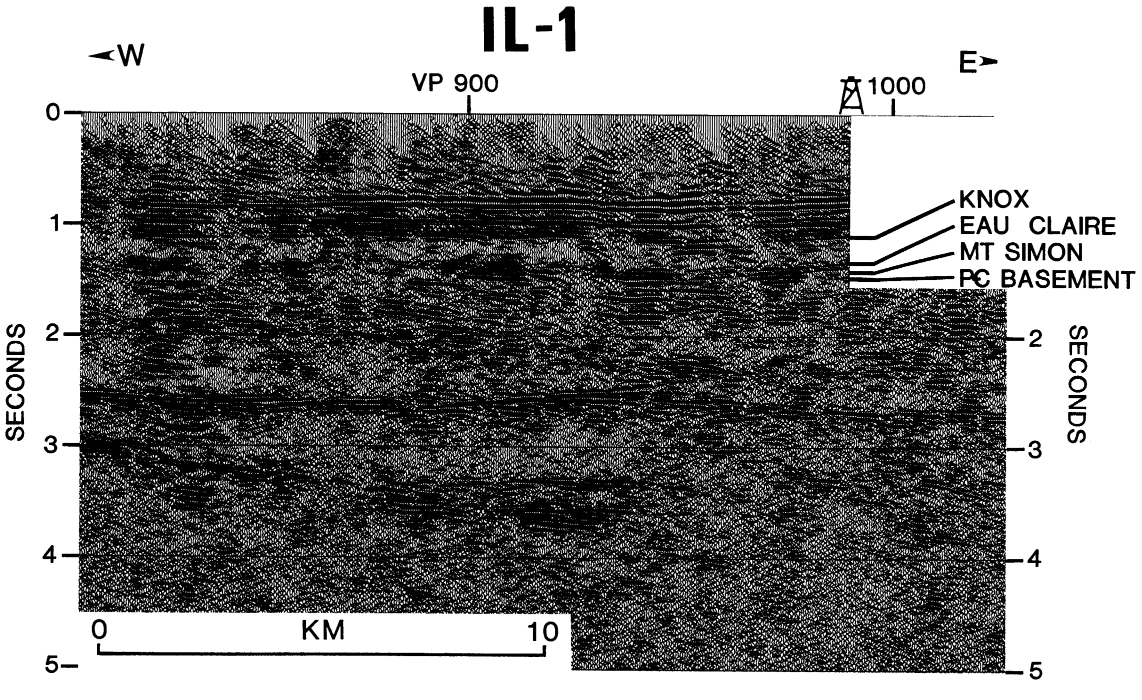

Figure 3. COCORP image (unmigrated) of part of Proterozoic layered rocks beneath Illinois with drill-hole correlations in Phanerozoic sedimentary rocks. Drill hole (derrick symbol) is Union Oil Company Cisne Community #1 in Wayne County, Illinois. Data are coherency filtered and plotted with no vertical exaggeration at velocity of 6 km/s.

Oklahoma and Texas (Oliver et al., 1976; Brewer et al., 1981), suggesting that large parts of the southern midcontinent granite-rhyolite terrane, and perhaps other parts of the midcontinent basement, are composed of stratified rocks.

As to the composition of these stratified rocks, one possibility is that they are entirely composed of ash-flow tuffs, rhyolite flows, and granites correlative with those seen in the St. Francois Mountains (Kisvarsanyi, 1981; Sides et al., 1981) and in drill holes throughout the region (Denison et al., 1984; Bickford et al., 1986). To test this hypothesis, we attempted to trace basement structure to outcrop in the St. Francois Mountains (Fig. 1); however, lines IL-2 and MO-1 indicate a relatively transparent crust, layering occurring only at the western edge of line MO-1 (0.5–4.0 s). Subhorizontal reflectors in the Precambrian basement are present on the northern third of line IL-2, but these apparently underlie north-dipping reflectors and terminate below VP 300 (Fig. 2). This evidence and the changes in character of the layering in east-central Indiana and western Ohio indicate that the layering is regionally variable and not ubiquitous throughout the granite-rhyolite provinces. Perhaps the layering is better developed away from the Proterozoic caldera complexes (e.g., the St. Francois Mountains).

The granites and rhyolites recovered in drill holes may be underlain or intermixed with other types of stratified rocks. Given the subhorizontal aspect of the layering, a relatively thin veneer of felsic rocks could conceal underlying rocks of different composition. Furthermore, if felsic igneous rocks are the only materials involved, the volume of the layering would imply melting of a huge amount of crust during Middle Proterozoic anatexis (Van Schmus et al., 1987; Emslie, 1978; Anderson, 1983). Because mafic volcanism is often cited as the source of heat for the formation of granites and rhyolites by anatexis (Emslie, 1978; Anderson, 1983), an obvious suggestion is that mafic rocks form part of the layered reflectors seen in the COCORP data.

Another possibility is that a large proportion of the layered reflectors are sedimentary rocks which provide the acoustic impedance contrasts to generate strong reflections. If so, petroleum production from Proterozoic rocks in Siberia (Meyerhoff, 1980) and hydrocarbon shows in Proterozoic rocks elsewhere (Jackson et al., 1988; Murray et al., 1980; Fritz, 1987) make the layered rocks a potential hydrocarbon exploration target.

The midcrustal (4–6 s) reflectors on the western part of line OH-1 are more problematical. They may be lithologic boundaries, perhaps correlative with the deeper part of the layered sequence to the west, but the large data gap makes this correlation uncertain. Another interpretation, suggested in Figure 2, is that the midcrustal reflections are deformation zones, perhaps formed during the Grenville event.

Grenville Front

Between VP 1000 and VP 1400 on line OH-1, a broad (40–50 km) zone of parallel reflectors dips eastward from the base of the Phanerozoic sedimentary rocks to midcrustal depths (Figs. 2 and 4). These reflections mark the Grenville front tectonic zone (GFTZ), whose position is also indicated by the drill-hole and potential field data (Lucius and von Frese, 1988; Bass, 1960). The reflectors have a consistent dip of about 28° (migrated) and no evident change in attitude across the zone. East of the GFTZ, the crust contains several scattered reflectors and diffractors that distinguish it from the crust to the west.

The GFTZ is mapped at the surface in Canada as a band of northwest-directed thrust structures whose western edge, the Grenville front, marks the western limit of major Grenville (1200–950 Ma) deformation (Wynne-Edwards, 1972; Moore et al., 1986; Rivers and Chown, 1986). The COCORP profile of the GFTZ has a reflector geometry that is remarkably similar to that on the GLIMPCE (Great Lakes International Multidisciplinary Program on Crustal Evolution) data for Lake Huron (Green et al., 1988), which also imaged a broad zone of east-dipping reflectors. Like the GLIMPCE reflectors, the COCORP reflectors likely originate from mylonites and/or transposed lithologic layering that characterizes the GFTZ (Davidson, 1986). On both the COCORP and GLIMPCE data sets, a subhorizontal midcrustal (4–7 s) reflector package lies to the west of, and is apparently truncated at, the Grenville front. If the same features are being imaged on both profiles, the dipping and midcrustal reflectors have a north-south extent in excess of 500 km.

Grenville Province

Although the Grenville front reflectors were expected because of the GLIMPCE experiment,

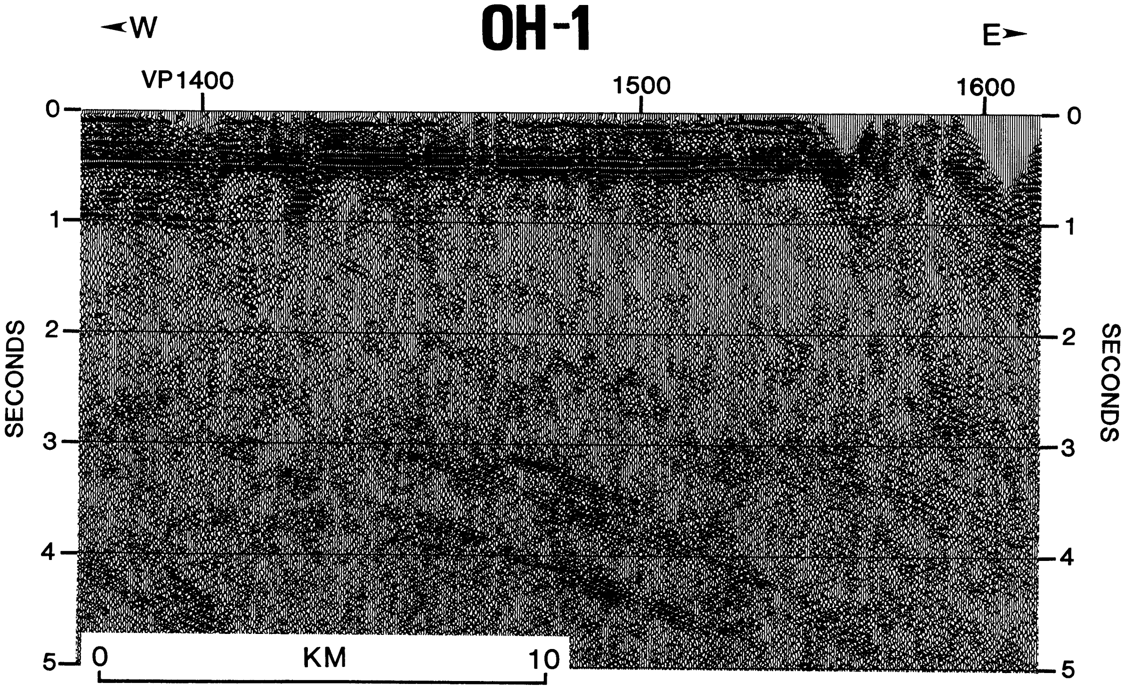

Figure 4. COCORP image (unmigrated) of east-dipping reflectors associated with Grenville front. Horizontal reflections in uppermost 0.5 s of figure are from Phanerozoic sedimentary rocks. Data are coherency filtered and plotted with no vertical exaggeration at velocity of 6 km/s.

the COCORP survey also found what appears to be an even more pronounced crustal feature to the east. Beneath eastern Ohio, *west*-dipping reflectors extend from midcrustal to deep crustal levels at angles of up to 40° (migrated) (Fig. 5). Short, subhorizontal reflections are also widespread on line OH-2, and some reflections of opposing dip are seen, particularly after coherency filtering, but the west-dipping reflections are much stronger and more pervasive. These dipping reflections persist across the easternmost 80 km of the transect despite traffic and other noise in the Ohio River area. To date, analysis of stacking velocities and geometric considerations (comparison of reflector dips or amplitudes and variations in line direction) indicate that these west-dipping reflections, like the east-dipping reflections associated with the Grenville front, are primary reflections and not artifacts of the seismic method.

Zones of deeply penetrating dipping reflectors have been seen on other deep seismic reflection lines within the interiors of Phanerozoic orogenic belts (e.g., Nelson et al., 1985; Ando et al., 1984) and have generally been interpreted as crustal-scale thrust ramps or suture zones. As with the Grenville front reflectors, these west-dipping events likely result from ductile deformation zones and associated lithologic contrasts, in this case perhaps marking a major collision zone.

Northwest-directed thrust nappes seem ubiquitous in the exposed Grenville province of Canada and northern New York (Moore, 1986; Mawer, 1987; McLelland and Isachsen, 1986) and are seen in shallow seismic reflection data over the buried Grenville province of the United States (Beardsley and Cable, 1983). These low-angle, *east*-dipping structures seem incompatible with the west-dipping reflectors seen on the COCORP data from eastern Ohio. Careful inspection, however, reveals that the west-dipping reflectors seen on the COCORP data may not subcrop beneath the Phanerozoic sedimentary rocks, suggesting that they are overlain and truncated by later (Grenville?) northwest-directed thrusts at shallow levels, as schematically suggested in Figure 2. Some shallow, albeit weak, east-dipping reflectors on the COCORP data may be a manifestation of such a thrust system.

The opposing sets of dipping reflectors imaged in Ohio may be a Proterozoic collision zone (west-dipping reflections) and an antithetic intracratonic thrust zone (Grenville front). In this model, the west-dipping reflectors beneath eastern Ohio represent a crustal fabric developed in response to subduction or subsequent closure during the Grenville event. The Grenville front would mark the western limit of extensive deformation and uplift associated with the collision. It is also possible, however, that the west-dipping reflectors represent an older, pre-Grenville feature preserved within the middle and lower crust and that the Grenville collision actually took place farther to the east. Further profiling may resolve this issue.

A set of west-dipping reflectors was imaged in northern Alabama on another recent COCORP transect. If this zone correlates with the dipping reflectors in eastern Ohio, they would compose one feature that is continuous for more than 600 km (Culotta et al., 1988). If so, delineation of crustal boundaries such as the Grenville front and the zones of dipping reflectors by these seismic reflection profiles may be providing the first look at a relatively simple structural framework for the Grenville province, in which a relatively few large crustal blocks are separated by major deformation zones. Mapping the pattern of crustal elements such as these may be the key to understanding the enigmatic Grenville province, as well as other poorly understood regions of the continents.

SUMMARY

Extensive Proterozoic layering and two major crustal boundaries were delineated by a recent east-west seismic reflection traverse across the eastern midcontinent of North America. The layering underlies the Phanerozoic sedimentary rocks of southern Illinois, Indiana, and western Ohio and reaches thicknesses of 11 km or more. Prominent layering extends laterally for at least 170 km on the COCORP profiles, and several strong reflectors within the layering can be traced for up to 80 km. The stratified sequence probably includes felsic igneous rocks of the ca. 1.48 Ga granite-rhyolite terrane sampled in basement drill holes in the area, but such rocks may be underlain or intermixed with significant quantities of mafic igneous or sedimentary rock.

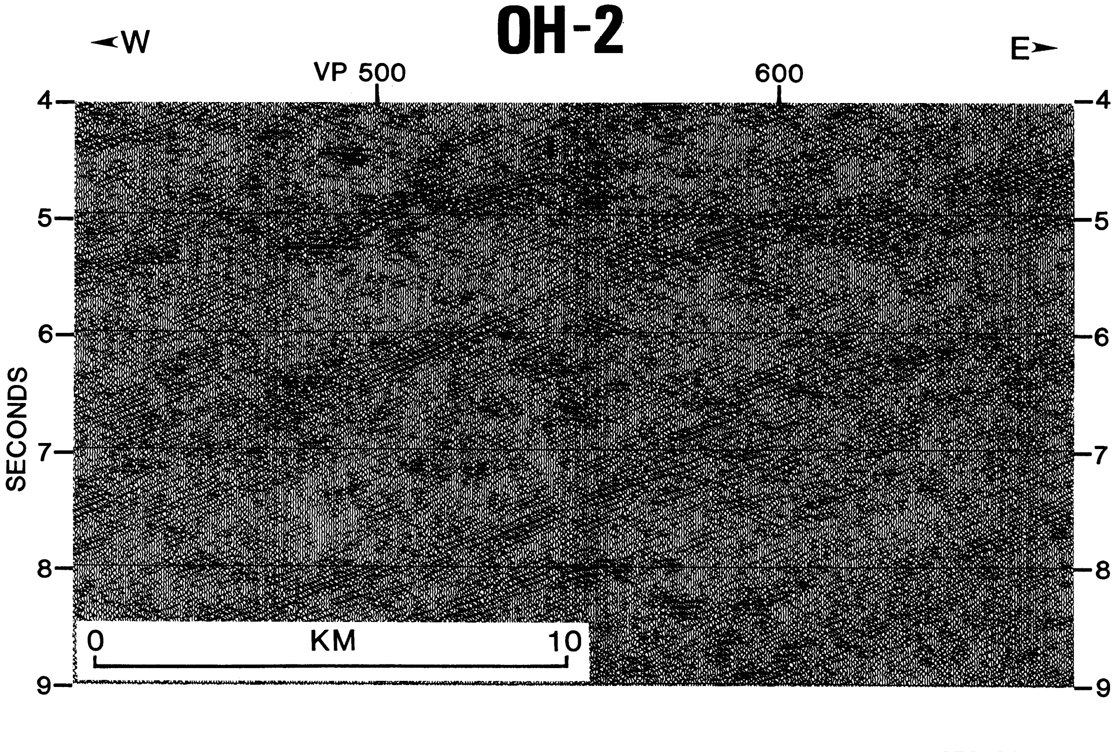

Figure 5. COCORP image (unmigrated) of west-dipping reflectors on line OH-2. Data are coherency filtered and plotted with no vertical exaggeration at velocity of 6 km/s.

A 40-50-km-wide zone of reflectors dips eastward beneath west-central Ohio at angles of 25° to 30° at the western edge of the buried Grenville province, as defined by drill-hole and potential field data. These reflectors are interpreted as resulting from ductile deformation zones associated with the Grenville front.

Eastern Ohio is underlain by a broad (>80 km) zone of west-dipping (<40°) reflectors extending through the middle and lower crust. These reflectors likely mark a major boundary (suture?) within the Grenville province. Correlation with other seismic reflection data suggests that each of these dipping crustal features is continuous for more than 500 km and that they outline a large crustal block within the Grenville province.

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Figure 2, p. 1 of 2

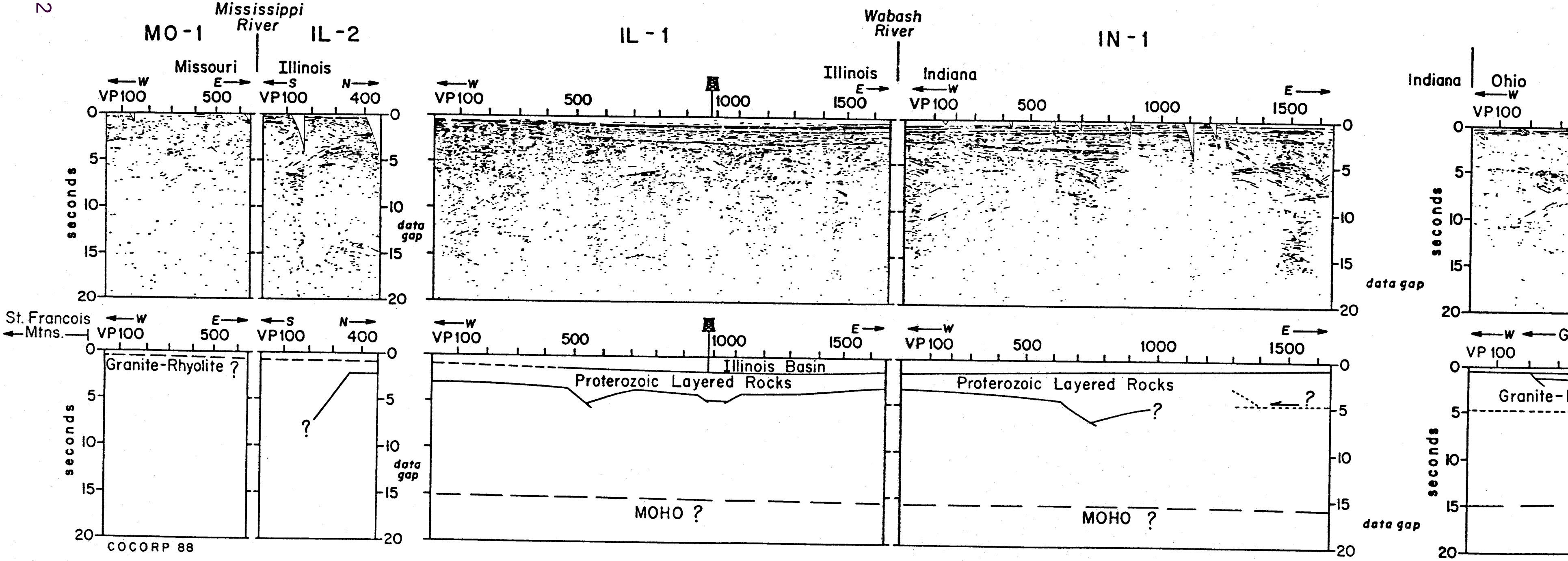

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Figure 2
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Figure 2. Top: Line drawing of COCORP seismic reflection data. Bottom: Possible interpretation of data as explained in text. GFTZ = Grenville front tec

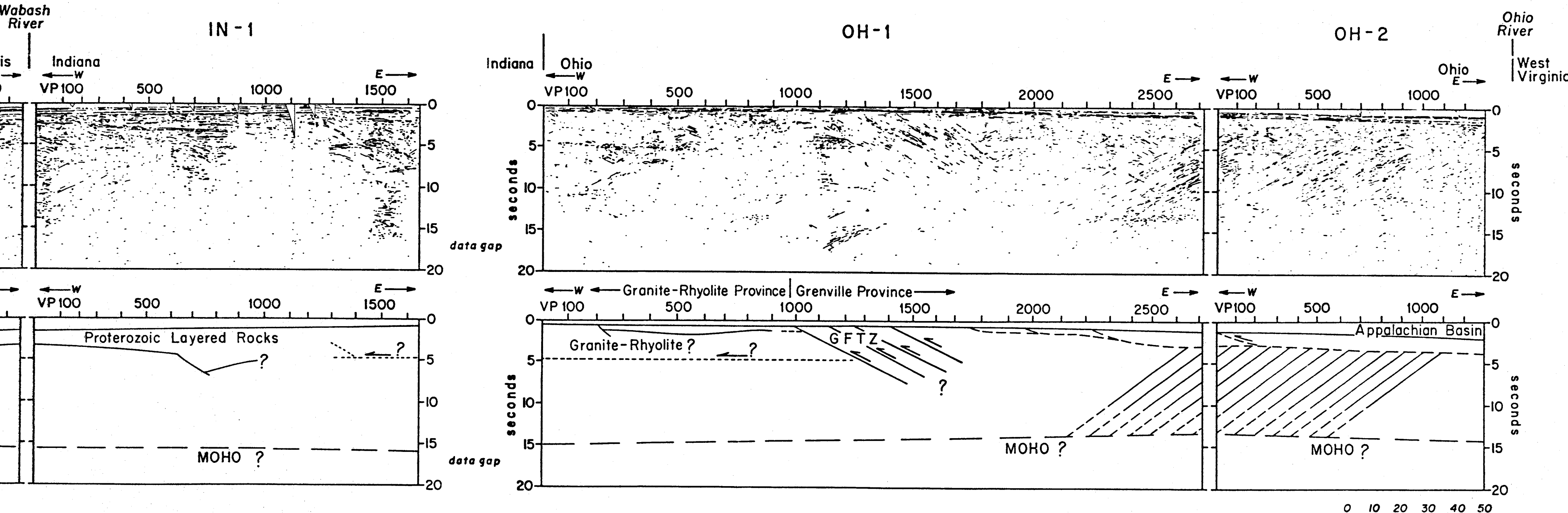

Figure 2. Top: Line drawing of COCORP seismic reflection data. Bottom: Possible interpretation of data as explained in text. GFTZ = Grenville front tectonic zone.

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