GLIMPCE Seismic Experiments

Long-Offset Recordings

PAGE 841, 852-853

GLIMPCE Seismic Refraction Working Group

The Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) was initiated in late 1985 by Canadian and U.S. scientists who share a common interest in the geology of the midcontinent. Its mandate is to promote and coordinate geoscientific research in the general area of the Great Lakes. This region contains some of North America's most interesting geological structures and offers a rare opportunity to study a large part of the continental interior using relatively inexpensive marine seismic techniques. Targets addressed by the first phase of GLIMPCE studies include the middle Proterozoic Midcontinent rift system centered on Lake Superior, the early Proterozoic Penokean orogen and Niagara suture south of Lake Superior extending through Lake Michigan, and the early Proterozoic Huronian continental margin and middle Proterozoic Grenville front in the vicinity of Lake Huron (Figure 1).

Since its formation, GLIMPCE has collected 1350 km of multichannel seismic reflection data along eight long profiles in lakes Superior, Michigan and Huron, flown new aeromagnetic surveys over lakes Superior and Huron, and encouraged a wide range of geological, isotopic and other geophysical studies. During the multichannel reflection survey, which was conducted via a contract to industry, high-resolution long-offset reflection/refraction data were recorded by seismographs deployed onshore and on the lake bottom by various government and university teams. With such coincident data, structures imaged on seismic reflection sections may be related to P- and S-wave velocity variations allowing for refinement of models required to explain both data sets.

In this report we show typical examples of the long-offset data and summarize the results of a recent GLIMPCE workshop held at the University of Western Ontario, London, Ontario. Although long-offset data were collected along all GLIMPCE reflection profiles, we will concentrate on the data from north-south line A across central Lake Superior (Figure 1).

Geophysical Background

Lake Superior lies at the northern end of the Midcontinent gravity anomaly and related gravity anomalies that extend more than 2000 km from Kansas northeast through Iowa, Minnesota and Wisconsin, before turning southeast through Michigan. The origin of these gravity anomalies and associated high-amplitude magnetic anomalies has been the object of studies for many years [*Wold and Hinze*, 1982; *Van Schmus and Hinze*, 1985]. Surface exposures around Lake Superior and drill data throughout the region indicate that their source is commonly a thick sequence of basaltic lava with minor intercalated sedimentary rock. Based on information from a variety of studies, it is now generally agreed that the potential field anomalies delineate a failed Precambrian rift of Keweenawan age (1100 Ma), widely known as the Midcontinent rift system (MRS).

Early seismic refraction surveys conducted in this region provided only limited resolution of the velocity structure (see review by *Halls* [1982]). Very long-offset data collected during the 1963 Lake Superior experiment [*Steinhart and Smith*, 1966] detected high mid-crustal velocities (6.6–6.7 km/s) and an anomalously thick crust (>50 km) beneath central Lake Superior, but structural relationships between the MRS and the thick crust were poorly defined. Higher-resolution refraction profiles recorded in the late 1960s [*Luetgert and Meyer*, 1982] indicated the presence of 10-km-deep basinlike structures underlain by material with velocities up to 6.8 km/s, interpreted to represent "mantle-derived" intrusions. The size and detailed structure of the high-velocity material were not determined by these older data sets.

In the early 1980s, COCORP acquired seismic reflection data across the western and eastern limbs of the MRS. An asymmetric rift basin extending to about 8 km (3-s travel time) depth was imaged in Kansas [*Serpa et al.*, 1984], and a relatively symmetric basin extending to 18 km (6 s) was outlined in central Michigan [*Zhu and Brown*, 1986].

GLIMPCE Near-Vertical Incidence Reflection Survey

The new GLIMPCE multichannel seismic reflection data expand our knowledge of the MRS beneath the waters of Lake Superior [*Behrendt et al.*, 1988; *Cannon et al.*, 1989; *Green et al.*, 1989]. They show that the total sedimentary and volcanic fill in rift basins under Lake Superior is up to 36 km (12 s) thick and is therefore much greater than anticipated on the basis of earlier studies of the MRS and studies of other intracratonic rifts. At the southern end of line A a strong band of reflections at 12 s is interpreted to represent the Moho, in agreement with Moho depths of about 35 km deduced from the 1960s refraction surveys [*Halls*, 1982]. Beneath north and central Lake Superior, however, there are no clear reflections that can be associated with the Moho, suggesting that the crust-mantle boundary was greatly disrupted during rifting.

GLIMPCE Long-Offset Experiment

Locations of seismographs deployed to record long-offset data are shown by dots (land) and stars (lake bottom) in Figure 1. A great variety of recording instruments was used, ranging from stand-alone single and three-component (X, Y, Z) FM-analogue and digital systems (land and marine), to 24-, 48- and 96-channel digital systems. The common energy source for the near-vertical incidence reflection and long-offset reflection/refraction surveys was an 80-m-wide tuned airgun array with a total capacity of 127 L and dominant frequency range of about 6–57 Hz. Depending on line location, the airgun was fired at 50-, 62.5- or 300-m intervals. Shooting and recording instruments operated on absolute time.

For line A a total of 31 sites was occupied, five of which were on the lake bottom. Good quality data recorded along this initial "test" line prompted an expansion of the on-land program to include long-offset recording of all seismic reflection lines. Both in-line and fan data were collected. A total of 23,196 shots was fired along the eight lines, and 137 stations were occupied at 86 locations, yielding a volume of long-offset data that is probably unprecedented in North America.

After the fieldwork, each institute was faced with the task of recovering and editing the data. The original field records were stored on diskettes, tape cartridges, and tapes according to each instrument's specifications and institute's format. A common format was needed for data exchange. After some discussion the SEG-Y format was selected and modified to accommodate the needs of long-offset data. One significant advantage of the SEG-Y format is that existing seismic reflection software packages can be used for basic processing and plotting. Seismic sections constructed from data recorded at three stations along line A are shown in Figure 2. The amplitude of first arrivals, which can be identified to distances exceeding 220 km at some sites, changes considerably as a function of offset. Moreover, the wavelet shape and efficiency of P- to S-wave conversion varies greatly along each line and from line-to-line. These variations are probably due to changes in water depth and differences in character and thickness of the uppermost sedimentary layers. There are numerous wide-angle reflections from the lower crust and crust-mantle transition zone.

Cover. Shaded relief map of the U.S. This 1989 map of the conterminous 48 states was produced by image-processing 12 million digitized elevations. The original version was made in 1988 by Gail P. Thelin, U.S. Geological Survey, Ames Research Center, Moffett Field, Calif., and Richard J. Pike, USGS, Menlo Park, Calif. Scale is about 1:19,000,000.

The surface-geometric character of 82 U.S. physiographic sections also was abstracted from the digital elevations, thus providing the first criteria suitable for comparing these areas quantitatively, that is, to assess topographic homogeneity between and within subdivisions.

Image courtesy of the U.S. Geological Survey. See "Shaded-relief Map of U.S. Topography from Digital Elevations" by Pike and Thelin.

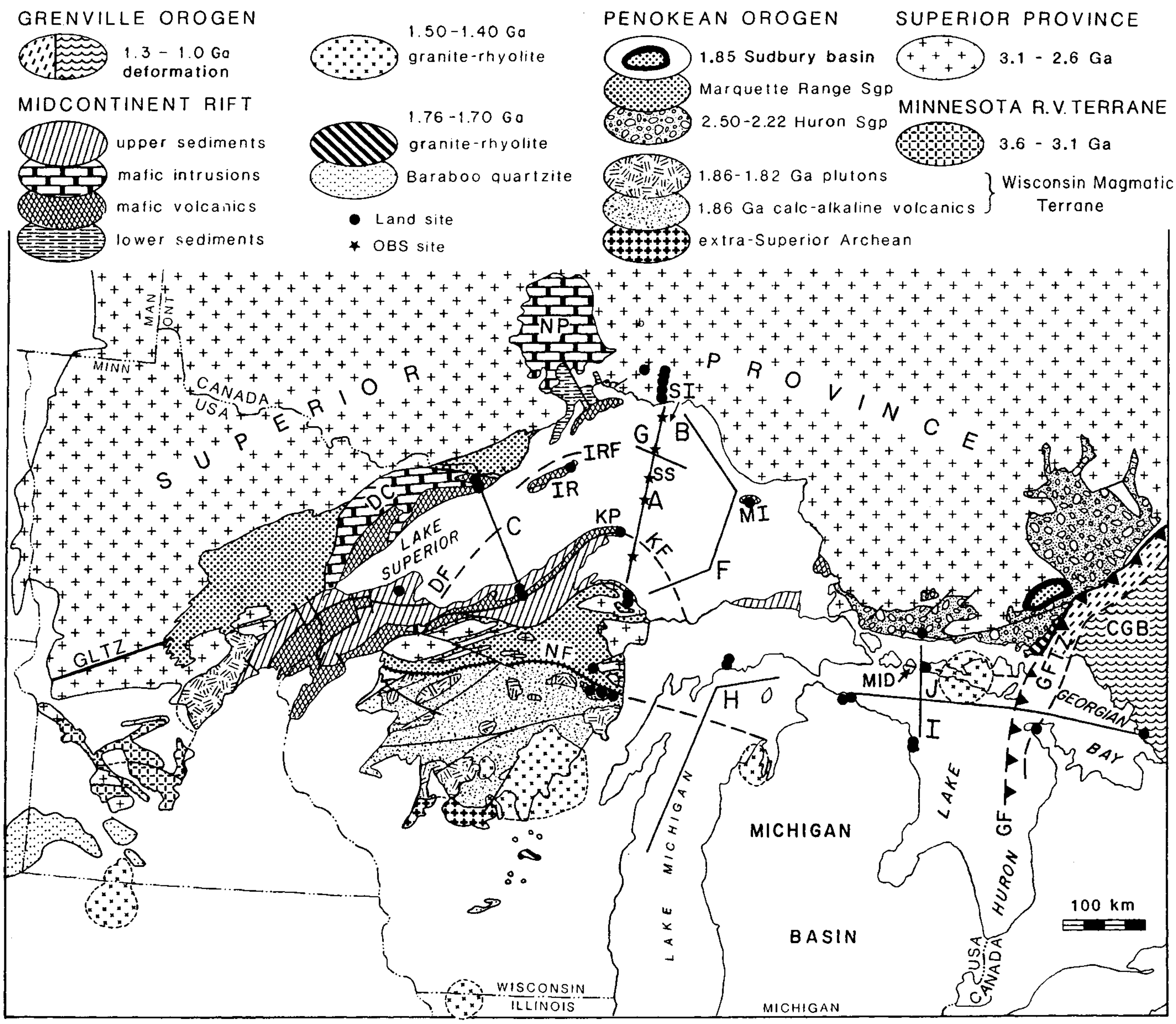

Fig. 1. Location map of the GLIMPCE 1986 seismic survey on geological background modified from *Hoffman* [1988]. CGB, Central Gneiss belt; DC, Duluth complex; DF, Douglas fault; GF, Grenville front; GFTZ, Grenville front tectonic zone; GLTZ, Great Lakes tectonic zone; IR, Isle Royale; IRF, Isle Royale fault; KF, Keweenaw fault; KP, Keweenaw Peninsula; MI, Michipicoten Island; MID, Manitoulin Island discontinuity; NF, Niagara fault; NP, Nipigon plate; Sgp, Supergroup; SI, Slate Islands; SS, Superior Shoals; A-C, E-J, seismic reflection lines.

University of Western Ontario Workshop

The current status of the long-offset data processing and modeling was discussed at a recent GLIMPCE workshop held at the University of Western Ontario. Figure 3 outlines the wide range of processing and interpretation techniques that have been employed by GLIMPCE participants. Deconvolution and frequency filters have been used to reduce the effects of water bottom reverberations and improve timing resolution. A number of processing teams have taken advantage of the data's unusually high spatial resolution by applying various coherency techniques (nth root stacking, beam steering, velocity filtering in time-space and frequency-wavenumber domains, semblance-based coherency filtering) to common receiver and common shot gathers. Coherency-filtered sections have allowed weak (signal/noise <1) first and later arrivals to be detected and better identified. Several teams have stacked normal moveout corrected in-line and fan data to produce multifold images that can be compared directly to conventional seismic reflection sections. One promising avenue of research has involved a refinement of *Milkereit's* [1987] slowness-weighted diffraction stack algorithm to produce migrated images from wide-angle reflections. Information on P- to S-wave converted phases extracted from three-component recordings have been analyzed to determine the variation of Poisson's ratio across the rift axis.

Most members of the GLIMPCE refraction group have been involved in some form of velocity modeling (Figure 3). Although the various models presented at the workshop differ in detail, they have many features in common with each other. The modeling strategy adopted by the Oregon team is fairly typical. They constructed an initial two-dimensional model by integrating information from GLIMPCE seismic reflection line A [*Cannon et al.*, 1989; *Green et al.*, 1989] with results of one-dimensional τ-sum inversions of travel times observed on individual record sections. A second stage two-dimensional velocity model shown in Figure 4, obtained through interactive ray tracing to match first arrivals on the land and lake bottom stations, shows Archean/early Proterozoic basement separated by two connected rift basins. Though preliminary in nature, the general shape of the deep rift basins and underlying high-velocity material in central Lake Superior is quite well defined by this model.

The Archean/early Proterozoic basement rocks are characterized by typical Precambrian Shield velocities ranging from 6.0 km/s

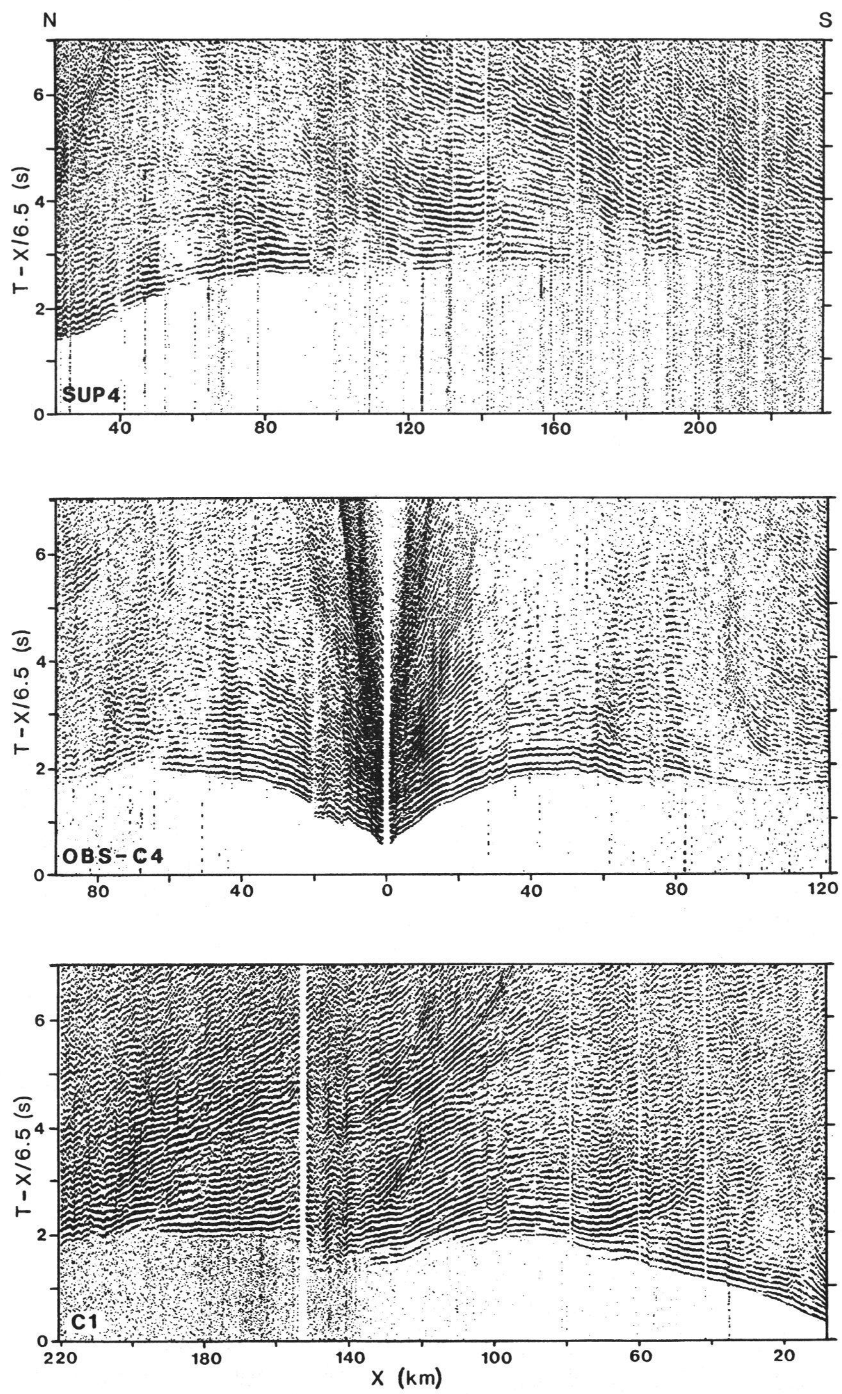

Fig. 2. Examples of data recorded along line A across central Lake Superior. Stations are land site SUP4 to the north of the lake, lake bottom site OBS-C4 near the center of the lake, and land site C1 to the south. All sections have been filtered 5–24 Hz, and offset dependent scaling was applied for offsets greater than 10 km—no scaling applied for offsets less than 10 km. Reduction velocity is 6.5 km/s.

near the surface to 6.6 km/s at the bottom of the model. The velocity distribution of the two rift basins is distinct from that observed on the flanks, with the velocity increasing rapidly from about 2.5 km/s at the lake floor to about 5.2 km/s at less than 2 km depth. A local high-velocity anomaly is associated with the Isle Royale (IRF) fault zone. Volcanic rocks, which have been dredged from Superior Shoals (SS in Figures 1 and 4), are the likely source of the high velocities. In the central rift basin, velocities continue increasing with depth, reaching more than 7.0 km/s near the base of the section. Such high velocities at relatively shallow levels, coupled with our knowledge of the region's tectonic history, suggest that there is a large volume of igneous rock within the basin. The northern basin extends to a depth of about 12 km and as for the central basin, contains a substantial volume of high-velocity material. Moho depths (not shown in Figure 4) deduced from wide-angle reflections recorded on the in-line and fan receivers increase from about 36 km under the southern flank to more than 55 km beneath the central basin, and then decrease to about 50 km beneath the northern basin.

Summary

The GLIMPCE seismic experiment was successful in obtaining coincident high-quality reflection and long-offset reflection/refraction data across a number of major geological structures in the midcontinent. The seismic reflection data provide outstanding images of the MRS, revealing structures that extend considerably deeper than had previously been suspected. Long-offset reflection/refraction data enhanced by modern data-processing techniques are providing additional constraints on the geometries and lithologies associated with these structures, information critical for resolving their nature and evolution.

Although modeling of the long-offset data is at an early stage, some conclusions about the MRS can be drawn at this time:

1. A rift basin to the north of the Isle Royale fault and a huge central rift basin located between the Isle Royale and Keweenaw faults have been outlined. Velocities determined from the refraction data allow the boundary between the upper sedimentary layers and the lower layers of intercalated volcanic and sedimentary rocks to be identified.
2. The Isle Royale fault is associated with a shallow high-velocity anomaly.
3. The relatively high velocities (up to 7 km/s at 18 km depth) required in the central rift basin are consistent with the presence of a thick sequence of primarily igneous (probably basaltic) rocks.
4. The normal moveout corrected in-line and fan profiles indicate deepening Moho from about 36 km beneath the southern flank to more than 55 km below the central rift basin. Moho probably shallows about 50 km under the northern basin.

Completion of the analysis of the GLIMPCE long-offset seismic data and its integration with the vertical incidence seismic reflection and new potential field data will undoubtedly contribute to our understanding of some of the major geological structures of the midcontinent region, which will in turn provide insights into the formation and evolution of the North American continent. Further results from the GLIMPCE seismic refraction working group were presented at the Union Symposium GLIMPCE and Related Studies of the Midcontinent held at the 1989 Spring Meeting of AGU in Baltimore.

Acknowledgments

Funding for the initial GLIMPCE surveys was provided by the U.S. Geological Survey, and the Geological Survey of Canada through its contribution to LITHOPROBE. The seismic reflection survey was carried out by Geophysical Services Incorporated (GSI) of Calgary. We express our thanks to the Canadian

INSTITUTE	DATA SETS	ACTIVITY
Geol. Surv. Canada	L. Superior & L. Huron single channel data	deconvolution filtering; migration of wide-angle reflections; 2-d ray tracing and synthetic seismogram modeling of P-wave data; integration of near-vertical incidence and long offset seismic results with potential field and geological data.
U.S. Geol. Surv.	all data	accurate determination of shot times, positions and bathymetry.
Univ. West. Ont.	L. Superior & L. Huron single component data	conventional and Nth root stacking; migration of wide-angle reflections; development and application of interactive inversion methods for fan and in-line data; 2-d ray tracing and synthetic seismogram modeling of P-wave data; studies of crustal "shingles" and P-to-S conversions.
Univ. Wisc. (Madison)	L. Superior, L. Michigan & L. Huron 3-component data	deconvolution filtering; studies of P-to-S conversions, Poisson's ratio, and wide-angle reflections on in-line and fan data; joint interpretation of GLIMPCE long-offset data and 1960's colinear sonobuoy data; comparison of the MRS with the East African Rift System.
Univ. Wisc. (Oshkosh)	L. Superior single & multichannel data	beam steering to enhance and identify selected P- and S-wave events; analysis of data in F-K domain; 2-d ray tracing and synthetic seismogram modeling of P- and S-wave data.
Ore. State. Univ	L. Superior 3-component data	deconvolution filtering; 2-d ray tracing and synthetic seismogram modeling of P-wave data; migration of wide-angle reflections; comparison of forward and inverse modeling techniques; integrated interpretatio of near-vertical incidence and long-offset seismic data.
S. Illinois Univ.	L. Superior & L. Huron single & multichannel data	application of reflection processing methods with emphasis on time-space domain velocity filtering of unequally spaced data for detecting and identifying refracted and reflected P- and S-waves; 2-d ray tracing and synthetic seismogram modeling of P-wave data.
Univ. Sask.	L. Superior multichannel data	slant stacking and determination of time variant coherency functions for enhancing and identifiying secondary arrivals; computation of velocity spectra for determining stacking velocity functions.
N. Illinois Univ.	L. Superior, L. Michigan & L. Huron single & multichannel data	processing and interpretation of selected onshore data; modeling of refraction phases recorded on near-vertical incidence data.

Fig. 3. Ongoing processing and modeling activities being applied to the GLIMPCE long-offset seismic data by the various participants.

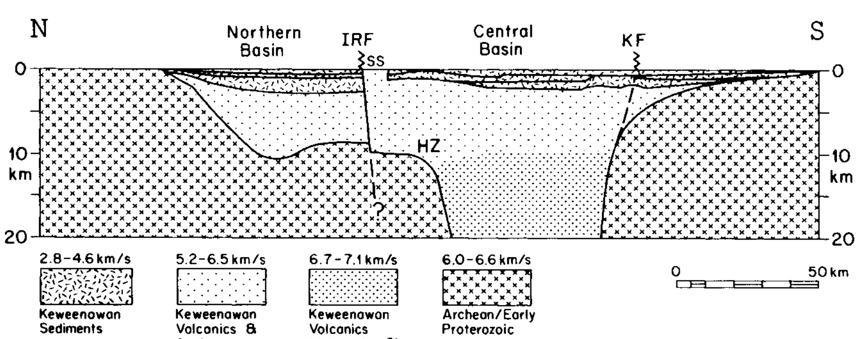

Fig. 4. Stylized model of the upper crustal velocity structure along GLIMPCE line A. HZ, Hinge zone; IRF, Isle Royale fault; KF, Keweenaw fault; SS, Superior Shoals. Note the 3:1 vertical exaggeration.

Coast Guard, who provided communications with the recording crew on Michipicoten Island; the U.S. Coast Guard, who provided the ship and helping hands for the deployment and the recovery of the lake bottom seismographs; and the Ontario Geological Survey, who provided logistic support. The University of Wisconsin-Oshkosh was supported by grants from the NSF Division of Earth Sciences (EAR-8617074 and EAR-8804359) and by the University of Wisconsin-Oshkosh Faculty Development Board. We also thank the students and assistants who helped gather the data and prepare it for processing. Geological Survey of Canada contribution 10789, LITHOPROBE contribution 100.

References

Behrendt, J. C., A. G. Green, W. F. Cannon, D. R. Hutchinson, M. W. Lee, B. Milkereit, W. F. Agena, and C. Spencer, Crustal structure of the Mid-continent Rift System: Results from GLIMPCE deep seismic reflection profiles, *Geology, 16,* 81, 1988.

Cannon, W. F., A. G. Green, D. R. Hutchinson, M. W. Lee, B. Milkereit, J. C. Behrendt, H. C. Halls, J. C. Green, A. B. Dickas, G. B. Morey, R. Sutcliffe, and C. Spencer, The Midcontinent rift beneath Lake Superior from GLIMPCE seismic reflection profiling, *Tectonics, 8,* 305, 1989.

Green, A. G., W. F. Cannon, B. Milkereit, D. R. Hutchinson, A. Davidson, J. C. Behrendt, C. Spencer, M. W. Lee, P. Morel-à-l'Huissier, and W. F. Agena, A "GLIMPCE" of the deep crust beneath the Great Lakes, in *Properties and Processes of Earth's Lower Crust, Geophys. Monogr., IUGG Ser. 6,* vol. 51, pp. 65-80, AGU, Washington, D.C., 1989.

Halls, H. C., Crustal thickness in the Lake Superior region, in *Geology and Tectonics of the Lake Superior Basin, Geol. Soc. Am. Mem.,* vol. 156, edited by R. J. Wold and W. J. Hinze, pp. 239–244, Boulder, Colo., 1982.

Hoffman, P. E., United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia, *Ann. Rev. Earth Planet. Sci., 16,* 543, 1988.

Luetgert, J. H., and R. P. Meyer, Structure of the western basin of Lake Superior from cross structure refraction profiles, in *Geology and Tectonics of the Lake Superior Basin, Geol. Soc. Am. Mem.,* vol. 156, edited by R. J. Wold and W. J. Hinze, pp. 245–256, Boulder, Colo., 1982.

Milkereit, B., Migration of noisy crustal seismic data, *J. Geophys. Res., 92,* 7916, 1987.

Serpa, L., T. Setzer, H. Farmer, L. Brown, J. Oliver, S. Kaufman, J. Sharp, and D. W. Steeples, Structure of the southern Keweenawan rift from COCORP surveys across the midcontinent geophysical anom-

aly in northeastern Kansas, *Tectonics, 3,* 367, 1984.
Steinhart, J. S., and T. J. Smith (Eds.), *The Earth Beneath the Continents, Geophys. Monogr. Ser.*, vol. 10, 663 pp., AGU, Washington, D.C., 1966.
Van Schmus, W. R., and W. J. Hinze, The Midcontinent Rift System, *Ann. Rev. Earth Planet. Sci., 13,* 345, 1985.
Wold, R. J., and W. J. Hinze (Eds.), *Geology and Tectonics of the Lake Superior Basin, Geol. Soc. Am. Mem.*, vol. 156, 280 pp., Boulder, Colo., 1982.
Zhu, T., and L. D. Brown, Consortium for Continental Reflection Profiling Michigan surveys: Reprocessing and results, *J. Geophys. Res., 91,* 11,477, 1986.

GLIMPCE Seismic Refraction Group

Geological Survey of Canada, Ottawa Patrick Morel-à-l'Huissier, Alan G. Green, Bernd Milkereit

Oregon State University, Corvallis Anne M. Tréhu, John Shay

University of Wisconsin-Madison Robert P. Meyer, Xiao Rung Shih

University of Wisconsin-Oshkosh John H. Karl, Tom Jefferson

University of Western Ontario, London Robert F. Mereu, Duryodhan Epili

Southern Illinois University, Carbondale-John L. Sexton, Scott Wendling

University of Saskatchewan, Saskatoon Zoltan Hajnal, Wai-Kin Chan

United States Geological Survey, Woods Hole, Mass. Deborah R. Hurchinson

Northern Illinois University, DeKalb C. Patrick Ervin

Editorial

Better Pre-College Textbooks

PAGE 841

We have all heard deplorable tales of the state of science education in U.S. grade schools and high schools. Teachers need textbooks that are accurate and current, but they have not always had the help they could use from the science community. The National Center for Science Education (NCSE) in Berkeley, Calif., is trying to remedy that situation, and AGU members can help them.

NCSE is a nonprofit organization affiliated with the American Association for the Advancement of Science and the National Science Teachers Association. One of its objectives is to improve the quality of pre-college science textbooks.

Eugenie C. Scott, executive director of NCSE, has described two programs in which AGU members could make a significant contribution: reviewing published pre-college textbooks, and pre-publication text review. Both programs have already established credibility with educators, school administrators, and publishers of pre-college textbooks.

I think the programs are best described in Scott's own words.

"We [NCSE] publish a newsletter called *Bookwatch Reviews* (*BWR*) which—believe it or not—is the only periodical dedicated to reviewing pre-college science textbooks. One would think that with the importance of the multimillion dollar textbook industry, information like this would be more available. Unfortunately, only a few periodicals occasionally review science textbooks, and then generally in brief reviews that do little more than summarize contents and list what 'peripherals' (slide sets, transparencies, etc.) are available. *BWR* reviews are long in comparison (1000 words each) and they concentrate on science content. Each issue of *BWR* reviews one book, with two reviews by scientists and one by a science educator. Having the input of scientists in the review of pre-college texts is important. They are the only ones competent to judge whether a given book is scientifically accurate and up-to-date or not.

"A second program in textbook improvement is called the Pre-Publication Review Project (PPRP), and is another one for which AGU assistance would be appreciated. Whereas *BWR* looks at books after they have been published, the PPRP tries to improve books before they get to the market. NCSE acts as broker to link textbook publishers with scientists for content review. Textbook publishers pay the scientist for his or her work, though NCSE gets no money for the service (to retain its independence). The professor may do as many or as few chapters as is desired and all arrangements are made between the scientist and the publisher."

Earth scientists are particularly needed to assist in reviewing pre-college textbooks for NCSE. AGU members who would like to be considered for participation in either program should send a brief letter expressing interest and a short curriculum vitae to AGU headquarters.

Do you want to make a substantive contribution to pre-college science education? Here's your chance.

Fred Spilhaus
AGU Executive Director