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Geophysical Investigations of the Grenville Front in Ohio, USA

Don Sunwoo[1]*, William J. Hinze[2] and Jeong Woo Kim[3]

[1]*Petroleum and Marine Resource Division, Korea Institute of Geoscience & Mineral Resources, Daejeon 305-350, Korea*
[2]*Department of Earth & Atmospheric Sciences Purdue University West Lafayette, Indiana 47906*
[3]*Department of Geoinformation Engineering Sejong University, Seoul 143-747, Korea*

미국 오하이오주에 위치하는 그랜빌 프런트의 지구물리학적 연구

선우돈[1]* · William J. Hinze[2] · 김정우[3]

[1]한국지질자원연구원 석유해저자원연구부
[2]미국 퍼듀대학교 지구대기과학과, [3]세종대학교 지구정보공학과

미국 오하이오주에 있는 Grenville Front의 위치와 특성을 이해하기 위하여 중자력, 탄성파 및 지질자료를 이용한 지구물리학적 연구를 수행하였다. 탄성파 자료에 의하면 서부 오하이오에서의 기반암은 Grenville Front와 관계가 있는 동쪽으로 경사를 이루는 반사면으로 나타나고 이에 반하여 동부 오하이오에서는 서쪽으로 경사를 이루는 반사면이 나타난다. 중자력 자료 분석에 의하면 Grenville Front는 저중력 이상으로 그리고 Grenville Front Tectonic Zone은 고중력 및 고자력 이상으로 특징 지워진다. 탄성파 자료를 근거로 수행한 중자력 모델링 결과는 Grenville Front 위치에서 하부지각은 두껍고 Grenville Front Tectonic Zone은 주로 변성도가 높은 변성암으로 구성된다는 것을 제안한다. Grenville Front 위치에서 저중력 이상은 두터운 지각 두께 때문에, 반면에 고자력 이상은 변성도가 높은 변성암들의 존재 때문인 것으로 해석된다. Grenville Front 바로 동쪽의 오하이오 중앙부에서 나타나는 고중력 이상은 밀도가 높은 하부 및 중부 지각이 상부지각으로 트러스팅 (thrusting) 되었기 때문이다. 과거 연구에서는 이 고중력 이상이 선캄브리아대의 열개지역과 관계된다고 하였는데 이를 뒷받침할 만한 근거는 없다.

주요어 : Grenville Front, Grenville Front Tectonic Zone, 중자력장 분석

Seismic reflection profile analysis, potential field analysis, and potential field modeling using deep seismic reflection, gravity, magnetic, and geological data were performed to better understand the location and nature of the Grenville Front in Ohio, USA. The seismic reflection profile reveals a broad zone of east dipping basement reflectors associated with the Grenville Front in western Ohio and a broad region of west dipping reflectors cutting through the entire crust in eastern Ohio. Potential field analysis indicates that the Grenville Front is characterized by a gravity low, an associated gravity positive and a magnetic high. The results of the gravity and magnetic modeling using seismic data suggest that the lower crust is thickened at the interpreted position of the Grenville Front and high grade metamorphic rocks make up the Grenville Front Tectonic Zone (GFTZ). The gravity low at the Grenville Front is due to the thickened crust, while the magnetic high is due to high grade metamorphic rocks. The gravity high immediately east of the GFTZ in central Ohio is caused by thrusting of high density lower and middle crustal rocks into the upper crust. There is no compelling evidence that this gravity high is related to a Precambrian rift zone as has been suggested in previous studies.

Key words : Grenville Front, Grenville Front Tectonic Zone, potential field analysis

1. INTRODUCTION

For many years the nature of boundaries between Precambrian provinces has been a focus of interest in the U. S. midcontinent because of their importance in developing the evolutionary history of continents. One of the most significant of these boundaries is the Grenville Front, which marks the

*Corresponding author: swd@kigam.re.kr

junction of the Archean and older Proterozoic terranes with the Middle Proterozoic Grenville Orogen.

The Grenville Front is a metamorphic boundary where it is exposed in the Canadian Shield. It represents the western margin of the Grenville orogen. The rocks in the east of the Grenville Front are younger and more highly metamorphosed than the rocks to the west (bass, 1960). Though considerable progress has been made in increasing our knowledge of the nature and evolution of the Grenville Province and its western margin, the Grenville Front, thick Phanerozoic sedimentary rock cover of the midcontinent limits our understanding of the geology of the Grenville Province and its associated boundary.

It is known only from sparse and widely distributed outcrops and drillhole samples that penetrated only a few meters into the Precambrian basement. Consequently, scattered basement drill-

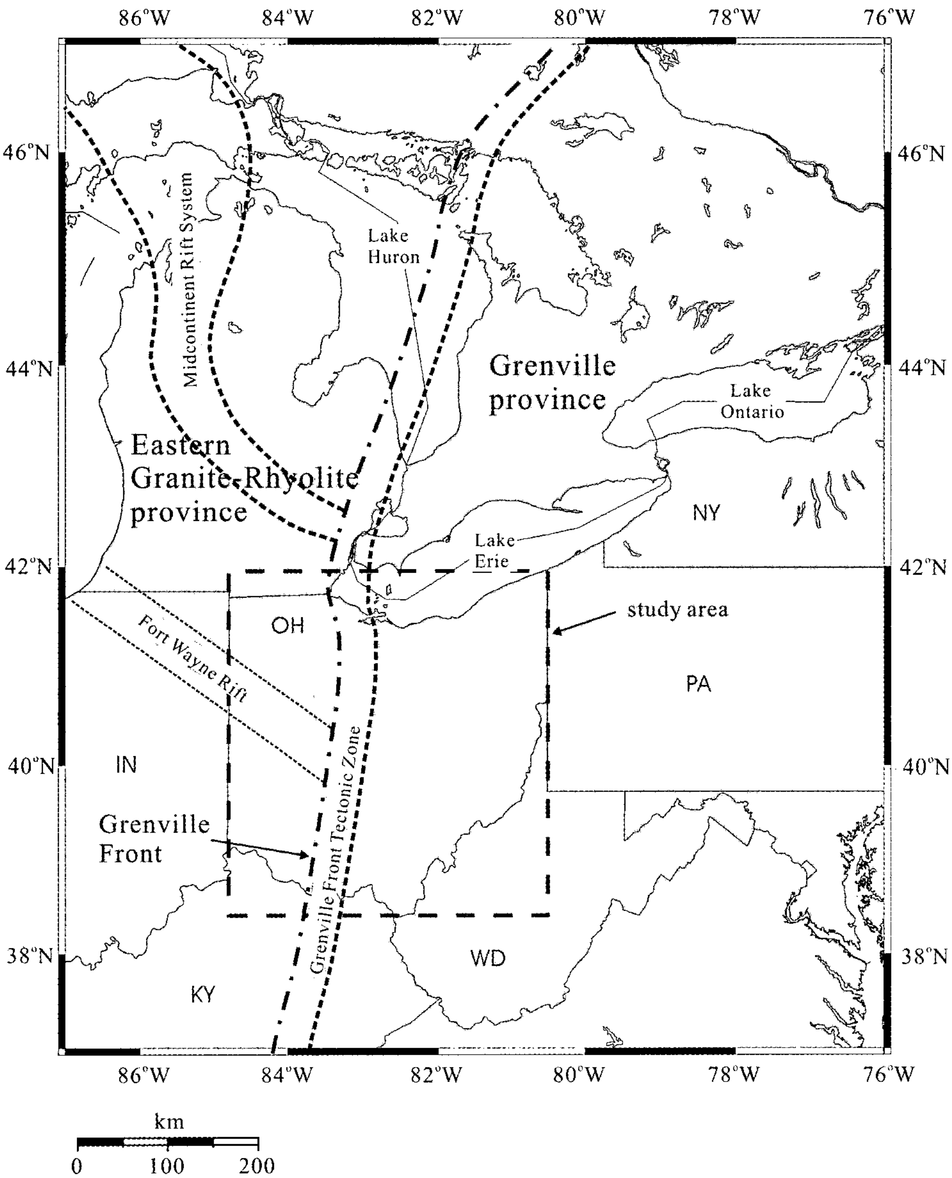

Fig. 1. Generalized tectonic map of Ohio and adjacent areas. Inferred rifting involves features mainly of the lower crust and Keweenawan age. OH = Ohio; NY = New York; PA = Pennsylvania; WD = West Virginia; KY = Kentucky; IN = Indiana.

hole samples and outcrops provide only limited information on the Grenville Province and the Grenville Front in the midcontinent of the United States. This has encouraged the use of geophysical data, particularly Bouguer gravity anomaly and total intensity magnetic anomaly, to study the Grenville Province and the associated front in the eastern craton.

The purpose of this study is to investigate the potential-field anomalies of the Grenville Province in Ohio, utilizing geological information obtained in the area and seismic reflection data. Special emphasis is placed on studying the location and nature of the Grenville Front and the subsurface structure in Ohio.

2. TECTONIC ELEMENTS AND GEOLOGIC SETTING

The basement of Ohio can be separated into two Precambrian provinces, Grenville and Eastern Granite-Rhyolite provinces (Bass, 1960; Keller *et al.*, 1983; Lucius and von Frese, 1988) (Fig. 1). The Grenville province is younger structural province and the metamorphosed rocks in the province were presumably formed as the result of the Grenville orogeny of 1.1 Ga due to a Late Precambrian plate collision (Hoffman, 1989; Hauser, 1993). The Granite-Rhyolite Province (EGRP) is characterized by unmetamorphosed felsic and intermediate volcanics and epizonal granite rocks of anorogenic origin. The rocks are generally between 1.2 and 1.5 Ga old on the basis of Rb-Sr and K-Ar age dating studies (Bell and Blenkinsop, 1980). Rocks of intermediate composition, sedimentary rocks, and metamorphic rocks are rare. The presence of widespread silicic rocks and the paucity of basaltic rocks associated with the high-silica extrusive rocks and plutons suggest that the province was produced during a period of crustal extension and melting of crust (Van Schmus *et al.*, 1987).

The Grenville Front separates the Eastern Granite-Rhyolite Province from the the higher metamorphic grade Grenville Province to the east. The Grenville Front represents the westernmost extent of Grenville deformation even though the exact tectonic nature of the front is uncertain (Easton, 1986).

The Grenville Front Tectonic Zone (GFTZ) is a belt which ranges from less than 20 km to more than 200 km in width along the northwest margin of the Grenville Province (Wynne-Edwards, 1972; Davidson, 1986). This tectonic zone, consisting of layered quartzo-feldspathic gneisses with well developed northeast-trending, southeast-dipping foliation and many parallel belts of cataclasis and mylonitization, is characterized by anomalous K-Ar and Rb-Sr apparent ages as low as 800-1,000 Ma resulting from later thermal, tectonic, or burial effects (Lidiak *et al.*, 1966).

Two tectonic units are also noticeable: the Midcontinent Rift System and the Fort Wayne Rift zone. The Midcontinent Rift System consisting of mafic extrusive and intrusive rocks and sedimentary clastic rocks, cuts across several Precambrian basement terranes of different age, structure, and composition in the craton composed of Archean and Proterozoic rocks. The rift originated at approximately the same time as the Grenville Orogeny that deformed a major part of the Canadian Shield in the east of the rift. In contrast, the Fort Wayne Rift zone is interpreted as a Keweenawan rift eunning subparallel to the eastern arm of the Midcontinent Rift System (Hinze *et al.*, 1975).

3. DATA SET

Four main types of data have been used in this study; gravity, magnetic, seismic reflection, and basement drillhole lithologic data. The gravity data are complete Bouguer gravity anomaly values gridded with a 2 km interval.

The magnetic data with the 1 km grid ionterval was obtained from the U.S. Geological Survey on open-file computer tape and regridded at 2 km intervals. To minimize spatial distortion of anomalies relative to geologic sources with negligible moments of remanent magnetization, the data were reduced to the north geomagnetic pola, using a wavenumber domain filter for a statewide average inclination of 70° and west declination of 4°.

Two seismic profiles (OH-1 and OH-2) were acquired from COCORP (Consortium for Continental Reflection Profiling), an organization of academic, government, and industrial geologists based at Cornell University. These two profiles together make up a nearly continuous east-west profile across Ohio (Fig. 2).

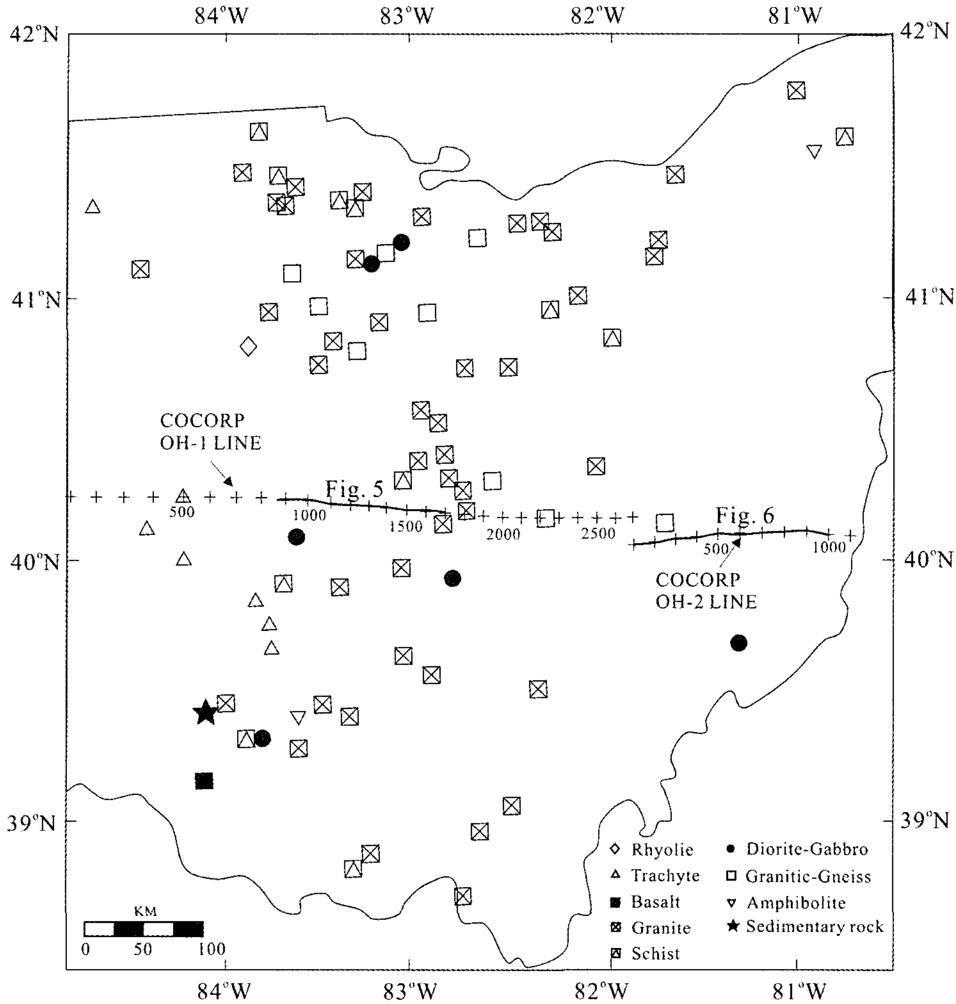

Fig. 2. Locations of the basement wells and COCORP Ohio seismic lines. Numbers on COCORP seismic lines indicate shot point (SP) numbers.

The lithologic data were obtained from a basement drillhole sample data set that penetrated into the Precambrian surface in Ohio (Fig. 2). In most cases, penetration into the Precambrian was less than 30 m, and only two of the wells penetrated as much as 300 m. These data provide valuable information for geophysical interpretation and basement evolution analysis, although suffering limitations due to the penetration depth to the basement, poor distribution, and concerns about the representative nature of the samples.

4. POTENTIAL-FIELD ANALYSIS

The study area covers two basement geologic provinces, the Eastern Granite-Rhyolite Province (EGRP) and the Grenville Province. The contact between two provinces in Ohio is particularly well represented on the magnetic anomaly map (Fig. 3). On the Bouguer gravity anomaly map it is more subtly delineated by the truncation of anomaly trends and the decreased anomaly gradients over the EGRP (Fig. 4). In Ohio, a number of the sharp and circular-shaped magnetic signatures correlative with positive gravity signatures can be observed. These anomalies were interpreted to be associated with mafic intrusive and extrusive rocks and medium grade metamorphic rocks, especially amphibolites (Lucius and Von Frese, 1988).

The EGRP shows no dominated magnetic

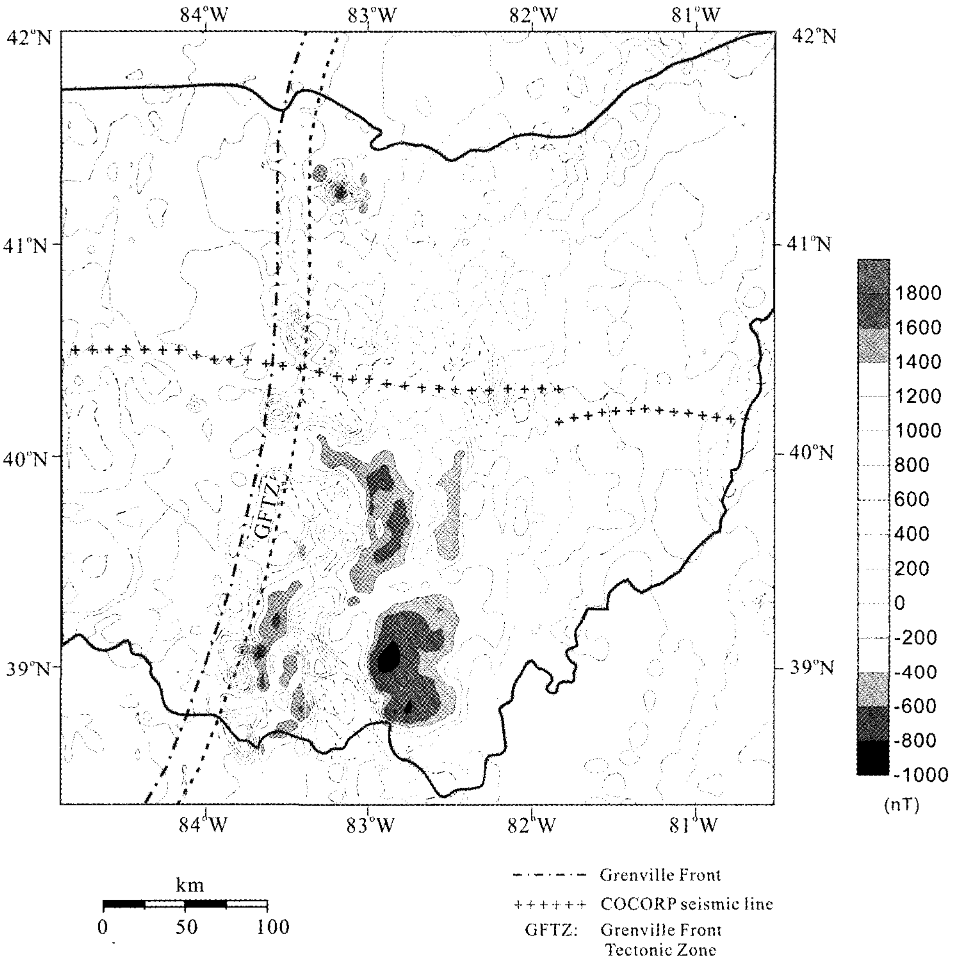

Fig. 3. Total intensity magnetic anomaly map of Ohio area with the location of COCORP Ohio seismic lines. Contour interval is in nT.

anomaly orientation within the study area, but it is characterized by long-wavelength and low amplitude anomalies. Northwest trending anomalies, which are characterized by a series of strong positive gravity highs in association with a correlative trend of weakly defined magnetic anomalies, are prominent in northwestern Ohio. It is suggested on the basis of the potential-field modeling that the anomalies are associated with the Fort Wayne rift complex which is an inferred Keweenawan rift zone (Hinze *et al.*, 1975). The anomalies are terminated by the prodominantly north-trending anomalies of the GFTZ.

The magnetic anomalies in the Grenville Province represent high-wavenumber, large-amplitude circular-shaped anomalies, while the Bouguer gravity anomalies generally show long-wavelengths than the magnetic anomalies.

In Ohio, the GFTZ is considered to be 20-40 km wide based on geophysical anomaly patterns. Including a variety of metasedimentary rocks, granitoid gneiss, amphibolite, granite, and gabbro, the GFTZ is characterized by northerly trending gravity and magnetic anomalies that parallel to the Grenville Front. The front is marked by a series of relatively narrow and complex north-trending magnetic highs and lows and broader gravity highs and lows.

The Grenville Province in the northern Ohio is generally characterized by magnetic and gravity lows having a broad northeast trend. However, a circular-shaped and high amplitude magnetic

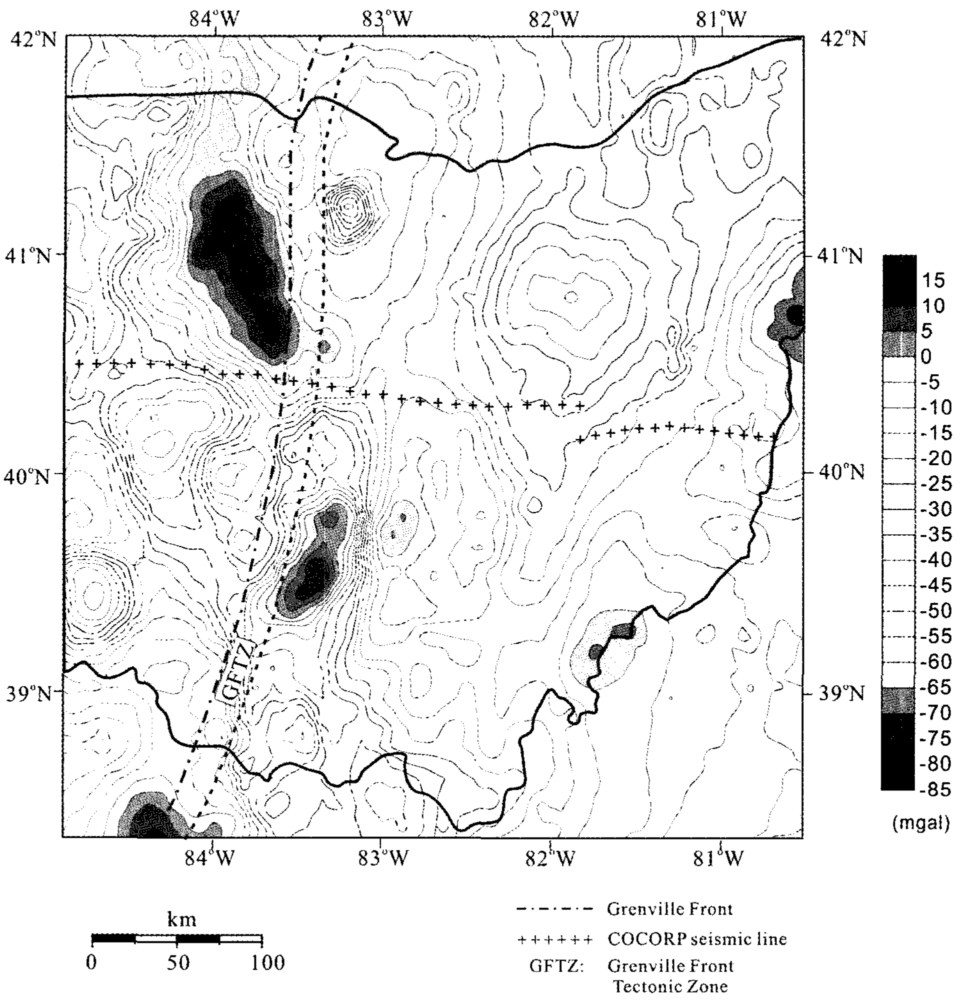

Fig. 4. Bouguer gravity anomaly map of Ohio area with the location of COCORP Ohio seismic lines. Contour interval is in mgal.

anomalies, and gravity highs distributed in the northern Ohio show a diameter of approximately 28 km.

The northern part of the Grenville province in the eastern Ohio is magnetically more subdued than the southern part. In addition, the western half of the southern part shows gravity and magnetic maxima, while the eastern half is represented by broad gravity and magnetic minima. the central Ohio is characterized by a complex of curvilinear high-amplitude magnetic highs and lesser magnetic lows. No distinct trend can be observed in the area. In southern Ohio, a linear gravity high flanked by a linear low is prominent. The gravity high which correlates regionally with an aeromagnetic high is considered to be part of a series of linear positive gravity anomalies associated with mafic igneous rocks extending to lower crustal depths.

5. SEISMIC LINE ANALYSIS

The Consortium for Continental Reflection Profiling (COCORP) conducted a seismic reflection survey along an east-west line in central Ohio that traverses the Grenville Front. The seismic reflection line contains three remarkable elements. They are an extensive sequence of Precambrian layered rocks beneath western Ohio, a broad zone of east-dipping basement reflectors associated with the Grenville Front beneath the western Ohio (Fig. 5), and a wide region of west-dipping reflectors pen-

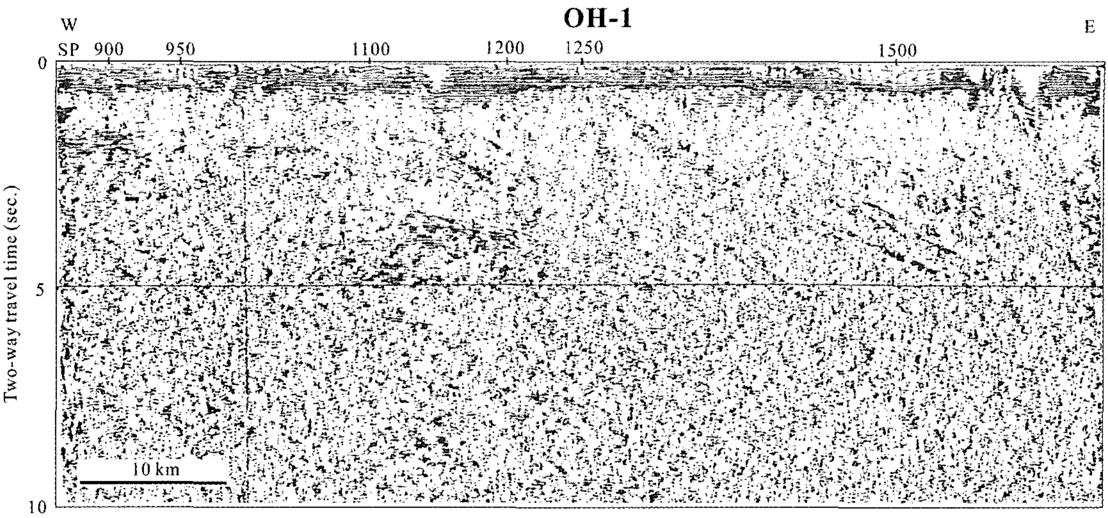

Fig. 5.COCORP OH-1 seismic image of the east-dipping reflectors associated with the Grenville Front Tectonic Zone. See Fig. 2 for location.

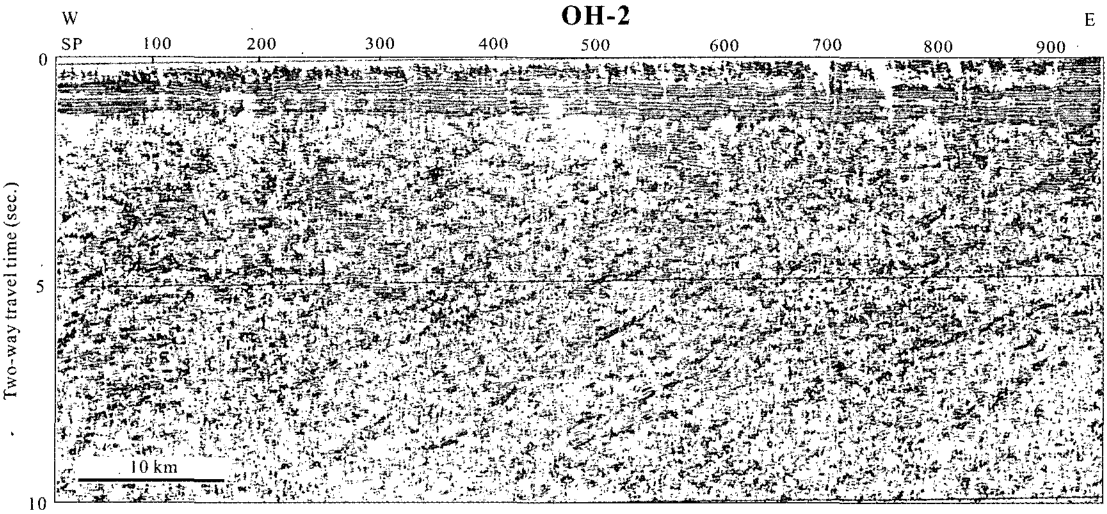

Fig. 6.COCORP OH-2 seismic image of the west-dipping reflectors in the eastern Ohio. See Fig. 2 for location.

etrating most of the crust beneath eastern Ohio (Fig. 6).

The seismic reflection line has provided an image of widespread layered rocks beneath the Phanerozoic sedimentary rocks of westernmost Ohio, which are more or less continuous and relatively flat reflectors. The layered rocks are clearly visible beneath the Phanerozoic sedimentary rocks at two-way travel time (TWT) of 4 to 5 second at Shot Point (SP) 900-1200 on the OH-1. It implies that the strata are several times thicker than the Phanerozoic sedimentary rocks.

The outstanding feature in the seismic section is a remarkable zone of east-dipping reflections between SP 1200 and SP 1600 of OH-1 line, which coincides with the Grenville Front Tectonic Zone (GFTZ) as interpreted from drillhole data and gravity and magnetic anomaly patterns. Its western boundary truncating a band of strong subhorizontal reflections of Eastern Granite-Rhyolite Province to the west of the GFTZ corresponds closely with the position of the Grenville Front predicted from the lithologic and geopotential data. The east-dipping reflections at the GFTZ extend from the base of the Phanerozoic sedimentary rocks to midcrustal depths, possibly to the lower crust. These dipping reflections are interpreted to result from ductily deformed lower-crustal zones during collision of a western Grenville terrane with the North American craton (Pratt *et al.*, 1989). Thrusted to upper crustal depth, strong, east-dipping reflections are recorded to 5 sec, and weaker reflections are traced to at least 10 sec, suggesting that the wide belt of intense ductile strain penetrates to mid to lower crust levels.

Another remarkable feature in the seismic secton is a zone characterized by strong, west-dipping reflections extending from mid to deep crustal depths beneath eastern Ohio. Strong, west-dipping reflections are recorded to at least 10 sec, suggesting that they penetrate the entire crust. These west-dipping reflections are considered to be a thrust zone in the eastern Ohio. The west-dipping reflections are more intense and the apparent dip of the reflections is greater than that of the easterly dipping reflections at the GFTZ. These reflectors are not very clearly seen above 3 to 4 sec TWT, possibly because of multiples of the primary reflections associated with the Phanerozoic sedimentary rocks.

It is difficult to determine the depth to the Moho because it is not defined by single reflection or reflection zone in this section. The lower part of the section below 10 sec consists of discontinuous, nonreflective, and curvilinear bands of reflections that display a gradational change of reflective energy at the approximate depth of the Moho. The transition to mantle probably occurs at approximately more than 10 sec. beneath the Eastern Granite-Rhyolite Province to the west of the GFTZ and beneath easternmost Ohio to the east of the zone of west-dipping reflections.

6. PROFILE MODELING

Gravity and magnetic anomaly profiles were modeled along the Ohio COCORP line. The results of gravity modeling of the Ohio seismic reflection line are shown in Fig. 7. Conversion from travel time on the seismic section to the depth used for the potential-field models was based on the velocity models deduced from a major long-range seismic refraction and reflection experiments across the Grenville Front in Canada (Mereu *et al.*, 1986). The depth to the basement is an approximately 1000 meter on the western end of the profile and thickens to 3000 meters on the eastern end of the profile.

The crust was divided into three layers to approximate an increase in density with depth: upper, middle and lower crustal layers. On the seismic section the upper crustal layer corresponds to the area extending from immediately beneath the Phanerozoic section to the depth of approximately 3.5 sec, possibly 4 sec, where continuous and relatively flat reflectors appear. The middle crustal layer extends from the bottom of the upper crustal layer to the depth of approximately 7 sec. The middle crustal layer is characterized by a complex geometry with dipping, subhorizontal and diffracted reflectors. The lower crustal layer corresponds to the area beneath the middle crustal layer and transition to the Moho.

Basement drillhole samples show that the Grenville Province occupied in the two-thirds of the eastern Ohio consists of medium-grade metamorphic rocks, such as schist, amphibolite, and gneiss, while the western portion of Ohio comprising the Eastern Granite-Rhyolite Province consist of intrusive and extrusive igneous rocks. Within the upper crustal layer, relatively high densities are shown in the western portions of the modeled profile, which correspond to the Granite-Rhyolite Province. Extending from the 33 to 94 km markers along the profile the bodies of high densities are related to a shallow source of less than 5 km depth. The bodies are associated with extrusive and intrusive igneous rocks, probably related to minor extension along the Keweenawan rift system. Another intrusive body appears to exist at between 202 km and 234 km markers. On the Bouguer gravity anomaly map the anomaly is encompassed by lower gravity anomalies. The source of the intrusive body, however, is speculative due to the sparse basement drillhole samples.

The western portion of the profile is characterized by a east-dipping zone, while the eastern portion of the profile are marked by a west-dipping zones. The dips of these reflectors were used to constrain the location of the sources used in the

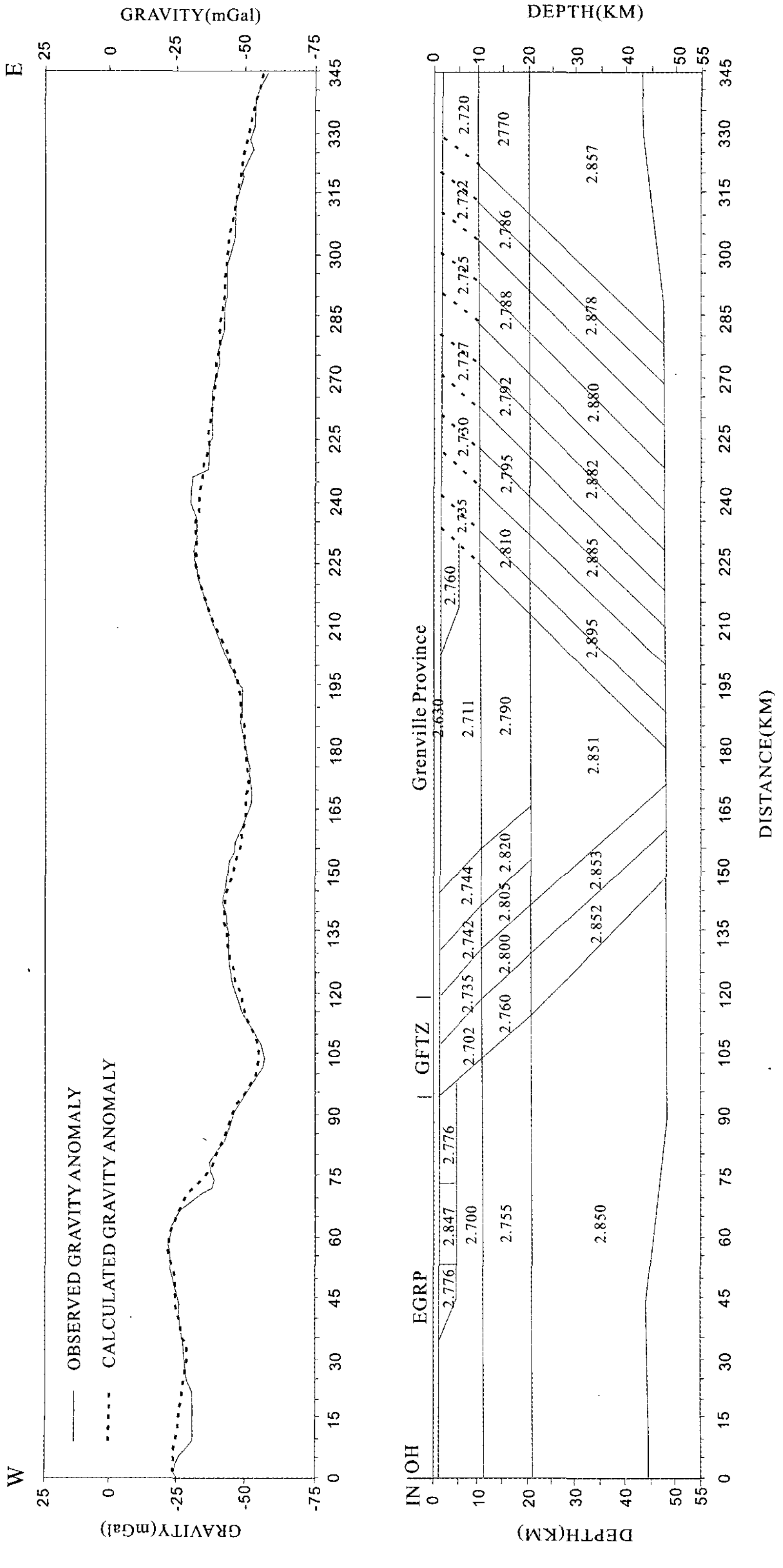

Fig. 7. Two-dimensional gravity model for COCORP Ohio seismic line with body coordinates-density in g/cc. IN=Indiana; OH=Ohio; EGRP=Eastern Granite-Rhyolite Province; GFTZ=Grenville Front Tectonic Zone.

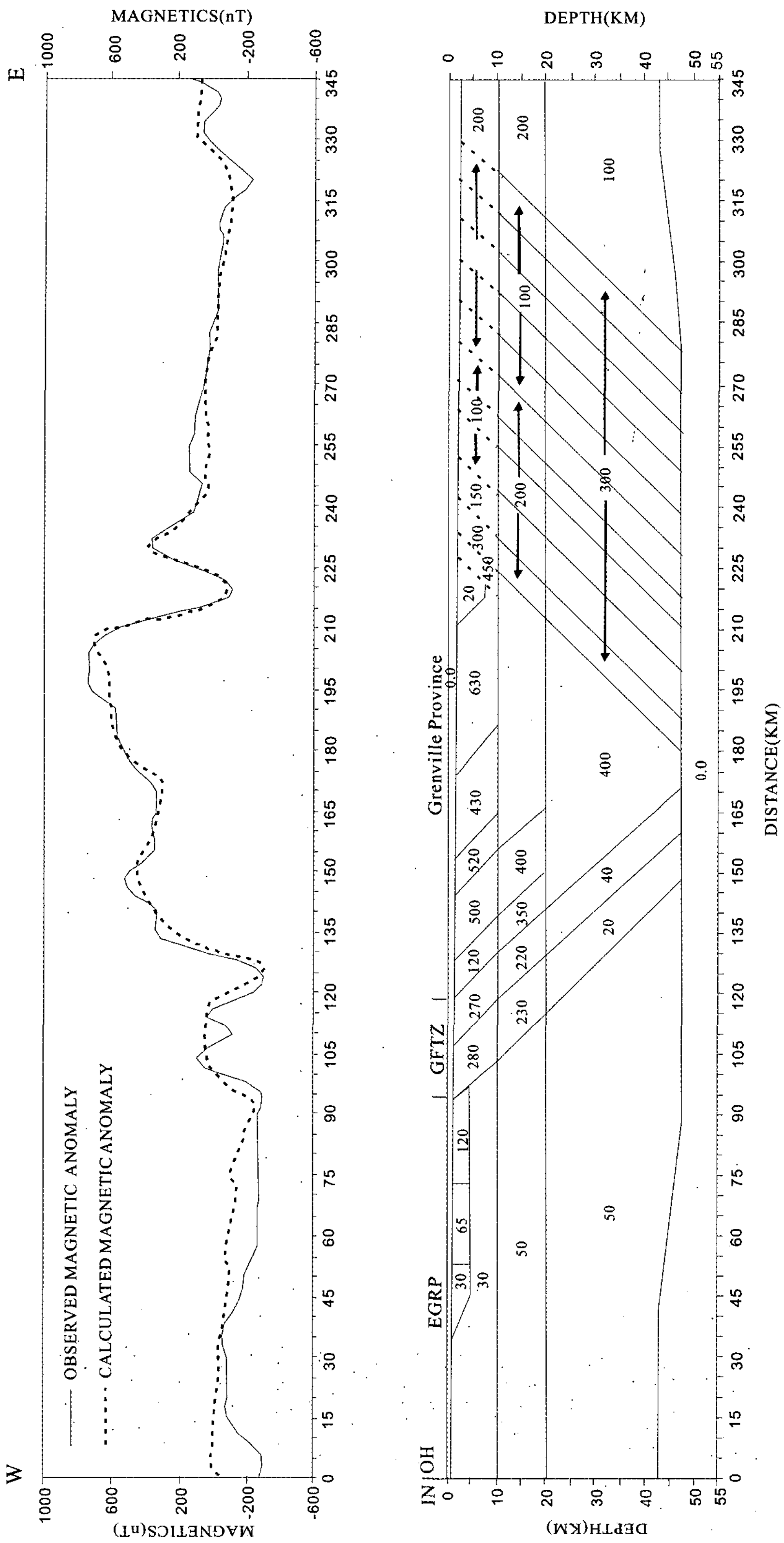

Fig. 8. Two-dimensional magnetic model for COCORP Ohio seismic line with body coordinates-magnetic susceptibility in emu/cm^3*10^{-5}. IN=Indiana; OH=Ohio; EGRP=Eastern Granite-Rhyolite Province; GFTZ=Grenville Front Tectonic Zone.

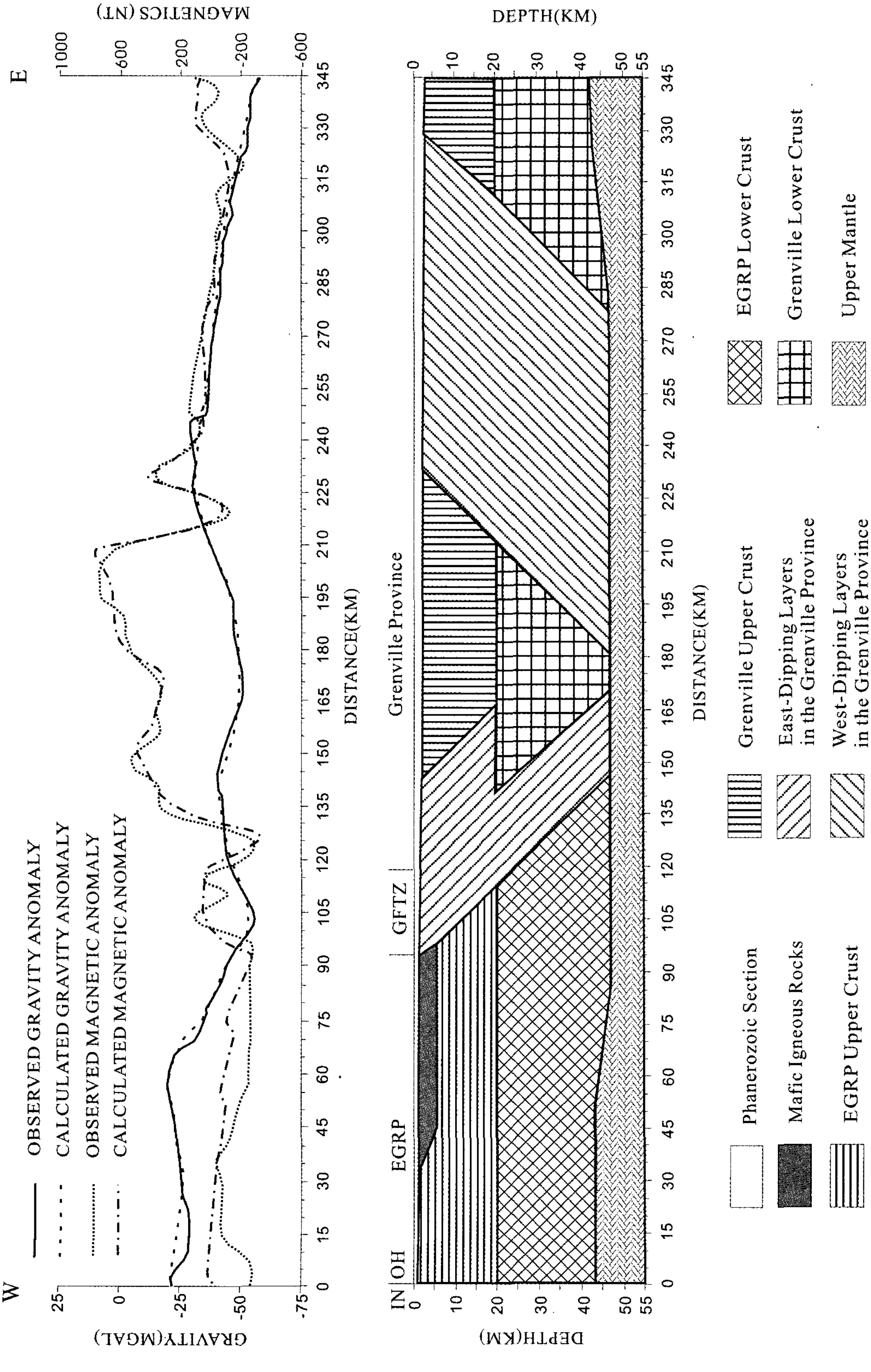

Fig. 9. Geologic model of COCORP Ohio seismic line with calculated and observed Bouguer gravity and total intensity magnetic anomalies. IN=Indiana; OH=Ohio; EGRP=Eastern Granite-Rhyolite Province; GFTZ=Grenville Front Tectonic Zone.

gravity and magnetic modeling. The results of the modeling are generally compatible with the interpreted dips. The dips of the east-dipping reflectors in the upper crust tend to decrease with distance from the Grenville Front. At the 94 km marker, the surface projection of the westernmost east-dipping zone corresponds with the position of the Grenville Front. Between the 94 and 119 km markers, the east-dipping zone is associated with the Grenville Front Tectonic Zone. At the western end of the model the depth to Moho in the Eastern Granite-Rhyolite Province is interpreted to be 43 km, increasing in depth toward the GFTZ. Beneath the denser rocks of the Grenville Front the depth to Moho is 47.5 km. This thickened crust at the front may have resulted from progressive stacking of microterranes against the older craton to the west during the initial stages of the Grenville Orogeny, depressing the rocks along the margin to lower crustal depth, or it may have been caused by ductile thrusting during the late stages of the Grenville Orogeny. The gravity anomaly at the Grenville Front is a relative minimum, although the dipping layers of the GFTZ show relatively higher densities due to higher metamorphic grade rocks. The source of the gravity low is caused by the thickened crust at the front and the thickened crust generally offsets the effects of denser rocks at the front.

It is also considered that the bodies between the 119 km and 143 km markers are not related to a rifting event in the Grenville Province, although some workers (Lyons, 1970; Halls, 1978) have proposed that the gravity high in western Ohio is associated with the possible southerly continuation of the eastern arm of the Midcontinent Rift System (MCR). The result of the gravity modeling for the Ohio seismic line provide no evidence for a rift-type structure in the area. No rift-type structure is observed on the COCORP Ohio reflection seismic section.

The gravity model shows that the crustal layers of the Grenville Province are denser than those of the EGRP, and the depth to Moho has increased to approximately 47.5 km. The eastern Ohio is characterized by a series of west-dipping layers. As with the east-dipping layers at the Grenville Front, the crust beneath the west-dipping layers is thickened to 47.5 km.

The results of magnetic modeling of the Ohio seismic reflection line are shown in fig. 8. The body coordinates used for the gravity model were retained as much as possible in the magnetic model. Geologically reasonable magnetization contrasts were used for crustal layers, but large magnetization contrasts were used for several magnetic anomalies which are high amplitude, short-wavelength. In the modeled profile, the minor extension of the Keweenawan rift system between the 33 km and 94 km markers is defined by relatively nonmagnetic bodies of high density material in the upper crust. The magnetic anomalies increase across the transition zone between the EGRP and the Grenville Province. The GFTZ shows relatively high magnetization contrasts due to higher grade metamorphic rocks. Between the 119 km and 234 km markers, the area is characterized by several magnetic peaks. Based on the basement drillhole samples the peaks are related to granite, gabbro, schist, and granite gneiss. In particular, the magnetic high occurring between approximately the 135 km and 150 km marker is probably related to the thrusting of high magnetization middle and lower crustal rocks into the upper crust. The gravity and magnetic models along Ohio seismic reflection line are summarized in a geologic model on the basis of structural geologic characteristics. The geologic model is shown in fig. 9.

7. CONCLUSIONS

Previous study of the Grenville Front in Ohio was based on the sparse and widely distributed basement drillhole samples and ambiguous geopotential field which provide only limited information regarding structure, lithology and evolutionary history of the Grenville Front. Interpretation of Ohio COCORP seismic reflection data has provided valuable information on the Grenville Front. An integrated geological and geophysical study has been useful in identifying and interpreting the Grenville Front beneath thick sequences of the Phanerozoic sedimentary rocks in Ohio. Integration of potential-field modeling with COCORP Ohio seismic reflection data successfully produces a geologic model for the Ohio area.

The results of gravity and magnetic modeling suggest that east of the Eastern Granite-Rhyolite Province, a series of east-dipping layers appears to penetrate to lower crustal depths. This zone of east-dipping layers may be caused by the collision of a western Grenville terrane with pre-existing North American craton. The Grenville Front which marks the western boundary of the zone of east-dipping layers is recognized by distinctive gravity and magnetic anomalies. The Grenville Front is characterized by a gravity low, an associated gravity positive and a magnetic high. Gravity and magnetic modeling shows that the crust is thickened along the Grenville Front. This thickening is responsible for the gravity low at the Grenville Front. The gravity and magnetic high over the Grenville Front is due to high-grade metamorphic rocks thrust to upper crustal levels along the front during the Grenville Orogeny. There is no compelling evidence that this positive anomaly is related to a Precambrian rift zone as has been suggested in previous studies. The gravity and magnetic modeling also show an approximately 85 km wide extensive west-dipping layers which penetrates to lower crustal depths beneath eastern Ohio. The west-dipping layers are interpreted to be collision-related ductile shear zones.

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