Seismic-reflection study of the Precambrian crust of central Minnesota

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ABSTRACT

A COCORP (Consortium for Continental Reflection Profiling) seismic-reflection survey across the boundary zone between the late Archean Superior Province granite-greenstone terrane and older Archean gneiss and granulite terrane of the Minnesota River Valley shows numerous north-to-northwest–dipping reflection events throughout the crust. A particularly prominent and continuous series of such events projects to the surface near the trace of a fault zone that had been previously identified as the boundary between these two terranes, within the Great Lakes tectonic zone. The moderate dips of these events (about 30°), their correlation with presumed faults near the surface, their continuity over tens of kilometres, and the persistence of these and other reflection zones throughout the crust suggest that these events correspond to fault zones, probably thrusts. They may have originated during late Archean collision between the Superior Province crust and older continental crust to the south.

Reflections are sparser and more concordant in the gneiss and granulite terrane than in the Superior Province. There are several prominent reflection groups with gentle northerly dips in the middle and upper crust of the granulite and gneiss terrane. Their distribution appears to correlate with the sources of aeromagnetic and gravity anomalies that are part of a belt that extends west to central South Dakota and that apparently reveal the position of the postulated Archean suture. The axes of deposition and deformation of Proterozoic metasedimentary rocks are approximately parallel to and apparently coincide with the boundary between two Archean terranes farther east in Minnesota, Wisconsin, and Michigan, but Proterozoic (Penokean) deformation has not been distinguished either in the study area or in the seismic sections.

The Minnesota COCORP survey has demonstrated the capability of this seismic-reflection method to reveal important but previously unsuspected structures in complexly deformed Archean terranes. This has provided structural evidence that the separate subprovinces of the North American Archean crust might have been assembled by subduction-related collision.

INTRODUCTION

The COCORP seismic-reflection survey in Minnesota was undertaken to study the geometry of the boundary between two different Archean terranes: a northern granite-greenstone superbelt of the Superior Province, and an older Archean gneiss and granulite terrane exposed in the Minnesota River Valley. The survey provided evidence that this boundary dips north at a moderate angle and may persist throughout the crust. The boundary might have originated in a late Archean collision, with older continental crust underthrust northward beneath younger Superior Province crust. The presence of numerous other north-dipping reflection events in the survey area suggests that the collision may have produced imbricate underthrusts.

The geology of the Precambrian rocks of central North America is primarily a two-dimensional science. Flat, glaciated terrane rarely permits observation of the depth dimension. Potential field (gravity and magnetic), electrical-conductivity, and seismic-refraction surveys have provided some insight into the properties and geometries of the middle and lower crustal rocks, and a few seismic-reflection surveys using explosive sources have shown the positions of reflecting interfaces in the Yellowknife region (Clee and others, 1974) and the western Superior Province (Godlewski, 1977; Green and others, 1978, 1979; Green, 1981). Still, little information has been previously available about the three-dimensional geometry of the structural-province boundaries and about how the granite-greenstone and gneiss superbelts were assembled.

The Minnesota survey was the first use of the COCORP seismic-reflection methodology in the study of a classical Archean terrane that had complexly deformed crystalline rocks at the surface. The survey demonstrates that a substantial amount of information on the basement can be obtained by this method in spite of the complexity of deformation and the problems associated with glacial cover. The glacial cover also obscures the Precambrian geology so that correlation of the seismic data with surface features is more limited and less productive in this case than in some other COCORP surveys. Some reasonable and important interpretations can be made, however, and more may be anticipated as additional geological knowledge is accumulated.

The geology of central Minnesota is complex, involving several distinct orogenic events in the Archean, as well as in the middle and late Proterozoic. Before discussing the COCORP survey in detail, it is useful to review the geology of these various terranes and of the boundary zone. The COCORP survey is especially informative about this boundary.

GEOLOGICAL AND GEOPHYSICAL SETTING

On account of the nearly continuous cover of glacial deposits, the geology of central Minnesota is known primarily by geophysically constrained interpolation from surrounding areas that have bedrock exposure. These areas include the granite-greenstone terrane of northern Minnesota and adjacent Ontario, the gneiss terrane south of the survey area in the Minnesota River Valley, and the Archean and Proterozoic regions of northern Wisconsin and Michigan (Fig. 1). There are also scattered exposures of granite, gneiss, and Proterozoic metasedimentary rocks along the rivers and in the iron mines of east-central Minnesota. The geological and

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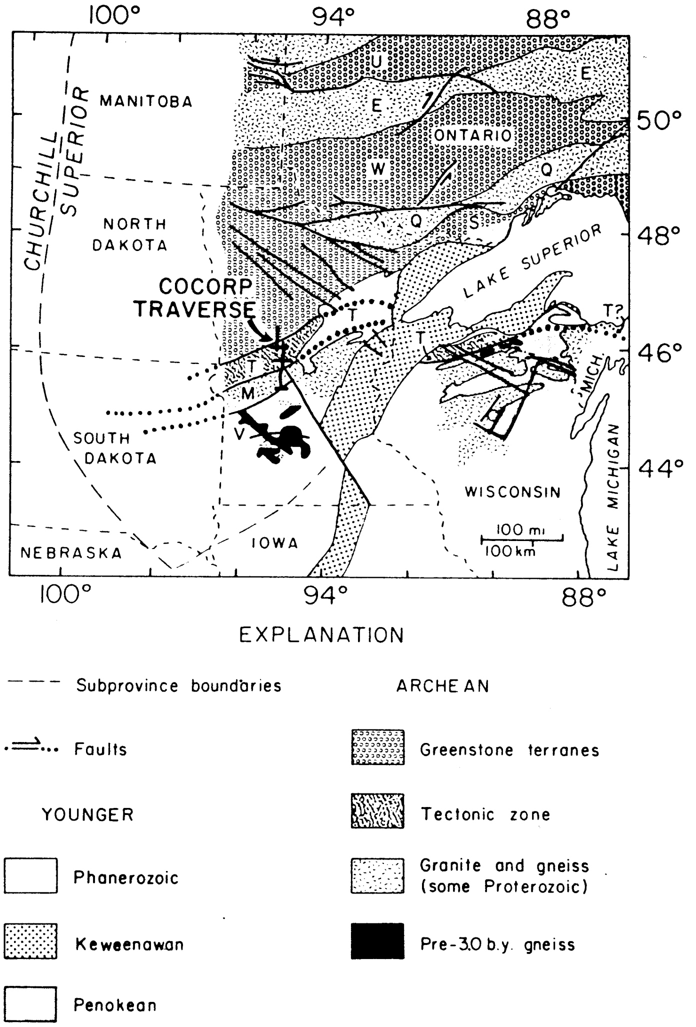

Figure 1. Geologic map of Minnesota and surrounding region, with location of the COCORP Minnesota traverse. Modified from Morey (1978a), Sims and others (1980), and Schwerdtner and others (1979). The extensions of the Churchill–Superior Province boundary and the Great Lakes tectonic zone (T) and of the N magnetic anomalous zone (M) are based on the aeromagnetic map (Zietz, 1981). Granite-greenstone subprovinces of the Superior Province: U, Uchi; W, Wabigoon; S, Shebandowan. Gneiss subprovinces: E, English River; Q, Quetico. Older Archean gneisses of the Minnesota River Valley: V, Keweenawan sandstones covering the older Precambrian basement west of the area shown in southern Minnesota (see Craddock, 1972).

geophysical characteristics of these surrounding areas are summarized in Tables 1 and 2, respectively.

Superior Province Greenstone-Granite Superbelts

Northern Minnesota is underlain by the extensions of the Abitibi-Wawa-Shebandowan greenstone-granite superbelt, the Vermilion Granitic Complex (an extension of the Quetico gneiss superbelt), and the Wabigoon greenstone-granite superbelt. Gravity lows and broad-wavelength aeromagnetic highs are characteristic of the elongate granitoid batholiths,

TABLE 1. PRECAMBRIAN GEOLOGIC HISTORY IN THE NORTH-CENTRAL UNITED STATES AND ADJACENT CANADA

Age, b.y.	Superior Province	Minnesota River Valley	Penokean terrane, Minn.-Wisc.-Mich.
1.1	Keweenawan rifting, sedimentation, mafic volcanism and intrusion		
1.2		Metamorphism of platform quartzites	
1.45-1.5			Anorogenic granite intrusion
1.6-1.7	Diabase dikes	Deposition of platform quartzites	Resetting of Rb-Sr ages by metamorphism
1.8-1.9	"Weak deformation"	Intrusion of mafic dikes, epizonal granites, and porphyries	Volcanism and deformation of sediments
1.9-2.1	Shelf sediments deposited		Sediments deposited
2.1-2.2	Diabase and gabbro	Mafic dikes	Mafic dikes
2.4		Shearing	
2.6-2.7	Faulting, cataclasis, and metamorphism	Mesozonal granitoid intrusion, deformation, metamorphism	
2.6-2.9	Volcanism, sedimentation, and granitoid intrusion		
3.0-3.1	English River Gneiss age, Ontario	High-grade metamorphism and granite emplacement	
3.5		Minimum age of gneiss precursors	

Note: data in this table are modified from Sims (1976), Morey (1978a), LaBerge and Mudrey (1979), and Van Schmus (1980).

TABLE 2. GEOPHYSICAL CHARACTERISTICS OF PRECAMBRIAN CRUST IN THE CANADIAN SHIELD

SEISMIC VELOCITIES AND DEPTHS TO DISCONTINUITIES:

Key: P1, P2, P3 — upper and lower crustal and upper mantle P-wave velocities. R, M — Riel and Mohorovicic discontinuity depth determinations.

Superior Province, general	R	20-25 km	Godlewski and West, 1977
	M	40 ± 3 km	
English River subprovince	P1	6.4 km/sec	Young and West, 1977
English River subprovince-Uchi belt transition zone	P1	6.05 km/sec	
	P2	6.85	
	P3	7.92	Hall and Hajnal, 1973
	R	14-22 km	
	M	32-38	
Wabigoon granite-greenstone subprovince	P1	6.1-6.3 km/sec	
	P2	6.5-7.0	Wright, 1977
	R	18-19 km	
	M	40-44	
Wabigoon subprovince: metavolcanic belts	P1	6.19 km/sec	Green and others, 1979
	P2	6.9	
	P3	7.15	
Wabigoon subprovince: Aulneau batholith	P1	6.07	
	P2	6.9	Green and others, 1978
	P3	7.15	
Quetico-Shebandowan subprovinces	P1+P2	6.0-7.5	Wright, 1977
DENSITY DETERMINATIONS			
Wabigoon subprovince:	metavolcanic rocks modes:	2.75-2.8 and 3.0-3.1 g/cm^3	
	felsic intrusives	2.6-2.65	Szewczyk and West, 1976
	gneisses	2.65-2.7	
Wabigoon subprovince:	metasediments and felsic metavolcanic rocks	2.75 ± 0.07	Dusanowskyj, 1977
	mafic metavolcanic rocks	2.95 ± 0.10	
	granitic rocks	2.95 ± 0.02	
	Mean density	2.70	

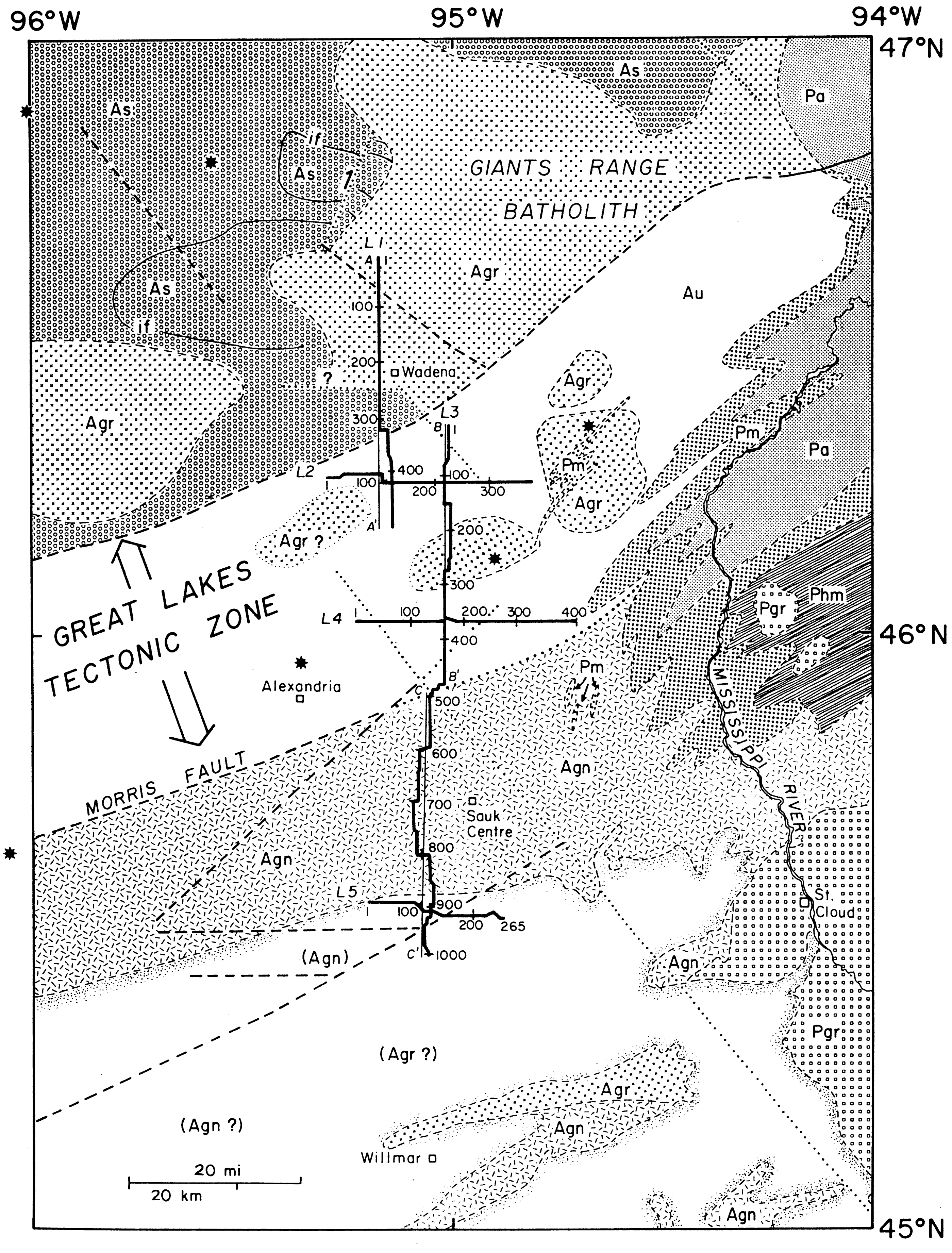
96°W
95°W
94°W
47°N
46°N
45°N
As
As
As
As
Pa
if
if
GIANTS RANGE
BATHOLITH
L1
A
1
Agr
Au
100
200
Wadena
?
Agr
Agr
300
L3
B
1
Pm
Pa
Pm
L2
1
100
400
100
200
300
Agr
A'
Agr ?
200
300
GREAT LAKES
TECTONIC ZONE
L4
1
100
200
300
400
400
Pgr
Phm
Alexandria
C
B'
Pm
500
MISSISSIPPI
RIVER
MORRIS FAULT
600
Agn
700
Sauk
Centre
Agn
800
L5
1
100
900
200
265
St.
Cloud
C'
1000
(Agn)
Agn
(Agr ?)
Pgr
Agr
(Agn ?)
Agn
Willmar
20 mi
20 km
Agn

Figure 2. Geologic map of the Minnesota COCORP survey area. The eastern half was modified on the basis of aeromagnetic and gravity interpretation from Morey and others (1981), and the western half was modified from an unpublished Minnesota Geological Survey map (D. L. Southwick and V. W. Chandler, 1982, personal commun.). Positions of faults are also based on geophysical interpretation and may not coincide exactly with surface geology. Earthquake epicenter locations are based on Mooney and Morey (1981).

Figure 2

EXPLANATION

- - - - Contact

- - - - Fault

300 ⌐ Seismic survey line, with vibrator points

✱ Earthquake

▭ Cretaceous

PROTEROZOIC (PENOKEAN):

Pgr granitoid rocks

Pa Animikie Group

Pm Mille Lacs Group

Phm Hillman migmatite (age uncertain)

ARCHEAN :

Au undifferentiated rocks in tectonic zone

if As supracrustal rocks, Superior Province, with iron formation (if)

Agr granitoid rocks

Agn gneiss

and by these criteria the Giants Range batholith is thought to extend to the northern end of the COCORP survey area (Figs. 2 and 3). This batholith is a complex of tonalite, granodiorite, and granite, 2,700 to 2,750 Ma old (Sims and Viswanathan, 1972). Other granitoid rocks of the Superior Province have ages in the range 2,400 to 2,750 Ma, with low initial $^{87}Sr/^{86}Sr$ ratios indicative of derivation from material with a short previous crustal history (Goodwin and others, 1972; Goodwin, 1981; Sims and Peterman, 1981a; Hanson and others, 1971; Hanson and Goldich, 1972; Jahn and Murthy, 1975).

The metavolcanic and metasedimentary greenstone belts typically have gravity highs and long-wavelength aeromagnetic lows, with high magnetic relief locally associated with iron formations and metabasalts. By these criteria, a small patch of greenstone has been mapped in the northern part of the traverse. The steep gradients and short wavelength of the associated gravity high demonstrate the near-surface position of the dense metavolcanic rocks of the greenstone belt. The metavolcanic rocks of the Superior Province greenstone belts of northern Minnesota and Ontario have radiometric ages ranging from 2,700 to 2,950 Ma (Krogh and Davis, 1972; Peterman, 1979; and Nunes and Thurston, 1980).

Gneiss Superbelts of the Superior Province

The English River subprovince of Ontario is an example of a Superior Province gneiss superbelt, recently examined by the Superior Geotraverse Project (Goodwin and others, 1972; Young and West, 1977; Goodwin, 1978; West, 1978; Schwerdter and West, 1979; Urquhart and West, 1979). This belt includes predominant paragneisses and granitoid intrusives with ages comparable to those of the adjacent greenstone-granite superbelts and several enclaves of granulite with ages in excess of 3,040 Ma, older than the metavolcanic rocks of the adjacent greenstone belts (Krogh and others, 1976; Harris and Goodwin, 1976). These high-grade metamorphic rocks have high aeromagnetic relief, an associated gravity high, and high upper-crustal seismic velocities (Urquhart, 1977).

All of the rock types of the Superior Province share general east-west and east-northeast–west-southwest strikes, associated with late Archean north-south compression following consolidation of the crust (Park, 1981). A conjugate set of northwest- and northeast-striking ductile shear zones is also common throughout the Superior Province, crosscutting the east-west folds. In many instances, the boundaries between the granite-greenstone and gneiss superbelts in both Ontario and Minnesota are the loci of prominent steeply dipping strike-slip faults that indicate northwest-southeast compression (Stone, 1977; Schwerdtner and others, 1979; Bau, 1977; Sims and Peterman, 1981a).

Minnesota River Valley Gneiss Terrane

The gneisses of the Minnesota River Valley are much older than the rocks of the Superior Province, with isotopic ages in excess of 3,500 Ma (Goldich and Hedge, 1974; Goldich and Wooden, 1980; Goldich and others, 1980). Later metamorphic and magmatic events include 3,000- to 3,150-Ma intrusion and upper amphibolite-to-granulite facies metamorphism with associated U-loss, and subsequent metamorphism and formation of mesozonal granites by anatexis of the older crust in the late

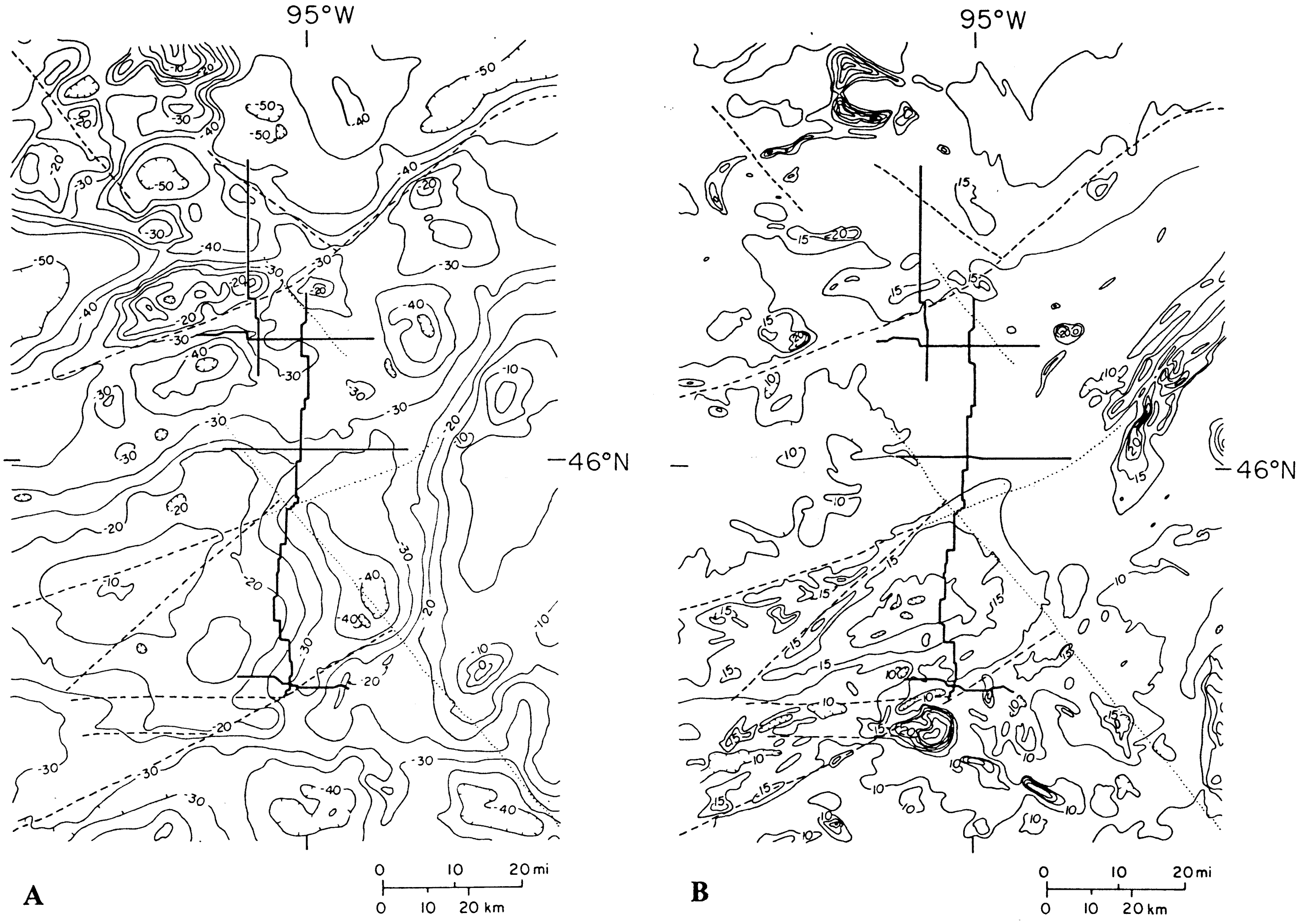

Figure 3. A. Bouguer gravity map of the COCORP survey area, from Ervin (1980) and McGinnis and others (1978). COCORP-line positions shown by solid lines. Thin dashed lines show inferred fault positions, as in Figure 2. Contour interval, 5 mgal. B. Aeromagnetic map of the COCORP survey area, from Bath and others (1965), Sims and Zietz (1967), and U.S. Geological Survey (1970). Inferred fault positions shown as in Figure 3A. Contour interval, 250 nT.

Archean, about 2,600 Ma (Doe and Delevaux, 1980). Bauer (1980) associated folding in the Minnesota River Valley gneisses and granites with both pre–3,050-Ma and late Archean events. Small, anorogenic, epizonal granites and mafic and intermediate dikes were intruded about 1,850 Ma ago (Hanson and Himmelberg, 1967; Morey, 1972a).

The Minnesota River Valley crosses an area of moderate aeromagnetic intensity and relief. An east-west–trending gravity high is present near the exposed early Archean Montevideo Gneiss. Farther southeast, the river crosses a broad gravity low, also over the ancient gneiss terrane.

Gneisses exposed in central Minnesota have a magnetic expression comparable to that over the gneisses in the Minnesota River Valley. They have been considered part of the older Archean gneiss terrane, although they have not yet yielded ages in excess of 2,700 Ma. These include the McGrath Gneiss east of Mille Lacs Lake and the Richmond Gneiss and Sauk Rapids Metamorphic Complex north and west of St. Cloud (Morey and Sims, 1976; Morey, 1978b).

A 50-km-wide belt of high aeromagnetic intensity (500–1,000 nT above background) and relief lies north of the exposed early Archean gneisses of the Minnesota River Valley. This belt extends west-southwest from just east of line 3 of the COCORP survey into central North Dakota, a distance of more than 400 km (shown in Fig. 3B and in Zietz, 1981). There is a wider (about 100 km) Bouguer gravity anomaly of about 15 to 30 mgal above background approximately coincident with the magnetic anomaly. (See Fig. 3A and Craddock and others, 1970; Woollard and Joesting, 1964; Morey and Sims, 1976; McGinnis and others, 1978; Ervin, 1980; and Hildenbrand and others, 1982). Both the gravity and magnetic anomalies are broken by local lows in several places, and line 3 of the COCORP survey is located at the western edge of one such low. There are also gravity and magnetic highs associated with the early Proterozoic sedimentary basin east of the surveyed area. These anomalies can be discerned almost as far east as Duluth. The McGrath Gneiss coincides with the peak of gravity high and with a subdued aeromagnetic high.

Rocks in the belt of combined gravity and magnetic anomaly described above are very poorly exposed. There are exposures of granitoid intrusives and granulite gneiss in the Ortonville-Odessa area of the Minnesota River Valley near the South Dakota border and minor exposures of mafic and quartzofeldspathic gneisses along this belt near Sauk Centre, in the vicinity of the southern end of the COCORP survey area. On the basis of lithological, metamorphic, and structural analogy, these rocks have been considered part of the early Archean gneiss terrane (Morey and Sims, 1976; Sims and others, 1980). Geochronological correlation has not yet been demonstrated. The only radiometric age determination from this geophysically delimited gneiss belt is an apparent Rb-Sr age of 2,600 Ma for quartz monzonite that intrudes the gneiss at Ortonville (Goldich and others, 1970). There is a break in the gravity and magnetic anomaly in the Ortonville area, and this age determination thus does not set an upper limit for the age of this gneiss belt.

Early Proterozoic Rocks

Metasedimentary and metavolcanic rocks of the Mille Lacs and Animikie Groups cover much of east-central Minnesota. The groups have an estimated stratigraphic thickness of about 2 km in the Mille Lacs Lake area (Morey, 1978b). The stratigraphic thicknesses and facies variation indicate that the present northwestern and possibly also the western limits of these metasedimentary rocks were also their approximate depositional edges and that the sources of sediment in this part of the Proterozoic basin were from the north and west (Morey, 1973). The two groups are separated by an unconformity (Marsden, 1972). Both consist of quartz-rich arenites, carbonates, and argillites, as well as mafic to intermediate volcanic rocks. Sedimentary iron-formations are also present in both. The iron-formations give rise to short-wavelength, high-relief aeromagnetic anomalies.

The area of the Animikie and Mille Lacs Groups coincides with a regional gravity high of about 15 to 20 mgal above the surrounding areas at the northwestern edge of these metasedimentary rocks (Figs. 2 and 3A). The gravity anomaly extends south beyond the area currently underlain by these groups, although there are outliers in the southern part of the anomaly.

The Mille Lacs Group adjacent to the survey area includes basal conglomerate and quartzite, overlain by pillowed basalt of the Randall Formation (Morey, 1978b). These rocks are folded about north- to northeast-striking, near-horizontal axes. The fold pattern is asymmetrical, with short, steeply dipping northwest limbs and more moderately dipping southeast limbs (see cross section of Sims and others, 1980, p. 693).

The oldest known Proterozoic rocks in Minnesota are northwest-oriented mafic dikes that are unconformably overlain by the Animikie Group (Southwick and Day, in press). These dikes are about 2,000 to 2,200 Ma old (Hanson and Malhotra, 1971; Beck and Murthy, 1983).

In east-central Minnesota, northern Wisconsin, and Michigan, the early Proterozoic sedimentary and volcanic rocks were deformed in the Penokean orogeny, which included tight folding, metamorphism, and intrusion of magmatic rocks with ages of 1,760 to 1,860 Ma (Sims, 1976; Maass and others, 1980; Van Schmus, 1980). There are early Proterozoic (Penokean) intrusive rocks about 60 km east of the COCORP survey area, including successive intrusions of gabbro, diorite, granodiorite, and sodic granite of the Stearns Igneous Complex of Morey (1978b) and minor felsic hypabyssal porphyry.

The Mille Lacs and Animikie Groups in east-central Minnesota have nodal metamorphic patterns. Metamorphism ranges from low grade in the north and west to staurolite grade in the vicinity of Mille Lacs Lake (Morey, 1973).

In both Minnesota and central Wisconsin, there are high-grade metasedimentary rocks of possible early Proterozoic age that apparently unconformably underlie and predate the other Proterozoic rocks described above, although the field relations and geochronological studies are not conclusive (the Hillman migmatite, described by Morey, 1978a and 1978b, and the quartzite clasts and xenoliths described in Wisconsin by LaBerge, 1981). The Dickinson Group of the Felch Trough area of Michigan might also be included in this category (Sims, 1981).

Younger Sedimentary Cover

Drill intersections of sandstones of the Keweenawan Fond du Lac Formation, Bayfield Group, have been reported from the southeast corner of the area of Figure 2, with thicknesses reaching several hundred metres just beyond the map area (Craddock, 1972). Cretaceous sedimentary rocks about 20 m thick occur in the extreme south of the area. Glacial till and outwash about 30 to 100 m thick form an almost unbroken cover (Southwick, 1980). These surficial units may affect the performance of the seismic system, but they are too thin to be seen on the COCORP sections as processed.

Epicenter locations of earthquakes in central Minnesota are shown in Figure 2. Several of these approximately coincide with the locations of aeromagnetically inferred fault traces, suggestive of recent movement on these faults (for example, the Morris fault, Mooney and Morey, 1981).

The Great Lakes Tectonic Zone

The boundary between the granite-greenstone terrane of northern Minnesota and the early Archean Minnesota River Valley gneiss terrane has been the subject of several recent papers—(Morey and Sims, 1976; Sims, 1976, 1980; Morey, 1978a, 1978b; and Sims and others, 1980). The last-named paper defined a broader feature, the Great Lakes tectonic zone, that includes this boundary and extends from Minnesota to the upper peninsula of Michigan. The following attributes of the Great Lakes tectonic zone have been described:

It contains the boundary between the older and younger Archean basement terranes.

The northern Penokean deformation within the zone affected both the early Proterozoic sedimentary rocks and the subjacent early and late Archean basement.

There is aeromagnetic and field evidence of east-northeast–striking faults along the northern and southern boundaries of the zone.

Near the western Minnesota border, there is apparent vertical offset of the Cretaceous sedimentary cover within the zone, with the south side lowered by 75 to 95 m (Schurr, 1979).

The nature, age, and location of the boundary between the Archean terranes are not well established. Although local unconformity between late Archean metabasalt and early Archean gneiss has been reported from northern Michigan, the early Archean rocks are considered unlikely to extend far beneath the Superior Province (Sims, 1980; Sims and Peterman, 1981b). There are late Archean granitoid intrusives in both the northern and southern basement terranes, but they have different lead isotopic characteristics, consistent with their derivation from crustal units of different ages (Doe and Delevaux, 1980). In Minnesota, the boundary between the Archean terranes has been considered as a fault, although it is difficult to determine which (if any) of several geophysically revealed faults to associate with the boundary. The preferred location in central Minnesota is at the southern edge of the tectonic zone, at or near the Morris fault (Sims and others, 1980). It is also possible that the Archean terrane boundary lies south of the Great Lakes tectonic zone as it has been mapped. A geophysically acceptable alternative site would be south of the magnetically high zone, just beyond the southern end of the COCORP traverse.

The age of the boundary between the Archean terranes has been considered late Archean, with reactivation along it during early Proterozoic Animikie and Mille Lacs Groups sedimentation (extensional), during the Penokean orogeny (compressional), and possibly later (Sims, 1980;

Sims and others, 1980). The evidence for a late Archean age includes the presence of granitoid rocks of that age in both terranes (possibly indicating a common thermal event) and the apparent deposition of early Proterozoic sediments across the boundary, indicating that the two terranes were solidly linked by that time.

Penokean deformation affected the region east of the COCORP survey area, as shown by the development of east-northeast–striking folds and foliation in the Animikie Group cover and subjacent Archean gneisses. Over the McGrath Gneiss, and in the northern Wisconsin and northern Michigan areas, the penetrative deformation dips southeast at about 50°, and this pattern is taken as representative of the zone by Sims and others (1980). This deformation and metamorphism are most intense toward the south of the area of Animikie Group exposure. Penokean deformation extends to the north beyond the fault taken as the northern edge of the Great Lakes tectonic zone (D. L. Southwick, 1982, personal commun.).

Within the COCORP survey area, it is more difficult to determine the nature of Penokean deformation. The map pattern (Fig. 2) suggests that the Penokean fold axes are oriented north to north-northeast adjacent to the COCORP area, at a high angle to the strike of the faults and geophysical anomaly belts. There is little field evidence to confirm this orientation, however (D. L. Southwick, 1983, personal commun.).

Structure of the COCORP Survey Area

The geological map of the survey area, Figure 2, is based on the geophysical criteria described above, together with the few bedrock exposures and drill cores (Southwick, 1980; Morey and others, 1981; and V. W. Chandler, 1981, personal commun.). Fault traces shown on the map are inferred from linear breaks in the aeromagnetic and gravity patterns. The locations of the traces at the surface may vary from these.

There are prominent east-northeast–striking boundaries between areas of differing magnetic and gravity expression. The fault at the northern edge of the Great Lakes tectonic zone is thought to dip steeply southeast. It is also thought to have had dip-slip offset during the period of early Proterozoic sedimentation (Morey, 1978b), and it may have been reactivated as a reverse fault during the Penokean orogeny (Sims and others, 1980). The southern fault, the Morris fault, is also considered to have a southerly dip (about 70°), on the basis of one of the surface-wave focal-plane determinations of a recent earthquake near Morris, Minnesota

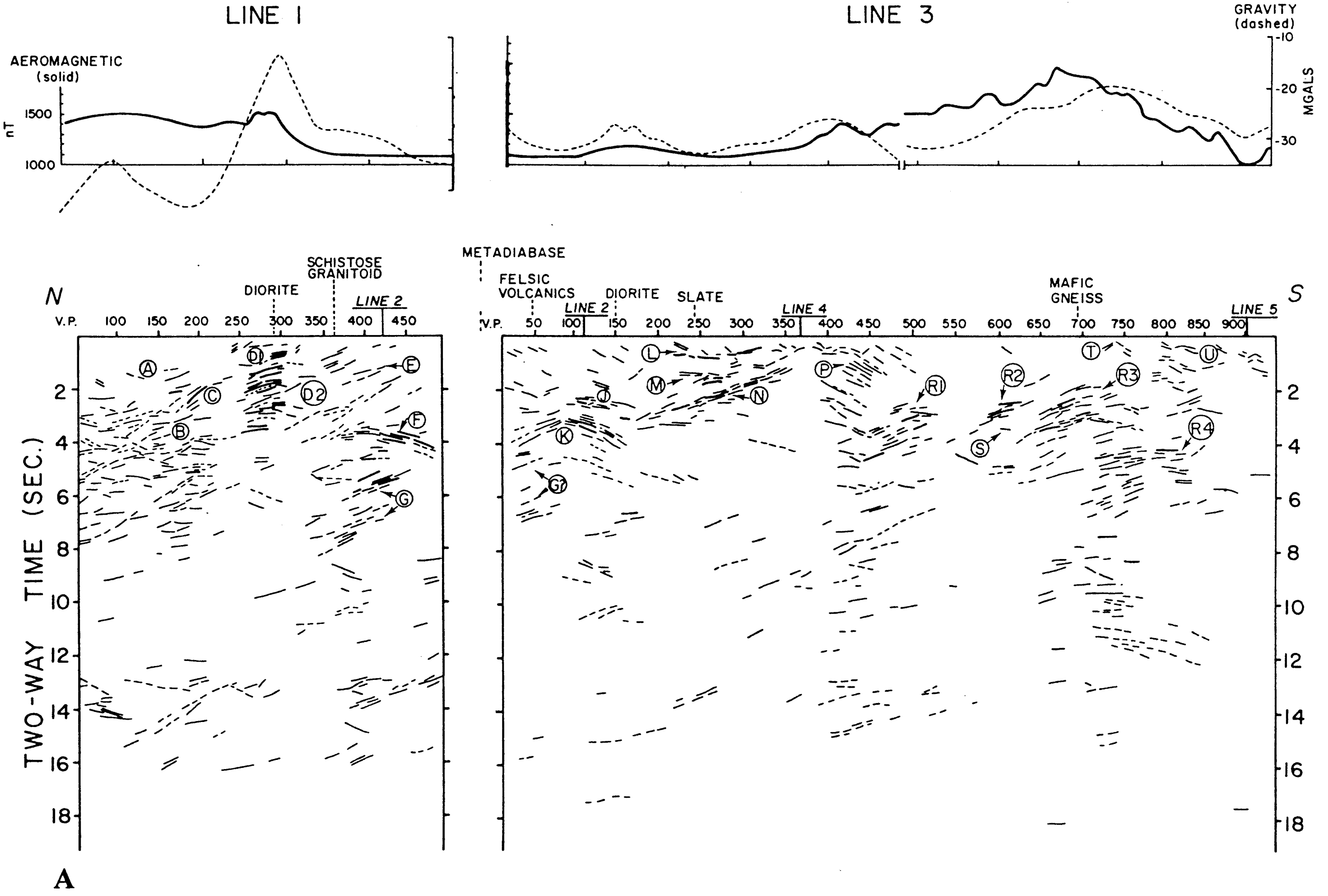

Figure 4. A. Line drawings of north-south seismic-reflection profiles, Minnesota lines 1 and 3. See Figure 2 for line positions. Bold, solid, and dashed lines indicate relative amplitude and coherence of the seismic events. These are time sections; the data have not been migrated. The superimposed gravity and magnetic profiles are from the sources listed for Figures 3A and 3B. Letters refer to events and zones discussed in the text. Rock types shown are from drill cores and nearby outcrops (D. L. Southwick, 1981, personal commun.; Morey and others, 1981). B. Line drawings of the east-west seismic-reflection profiles, Minnesota lines 2, 4, and 5.

(Hermann, 1979). Hermann's other focal-plane determination dips vertically and strikes northwest, and faults of this orientation are also apparent on the aeromagnetic map of the Morris area. Another northwest-southeast–striking fault, in the southeast quadrant of Figure 2, strikes toward the prominent transform or strike-slip Belle Plaine fault, which offsets the Mid-Continent Geophysical Anomaly in southeastern Minnesota (Craddock, 1972). There are numerous other northwest-striking faults with comparable geophysical expression throughout Minnesota, some of which cut the Animikie Group (Morey, 1972b).

THE COCORP EXPERIMENT

During the summer of 1979, seismic-reflection profiling was carried out by COCORP along the lines shown in Figure 2. The lines, totaling 280 km in length, were selected to cross the Great Lakes tectonic zone along suitable roads. The survey was done in the conventional common depth point (CDP) manner. The VIBROSEIS (trademark, Continental Oil Company) source was used. The field tapes were demultiplexed and correlated by Geosource, and subsequent processing was conducted at Cornell using the Megaseis (trademark, Seiscom Delta) computer system. The standard processing consisted of elevation statics correction, CDP sorting, velocity analysis, and appropriate normal moveout correction, range sorting, bandpass filtering, amplitude balancing, and stacking. In addition, migrated sections were prepared for the north-south lines.

The straight farm roads in the survey area permitted very straight seismic lines, with minimal lateral mid-point scatter, and the flat topography minimized elevation statics problems. Editing of the field data was necessary due to the recording of high-amplitude noise from several sources, including heavy machinery used in farming and railroad traffic.

The common mid-point method collects seismic records from shot-receiver pairs that share a common mid-point. From the groups, or gathers, of mid-point sets, estimates of the stacking velocity were made using the velocity spectra (plots of signal coherence against time and velocity) on the Megaseis computer, and the optimal normal moveout correction was applied. The velocity function was smoothed to ensure realistic interval velocities. The stacking velocities referred to in this paper have been corrected for dip.

The common mid-point method works best in areas with horizontal strata. The geology of this region is more complex, however, with significant lateral variations in stacking velocity. In order to alleviate some of the

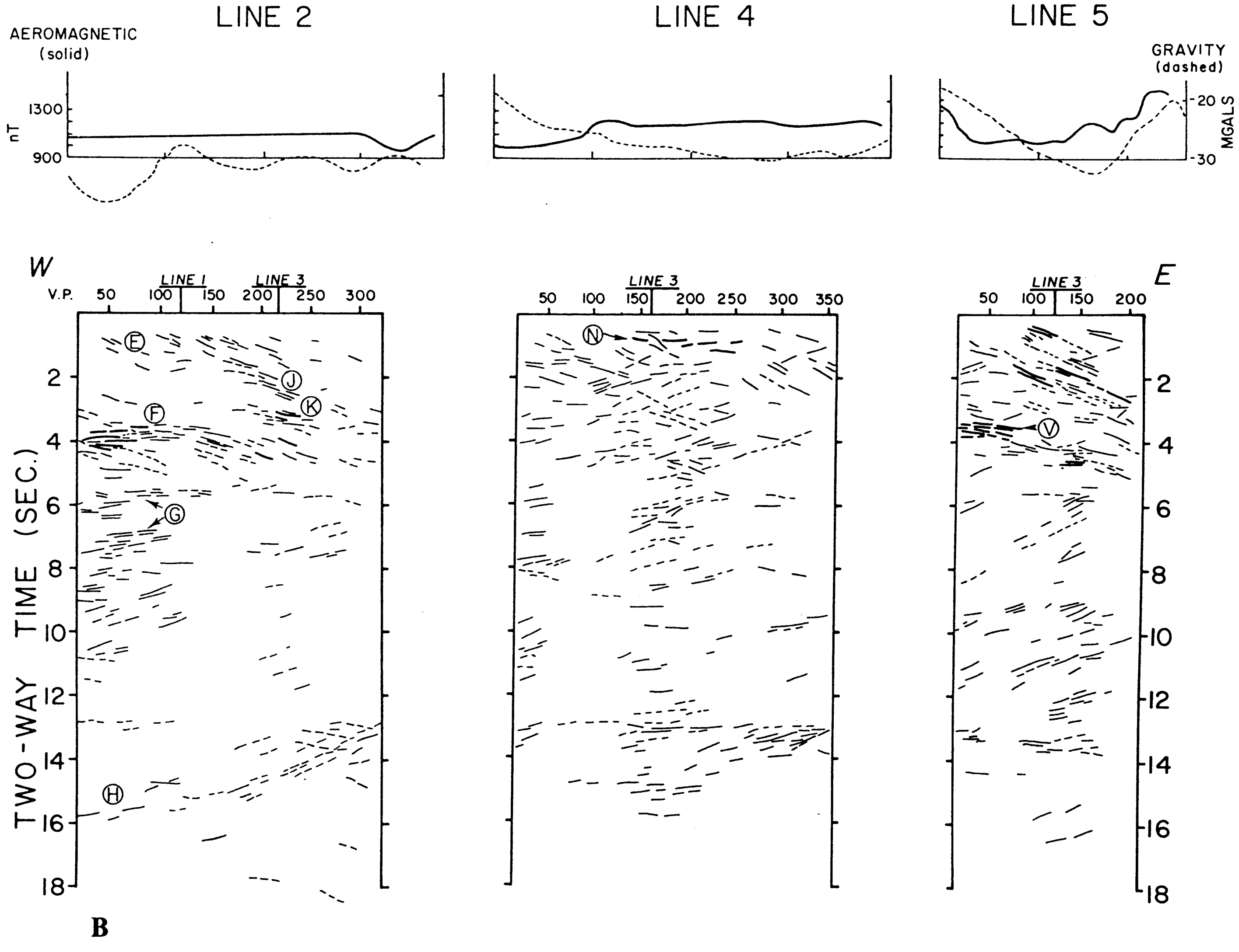

Figure 4. (*Continued*).

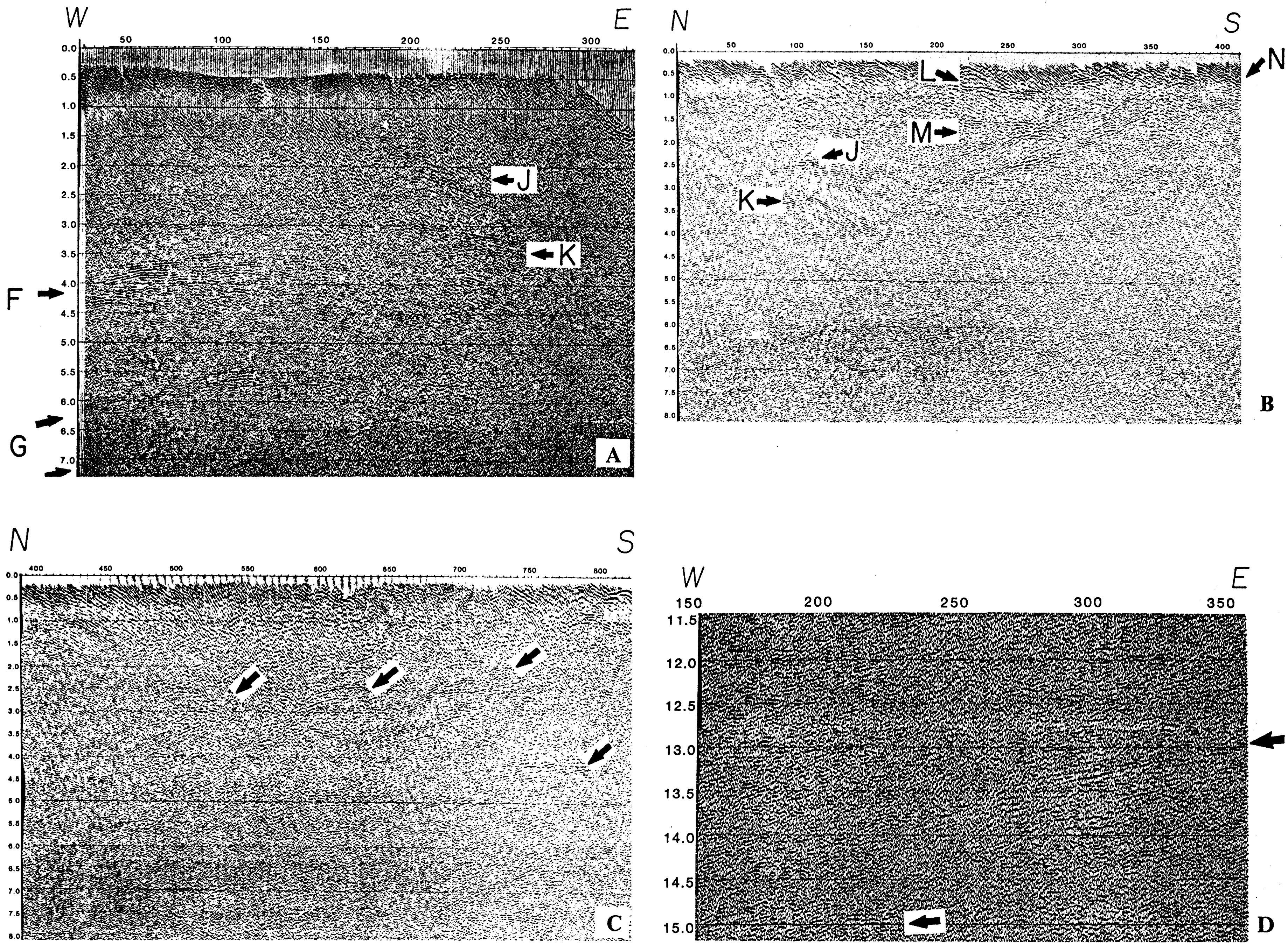

Figure 5. Time sections of portions of line 2 (A), north half of line 3 (B), south half of line 3 (C), and lower part of line 4 (D). Arrows point to features referred to in the text and shown in Figures 4A and 4B. Numbers across the top refer to VP numbers. Two-way traveltimes are shown in seconds.

effects of lateral velocity variation and dip of the reflectors, a stacking procedure known as range sorting was used. This involves selection of source-receiver pairs that are separated by distances within a specified range. The traces thus have similar ray paths, and the similarity improves the detection of coherent signals. The traces from receivers very close to the vibrators were consistently noisy and were excluded.

One suspected source of signal degradation is the ubiquitous glacial cover in the area of the surveys. Glacial till, with its large velocity contrast with underlying basement—about 1.2–2.0 km/sec (Gendzwill, 1978) compared to 5.0–6.0 km/sec—and variable thickness (0–100 m) (Southwick, 1980), is a known source of statics problems in other areas (Caughlin and others, 1976). The glacial cover also may contribute adversely by generating unusually large surface-wave interference.

Although both the data acquisition and processing used in these surveys discriminate to some extent against steeply dipping geologic structures (Lynn and Deregowski, 1981), seismic sections specially stacked to enhance dipping events were consulted during the interpretation. These sections suggest that the unmigrated sections shown in Figures 4A and 4B are not unduly biased against dipping events. Bear in mind that the maximum apparent dip on an unmigrated seismic section, 45°, corresponds to reflection from a vertical interface.

Migration of the sections was performed by computer for the top half of the data, using a variable velocity function. The most important events in the deeper data were migrated by hand, using an assumed velocity of 6.5 km/sec.

RESULTS

The most readily apparent reflections or seismic events are shown in line drawings, Figures 4A and 4B. Some of the details of the time sections are shown in Figures 5A to 5D. The results of migration are included in Figure 6. Key features are alphabetically indexed, starting from the north. A few general observations are warranted before referring to individual events.

The (dip-corrected) stacking velocities for this survey range from about 5.0–5.6 km/sec in the top second to about 7 km/sec at 10 seconds. Stacking velocity is not the same as interval velocity, which is more directly comparable with laboratory and refraction measurements. When allowances are made for the low velocities of glacial overburden, the stacking velocities are generally in the range expected for igneous and medium- or high-grade metamorphic rocks, and they correspond in general to the velocity profiles determined by refraction experiments in the Canadian Shield (see Table 2).

There are notable lateral variations in the abundance of reflections throughout the range of arrival times. This is particularly true of line 3. Although some of these lateral variations may correspond to differences in bedrock geology, others may be due to propagation differences in the near surface. The shallow strata, including glacial deposits and Cretaceous sedimentary rocks, are too thin to be effectively resolved with the seismic-array configuration and processing used.

With the processing used, there is a strong tendency for the first second on each profile to show coherent events—actually artifacts—that dip in the vibrator-to-geophone direction. The dips of these artifacts are thus to the north on line 1, to the south on line 3, and to the east on crosslines 2, 4, and 5. This effect, known as "spatial aliasing," can mask shallow features. We therefore do not believe that the first second of the data places strong constraints on interpretation.

The COCORP survey proceeded from the granite-greenstone terrane of the Superior Province in the north toward the region of transition to older Archean crust in the south. Zone A on line 1 (see Fig. 2 for line position, and Fig. 4A) is most likely correlatable with the western extremity of the Giants Range batholith, as mapped on the basis of gravity, magnetic, and limited drill-hole data. The zone has relatively low-frequency seismic data, with few reflections. A relatively homogeneous batholith might be expected to produce few internal reflections. There are, in contrast, numerous reflections in zones B and C, suggesting that the batholith may not extend to depths beyond about 6 to 8 km. A northwest-southeast–trending series of gravity highs centered at vibration point (VP) 80 breaks the regional gravity low that is associated with the batholith. The stacking velocities for reflections in zones B and C are approximately 6.0 km/sec; reflections in zone A stack at about 5.6 km/sec. Reflections in zone B are particularly complex; many of them appear to cross one another. This pattern might arise from folded strata, such as those modeled by Wong and others (1982), or from the three-dimensional effects of reflectors out of the plane of survey.

There is a zone with relatively few reflections, coinciding with a change in the nearby reflection patterns, between zones C and D on line 1. This zone also coincides with changes in the gravity and magnetic profiles. A steeply dipping fault with an east-west strike as indicated in Figure 2 might be present here.

The amplitude, coherence, and conformity of reflection groups D1 and D2 contrast with the reflections farther north. The stacking velocity of D1 is about 6.1 km/sec, higher than most other shallow reflections on this line. Group D2 stacks at velocities between 6.1 and 6.3 km/sec. There are positive gravity and magnetic anomalies over D1. A drill hole through the glacial cover just north of VP 300 found diorite (D. L. Southwick, 1981, personal commun.). Although the drill-core, gravity and magnetic anomalies, and seismic reflections might not all be associated with the same geological features, they are all consistent with this region being south of the Giants Range batholith or along a mafic southern margin of it. The short wavelength of the gravity and magnetic anomalies over D1 indicates that they originate near the top of the crust, at least within the top kilometre. Elsewhere in northern Minnesota, such patterns are correlated with greenstone belts, and this assignment on the geologic map (Fig. 2) is probably correct. The seismic character above D1 is complex, consisting of short reflections with variable dips, on both the time and migrated sections. Such a complex pattern is consistent with the steeply folded structure that is typical of Archean greenstone belts.

The seismic characteristics of the D reflections are very different from those of the overlying zone of inferred greenstone-belt rocks. A reflection zone dipping gently north at the top of D is considered a possible fault (shown in Fig. 6), separating greenstones and diorite at the surface from the strongly layered reflection zone below. The geologic cause of the D reflections is uncertain. Stratified igneous rocks, either extrusive or intrusive, might give rise to this pattern.

There is another zone with few reflections and a change in the adjacent reflection patterns at about VP 325–350 on line 1, also coincident with breaks in the gravity and magnetic patterns. The abrupt smoothing of these potential fields to the south is considered to mark the east-northeast–striking fault at the northern edge of the Great Lakes tectonic zone. The break in the seismic pattern here may correspond to a steeply dipping fault zone, extending to the bottom of the D reflection groups at about 4 sec (about 12–13 km), and possibly deeper if it truncates reflections G at 7.5 sec (about 25 km). The northern limit of the Great Lakes tectonic zone thus might be a steeply dipping fault, persisting to great depth. Faults of other dips, surfacing near VP 325, might also be present. The discontinuous, weak reflection zone dipping about 20° to the north, referred to above, might be associated with a fault. A south- (lines 1 and 3) and east- (line 2) dipping fault, sketched in Figure 6, is also possible.

In zone E, the near-surface seismic section has generally low-

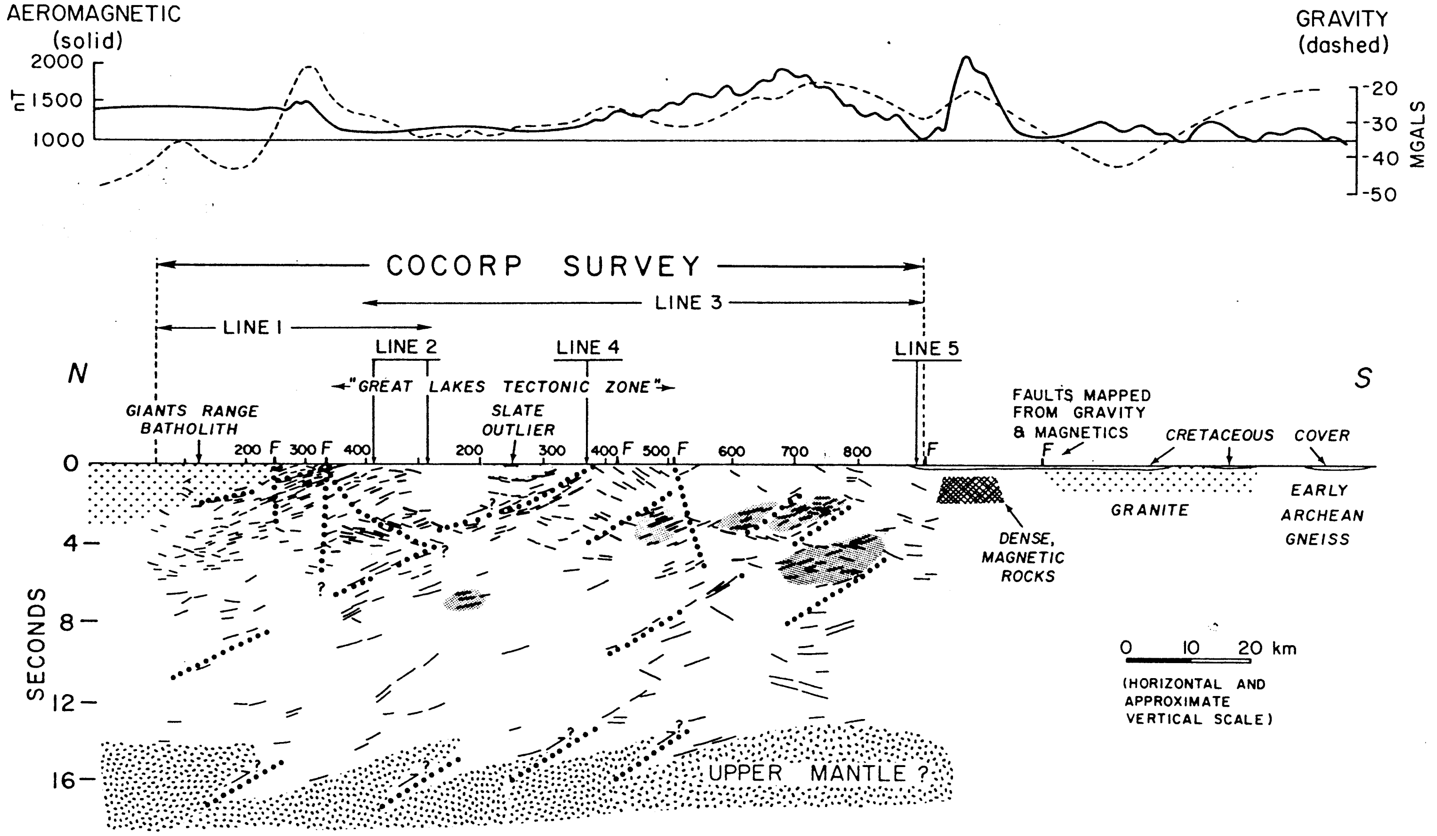

Figure 6. Migrated sections of the north-south seismic-reflection profiles, with line 1 projected northeast to line 3 (see Fig. 2). Interpreted lithologies and structures are shown schematically. The Superior Province (shaded area, top left) is inferred to be in faulted contact with the gneiss and granulite terrane of the rest of the section. Dotted lines indicate inferred faults. The steeply dipping faults are thought to have major strike-slip offset; the shallow north-dipping faults are interpreted as thrusts generated during late Archean collision of the older Archean southern continental crust with the Superior Province crust. Complex reflections near the base of the crust may originate from the crust–upper-mantle boundary with local fault offsets as shown.

frequency, north-dipping events. Some linear, relatively steeply dipping events in this zone, and in similar depth ranges on lines 2 and 3, are probably artifacts created by spatial aliasing, but the lines shown in Figure 4A are possibly real reflections. They may be correlated with similar events on line 2 (Fig. 4B). Stacking velocities for E are about 5.9 km/sec. Seismic velocities in this range are common in granitoid rocks. A shallow drill hole cored intensely cataclased rocks near here (D. L. Southwick, 1982, personal commun.).

The prominent reflections marked F on lines 1 and 2 (Figs. 4A, 4B, and 5A) form a broad, open fold pattern with its axis plunging at a shallow angle to the south. The high amplitude of F indicates a high contrast in impedance. This is one of the largest continuous groups of reflections in the Minnesota survey. The stacking velocities for F are about 6.2 km/sec, higher than for events in the rest of the survey area at equivalent times, but similar to the group of events at D2. Reflections F become diffuse, but they apparently persist, toward the eastern end of line 2.

Below F, there are several reflection zones with apparent 20° to 25° north-northwest dips, marked G in Figures 4A, 4B, and 5A. These are similar in character and apparent dip to north-dipping reflection zones in the northern part of line 3, marked G? and N. Events with comparable northerly dips are particularly common on lines 1 and 3, and, as explained below, these are interpreted as possible north-dipping thrust-fault zones.

There are scattered events in the 8- to 12-sec range on lines 1 and 2, most with shallow apparent dips to the north. There is a greater concentration of events in the 12- to 16-sec range. The majority of these dip to the north (line 1) and west (line 2). The same increase in number of reflections below about 12 sec occurs on all of the lines. Reflections H (Fig. 4B) do not appear to be simple multiple reflections from shallower features. If H can be correlated with the deep reflections on line 1, their true dips are to the northwest. The arrival times of these reflections indicate depths that are comparable to depths of Mohorovičić discontinuities as determined by refraction studies in other parts of the Canadian Shield (see Table 2).

There is a change in the character of the seismic data above the diffuse eastern end of reflection group F on crossline 2 (Figs. 4B and 5A). A southeast-dipping fault could be present in the position shown in Figure 6, and separating groups F from E and K on line 2, extending from near the surface to about 5 sec. Such a fault might account for apparent offsets of reflection groups F to K and G to N (line 3), and possibly also the northern truncation of group E on line 1. The apparent offset of these features indicates that the crust above the interpreted fault moved up to the northwest.

A discontinuity is discernible between the events labeled G on crossline 2 and the westerly dipping reflection zone beneath them. The discontinuity rises from about 9.5 sec at the west end of the line to about 6 sec at the east end. Comparable discontinuities are also present in the middle and lower parts of crossline 5. Such features might indicate fault zones. The absence of clear and correlatable discontinuities on the north-south lines leaves their three-dimensional orientation indeterminate.

Event groups J and K on lines 2 and 3 are relatively short, strong, and distinct (Figs. 5A and 5B). They have stacking velocities of about 5.8 to 6.0 km/sec, lower than the 6.2 km/sec stacking velocities above F on the western part of line 2. These events on line 3 change in shape on migrated sections (Fig. 6) to form an open syncline (K) beneath a wedge-shaped reflection, thinning to the south (J). In dimensions and seismic character, they resemble the F reflections of lines 1 and 2. The speculative southeast-dipping fault referred to above might account for the offset.

Events L (Figs. 4A and 5B) have the highest amplitude of those in the Minnesota survey. In detail, L is composed of four slightly oblique overlapping segments with stacking velocities of about 5.5–5.6 km/sec. A gravity low of a few milligals in magnitude is approximately coincident with L, and an unpublished gravity model (C. P. Ervin, 1981, personal commun.) shows a low-density body of approximately the same depth and shape as the area above L. Granitoid rocks or metasediments could equally well fit the geophysical data, but slate, possibly of the Mille Lacs Group, found in three drill cores of the bedrock surface along this part of the survey line is the most likely rock type (D. L. Southwick, 1982, personal commun.).

Reflection group M has both relatively flat and north-dipping components. The flat ones might be multiples of the overlying L group, as their arrival times are twice those of L reflections. The north-dipping reflections parallel those of group N. Group N is one of the most prominent features of the entire survey, extending from near the surface at about VP 400 to below 3 sec near VP 150 (Figs. 4A and 5B). The N reflections are weak or absent beneath event K, but similar features are present farther north, and deeper, on lines 1, 2, and 3 marked “G”. The shallow, southern end of group N is diffuse. The stacking velocity of N is lower than that of M, which overlies it: 5.7–5.9 km/sec for N and 5.9–6.1 km/sec for M. Stacking velocities below N are apparently higher, but the reflection quality for that zone limits resolution.

Reflection group N separates the line 3 seismic data into two major areas with different characteristics. Above and to the north of N, the reflection groups are relatively discordant and irregular. Below and to the south of N, the reflection groups are more regularly aligned, with fewer crosscutting features.

Crossline 4 has a series of shallow, nearly horizontal reflections that are tentatively correlated with N on line 3. The (migrated) true dips of N in this region might thus be about 25° to 30° to the north, as shown in Figure 6. Gravity and magnetic contours in the vicinity of line 4 strike east-west, with highs to the south. The parallelism of the gravity and magnetic contours with the apparent strike of N suggests correlation between them. One interpretation is that N is associated with a north-dipping fault, with the rocks below it denser than those above. Although not precisely coincident with the southern margin of the Great Lakes tectonic zone as previously described, it coincides with the northern limit of the prominent gravity anomaly belt (Figs. 1 and 4A).

On crossline 4, there are many discontinuous and crossing events between about 1 and 7 sec. Over the same depth range, line 3 has hardly any events continuous enough to mark. This disparity in seismic character may be due to general east-west strikes of complexly deformed rocks in the upper crust of this area, allowing better imaging on the east-west crosslines than on the north-south lines. Below 7 sec, there are diffuse but generally consistently dipping discontinuous events on both lines 3 and 4. If the two apparent dips are correlated, the true dip of most of these events is about 30° toward the north-northwest.

There are flat, coherent reflections at 13, 14, and 15 sec on crossline 4 (Figs. 4B and 5D). A zone of west-dipping events crosses these flat reflections. The deep reflections on crossline 4 cannot be correlated with specific features on line 3, but there are diffuse events between 13 and 15 sec on line 3 that dip about 15° to 20° to the north. These deep reflections are shown in their migrated form in Figure 6. The common occurrence of deep reflections on these lines indicates that there are north- and west-dipping structures or lithological boundaries at or near the base of the crust in this region.

Just below and to the south of N on line 3, there is a zone of consistently south-dipping reflections, marked “P.” Anomalously high stacking velocities are present in the top of the section from VP 400 to VP 550, reaching 6.1 km/sec at an arrival time of 1 sec. This is consistent with the presence of high-grade metamorphic rocks in the shallow crust. There is a low-velocity zone below P at about 2 sec. On the time section (Fig. 4A), group P extends downward to the top of group R1. On a migrated section (Fig. 6), there is a shallow, north-dipping zone of events parallel to N near VP 560. This appears to truncate some of the migrated reflections of group P and might indicate another north-dipping fault zone.

The most prominent events in the southern half of the survey area are the separate but similar reflection groups marked “R1” to “R4” (Figs. 4A and 5C). These are broadly similar to one another in amplitude and thickness, they have similar dips to the north, and there is an arcuate character to them on the time sections that may be due to diffraction. The groups have different stacking velocities: the northern two between 5.5 and 6.0 km/sec, and the southern two between 5.9 and 6.3 km/sec. These differences in stacking velocity indicate differences in the crust above the R groups, rather than differences in the seismic character of the groups themselves. R1 through R3 also share a tendency for the shallower reflections in each group to dip less steeply than the deeper ones. On the migrated section (Fig. 6), they form shorter groups of reflections, without arcuate northern extensions. Their similarity to one another might be simply coincidental, or it may indicate that a reflective, and originally continuous, segment of stratified crust has been broken and offset by faulting. The dotted lines in Figure 6 indicate some of the possible fault locations, constrained only by the apparent patterns of continuity and offset on the time and migrated sections. If such faults are responsible for the distribution of the dense and magnetic rocks that create the regional potential-field anomalies (Figs. 3A and 3B), they must strike about east-northeast.

There is an interesting correlation between the shape and position of the R groups and the broad-wavelength gravity and magnetic fields above them (Fig. 4A). The maximum on the aeromagnetic anomaly above VP 700 corresponds with the minimum depth to the top of R3. Superimposed on the broad aeromagnetic high are numerous short-wavelength anomalies that must originate within the uppermost 1 or 2 km. There is less perfect correspondence between the gravity profile and the position of the R groups: a gravity high at VP 400 is separated from the broad high (VP 600–800) by a low centered at about VP 525. Shallow, low-density rocks with low seismic velocity, such as granite, located in the vicinity of VP 500 would account for both the gravity and velocity data discussed above. The lack of reflections in this zone is also consistent with such an interpretation.

Simple estimates of the depths of origin of the gravity anomalies indicate maximum depths of about 8 to 12 km to the tops of the regional density contrasts. This is consistent with the 5- to 10-km depths to the R groups estimable from their seismic traveltimes.

The potential-field anomalies just described are the eastern extremities of the regional anomaly belt that extends west-southwest into South Dakota. The expressions of these anomalies along the COCORP traverse are subdued, presumably because the dense, magnetic rocks do not continue to the east. The truncation of the gravity anomaly appears to be irregular in shape, approximately coinciding with the position of line 3 (see

Fig. 3A). The aeromagnetic anomaly continues about 10 km farther to the east, where it is truncated along a northwest-southeast–striking trend. Both anomalies are also interrupted at the southern end of the line, just north of a distinct gravity and magnetic anomaly about 10 km in width. This southern truncation strikes east-northeast and crosses the eastern half of line 5.

The sparse exposures of rocks in the vicinity of the southern half of line 3 include gneisses and granulites. One interpretation of the correlation between the gravity and magnetic anomaly patterns and the R groups is that the latter are approximately coincident with rocks that have relatively high densities and magnetic susceptibilities.

The R features differ from most of the reflection groups in the northern one-half of the survey area. Reflection group D, with a distinctive gravity anomaly centered near VP 300 on line 1 (Fig. 4A), lacks a correspondingly broad magnetic anomaly. F, J, and K also lack anomalies. The R groups might be correlated with deeper features farther north. The reflection zone at about 8 sec below VP 150–200 on line 3 is one possibility.

The question of the nature of groups R will have to be solved by indirect methods: they do not appear to reach the surface either here or at any other location, judging from the gravity and magnetic data. The discrete anomaly just south of line 3 (beyond the present survey) may be caused by such dense, magnetic rocks at their shallowest occurrence.

Imaging of a discontinuous band of reflections marked "S" in Figure 4A is particularly enhanced on the migrated section, shown in Figure 6. Although there is no change in apparent dip of the R-group reflections across S, many individual R reflections appear to be truncated by S reflections, particularly on the migrated section. S might thus be associated with a fault.

The shallow reflections of the southern end of line 3 show several short-wavelength fold patterns. The positions of two antiform crests, marked "T" and "U", coincide approximately with short-wavelength aeromagnetic lows. This might be fortuitous, or else some of the shallow features with magnetic expression in the gneisses might also give rise to seismic reflections.

There are few reflections on line 3 at its intersection with crossline 5. East-dipping events are prominent on line 5 in the top 5 sec, and west-dipping events predominate between 5 sec and a distinctive group of nearly flat reflections at 13.5 sec. Separate west-dipping reflections at 16 sec migrate as far as levels at or above the 13.5-sec events. A coherent group of reflections marked "V" in Figure 4E at about 3.5 sec bears some resemblance to groups R on line 3.

Line 5 crosses the gravity low that truncates or interrupts the regional gravity-anomaly belt. There are steep gravity gradients on the eastern edge of this low, indicative of its correlation with density differences in the shallow crust. An east-dipping zone of low-density rocks, with higher-density rocks above and below it, might accommodate both the gravity and seismic data.

The reflections at 13.5 sec on line 5 are similar in arrival time and seismic character to the deep events on crossline 4. This may indicate the existence of a seismic boundary at depths of about 40 km. On lines 1, 2, and 3, reflections from these depths dip north and west and are much less continuous, possibly due to greater structural complexity at or near the base of the crust in the north, and in north-south sections compared to east-west sections.

DISCUSSION AND CONCLUSIONS

The most significant structural problem of this region concerns the nature of the transition between the Superior Province and the older Archean gneiss terrane of the Minnesota River Valley. The COCORP survey revealed major reflections in this zone dipping northward. These reflections might be generated by fault zones that developed during an Archean collision.

The most important groups of these reflections, labeled "N", "M", and "G", have migrated dips of about 25° to 30° to the north. Faults of parallel or subparallel orientation are also suggested by similar discontinuous reflections throughout the crust and by the apparent requirements of continuity and offset in reflection groups R and elsewhere. The existence of a major set of imbricate faults, probably persisting throughout the crust, is thus suggested. If all of the material south of and below N belongs to separate, older continental crust, then N can be interpreted as a thrust zone and suture, as shown in Figure 6. Alternatively, the crust below and to the south of the N reflections might be middle and lower crust of the Superior Province, and a suture with the older, southern crust might be located farther south. It is also possible that Archean sutures exist both across line 3 and farther south.

Persistence of relatively planar reflection zones in the Minnesota crust is one of the most surprising results of this survey. The surface geology of this region shows complex folding and characteristically steep dips. These patterns, established in the late Archean and earlier, must have predated the formation of the planar-reflection zones, because the latter are not affected by the folding. The complex, disrupted seismic pattern within the Superior Province (as seen in the top portion of line 1) is consistent with the conventional view of such terranes. An extensive, planar feature such as N must either postdate the late Archean folding of the Superior Province, or else, if it is contemporaneous with the latter, it marks a transition in deformation style from irregular folding in the overlying crust to imbricate faulting possibly along the contact with older continental crust. The presence of late tectonic or post-tectonic granitoid rocks of late Archean age (2,400–2,600 Ma) in both terranes is consistent with a collision event of this age. Deposition of the Mille Lacs and Animikie Groups must have postdated the faulting and collision.

Faults of other orientations are also revealed or suggested by the seismic sections. There are changes in the character of seismic reflections across zones with relatively few reflections in line 1, and these changes are probably associated with steeply dipping faults. Another such fault might be present near VP 550 on line 3. A southeast-dipping fault is speculatively identified at the northern end of line 3. The changes in characteristic reflection dips at about 6 to 7 sec on crosslines 2 and 5 may correspond to fault locations. These discontinuities on the crosslines are not apparent on the north-south lines, so their orientation is not known.

There is field evidence that major strike-slip faults in the Superior Province involve shear zones as much as several kilometres wide and that the stratification of the surrounding rocks is subparallel to the fault planes near the fault zones (Stone, 1977). Green and others (1979) noted that acoustic impedance contrasts may occur in the Superior Province along faults due to shearing and metasomatic alteration. Such features are likely to be characteristic of the faults in central Minnesota and may account for the relative lack of reflections in the vicinity of steeply dipping faults and for the presence of reflection zones, rather than isolated reflections, along major faults of lower-dip angles.

The COCORP surveys in other areas provide examples of the seismic character of fault zones with moderate dip. The Wichita Mountains in southern Oklahoma have south-dipping faults with a strong thrust component, and discontinuous reflections persist below the depths at which coherent, distinct faults can be identified (Brewer and others, 1983). The Laramide fault zones in the Rocky Mountains also share this character (Brewer and others, 1980; Allmendinger and others, 1982).

If this portion of the Great Lakes tectonic zone includes a suture, part of the sedimentary margin of the older, southern continent might be preserved in the vicinity of the thrust faults. There is some evidence that late Archean continental sedimentary rocks are preserved as metamorphosed outliers in the older Archean gneiss terrane of Wisconsin and Michigan

(Sims and Peterman, 1981a). Preservation of such a continental marginal sequence along the postulated suture zone might account in part for reflection zones N and G, but this is highly speculative.

The definition of the Great Lakes tectonic zone as including major Penokean deformation should be modified, as least for the portion of the zone along and to the west of the COCORP survey. The persistence of relatively straight reflections in the upper crust in the middle of line 3 (events L and N) indicates that Penokean folding about northeast-southwest axes, like that mapped east of the survey area, is not important along this traverse. It is possible that some of the variation in reflection dips in the upper parts of crosslines 2 and 4 is the result of Penokean folding. The only evidence of the existence of middle Precambrian rocks in the survey area, or anywhere this far west in Minnesota, is the cores of slate, not yet dated, drilled near VPs 250, 300, and 350, and several mafic dikes and epizonal granitic intrusives in the Minnesota River Valley. The pervasive Penokean resetting of radiometric ages that occurred in east-central Minnesota and in Wisconsin and upper Michigan apparently did not occur this far west in Minnesota. If the Penokean orogenic belt is in fact connected with the Churchill-Superior boundary, as suggested by Baragar and Scoates (1981), then the axis of major Penokean deformation apparently lies south of the COCORP survey area, and possibly even south of the Minnesota River Valley gneisses.

The gravity-anomaly pattern in the central Minnesota survey area differs from the characteristic pattern found in other parts of the periphery of the Superior Province. In the latter areas, broad gravity lows due to crustal thickening in the peripheral Proterozoic crust are paired with narrower highs over the Superior Province margin due either to the greater average density of the Superior crust (Gibb and Thomas, 1976) or to elevation of upper-mantle rocks near the boundary. There is also no marked difference in strike between the rocks north and south of the Great Lakes tectonic zone, unlike the structural boundaries at the Churchill front and the Circum-Ungava geosyncline. The transition from the English River gneiss superbelt to the Uchi greenstone-granite superbelt (as described by Thurston and Breaks, 1978; Schwerdtner and others, 1979; and Urquhart and West, 1979) may be more closely analogous to this part of the zone.

Riel discontinuities located at mid-crustal depths in the Superior Province by refraction experiments (Hall and Hajnal, 1969, 1973) and reflection experiments (Green and others, 1978, 1979; Green, 1981) are not readily apparent in the Minnesota data. The most prominent reflection zones in the middle and upper crust of this region have moderate dips, are laterally discontinuous, and have highly variable depths (two-way traveltimes between 2 and 8 sec). The refraction studies by Wright (1977) across the Quetico and Shebandowan superbelts also found no laterally extensive Riel discontinuity. Oliver (1978) argued that mid-crustal discontinuities such as the Riel have lost significance as the complexity and heterogeneity of the crust have been revealed by reflection profiles.

The refraction work done in other parts of the Superior Province (Table 2) has established that the Mohorovičić discontinuity is located at depths that correspond to those of the 13- to 15-sec reflections, the lowest on the sections. These reflections are laterally discontinuous and have moderate dips, predominantly to the north and west. Lower-crustal reflections, also complex and laterally discontinuous, were previously observed in the Wabigoon superbelt (Young and West, 1977) and in the Archean granite-greenstone terrane near Yellowknife (Clee and others, 1974).

There are other examples of Archean and early Proterozoic tectonic zones with significant thrust faulting and juxtaposition of high- and low-grade metamorphic rocks. The Limpopo belt of southern Africa is probably the best known of these and collision models have been proposed for it (Coward and Fairhead, 1980; Light, 1982). Berthelsen (1977) described such zones in the Precambrian rocks of Sweden and Norway and noted their similarity to the thrusted core of the Himalayas. The Proterozoic boundaries around the Superior Province have also been considered collision zones (Baragar and Scoates, 1981; Thomas and Gibb, 1982). The Archean-Proterozoic boundary in southern Wyoming is another excellent example. There, Proterozoic sediments on the margin of the Archean crust have been thrust northward onto the older craton (Houston and others, 1979) and the COCORP survey in the Laramie Range showed reflections with moderate southerly dips located within and at the surface of the underthrust older crust (Allmendinger and others, 1982). In the Wyoming case, both strike-slip and thrust faulting are present. This is probably also true in Minnesota. The seismic images of the thrust zones in Wyoming and Minnesota are also similar. The thrust zones of both appear as bands of variably dipping reflections, in a zone with many other similarly oriented events. In both Wyoming and Minnesota, there are also discontinuous dipping events in the deep parts of the crust in the zones of underthrusting, although they are at the limits of perception.

The present survey has demonstrated the ability of the seismic-reflection method to image features throughout the crust of this glacially obscured region, it has revealed part of a major Precambrian tectonic zone, and it has shown some of the seismic characteristics of both granite-greenstone and gneiss belts. There are several obvious targets for further reflection profiling in this region. These include:

Extension of the Survey to the South. From the potential-field maps, several major faults can be inferred, separating the Minnesota River Valley gneisses from the terrane traversed by line 3. Until the survey lines are extended all the way south to the Minnesota River Valley gneisses, or geochronological studies establish an older Archean age for the granulite and gneiss terrane on the southern half of line 3, we cannot be sure that the actual suture, if one exists, has been crossed.

A line parallel to line 3, located farther west, would cross the same important structural features as does line 3 and would permit determination of the strikes and true dips of these features and resolution of their character in a less complex and, therefore, less ambiguous setting. Some of the ambiguity in the interpretation of the present data is due to the interruption of the potential field anomalies near line 3; this would be avoided farther west.

Finally, there are other important structural problems of the typical greenstone-granite superbelts and metasedimentary-plutonic gneiss superbelts that can be addressed by reflection seismology. Extension of the profiling to the north would cross some of the more typical greenstone, metasedimentary-gneiss, and granitoid-batholith boundaries, providing a vital new perspective on the development of the Superior Province and a further test of the hypothesis that these superbelts were joined to one another by Archean collisions of continental or protocontinental crust.

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