

INSIDE

- Penrose Conference, p. 14
- Selling Science, p. 20
- Employment Service, p. 22

Probing the Archean and Proterozoic Lithosphere of Western North America

Deep Probe Working Group

Timothy J. Henstock and **Alan Levander**, Department of Geology & Geophysics, Rice University, Houston, TX 77005; **Catherine M. Snelson**, **G. Randy Keller**, **Kate C. Miller**, and **Steven H. Harder**, Department of Geological Sciences, University of Texas, El Paso, TX 79968; **Andrew R. Gorman** and **Ron M. Clowes**, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada; **Michael J. A. Burianyk**, Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1, Canada; **Eugene D. Humphreys**, Department of Geological Sciences, University of Oregon, Eugene, OR 97403

ABSTRACT

The 1995 western North American Deep Probe seismic experiment, a continental-scale, long-range refraction investigation, extended from the Colorado Plateau to the Archean craton in Canada. The profile crossed the Proterozoic terranes of the southern Rocky Mountains and Colorado Plateau and the southern part of the Archean Wyoming province—a region modified by Phanerozoic tectonism, and the northern part of the Wyoming province and the Archean Hearne province—a region that has been relatively stable since the Archean. Each geologic province has a distinctive crustal type, that of the Wyoming province being the thickest and fastest. In the mantle, the change from low to high upper-mantle seismic velocity that marks the passage from the orogenic plateau to the craton in published teleseismic tomographic images is seen to occur abruptly in the vicinity of the Cheyenne belt, which separates the Proterozoic Rocky Mountain terranes from the Archean Wyoming province. To the south, the upper mantle beneath the southern Rocky Mountains has a well-developed P-wave low-velocity zone like that beneath the Gulf of California spreading system. To the north, the upper mantle beneath the Archean provinces resembles the teleseismic average for the Canadian shield.

INTRODUCTION

The 1995 Deep Probe investigation is unique among modern seismic refraction studies of western North American lithosphere in scale and spatial sampling (Fig. 1). The study provides seismic observations between the scale of regional reflection or refraction crustal studies and of teleseismic earthquake mantle studies. The Deep Probe corridor approximately follows the 110th meridian, spanning ~29° from north of the U.S.-Mexican border to Great Slave Lake in

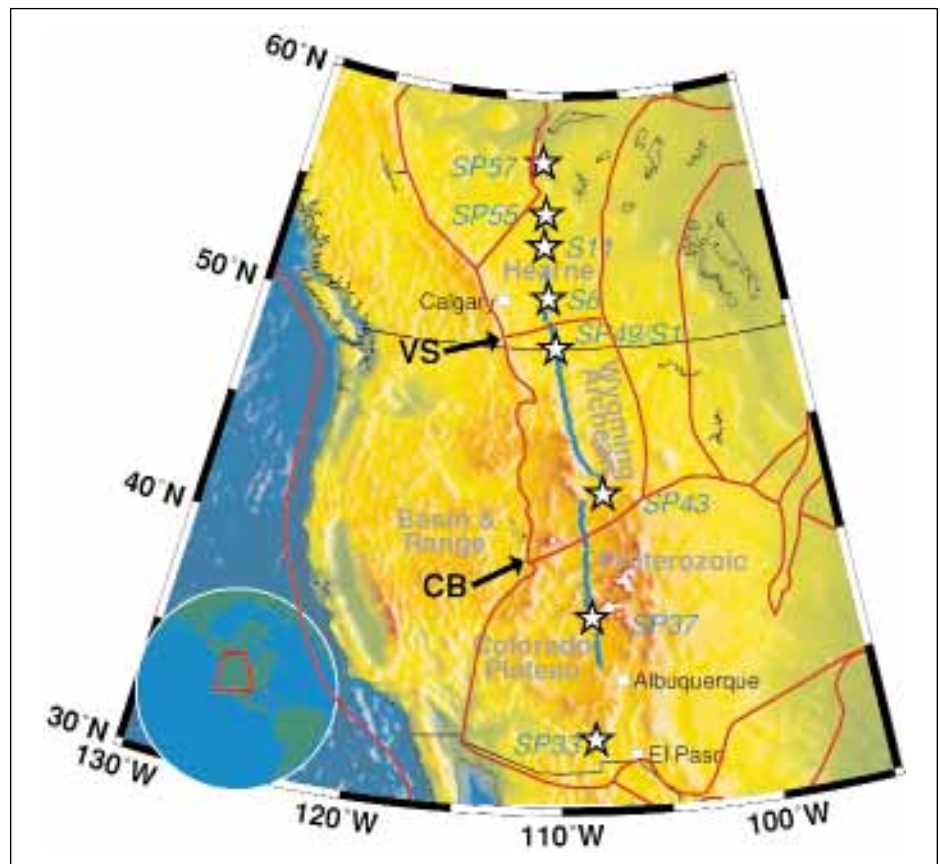


Figure 1. Location map showing the Deep Probe corridor in western North America. Blue line shows seismograph stations occupied for 1995 active-source experiment. SP refers to Deep Probe shotpoints, S to SAREX shotpoints used in this study. Red lines denote borders of major geologic provinces (after Hoffman, 1989). VS—Vulcan structure between Hearne and Wyoming Archean provinces; CB—Cheyenne belt suture between Archean Wyoming province and Proterozoic accreted terranes.

Canada. From north to south, the profile crosses the Archean Hearne and Wyoming provinces, the Cheyenne belt, and the Proterozoic terranes of the southern Rocky Mountains and Colorado Plateau.

Beginning in the north, the Hearne province of central-south Alberta is the westmost extension of the Canadian craton. On the basis of basement drill core, gravity, and aeromagnetic studies, the province con-

sists of several Archean domains (Ross et al., 1991). Sedimentary sequences in southern Alberta and northern Montana indicate that the region has been a largely stable topographic high for 1.5 b. y. A prominent crustal feature known as the Vulcan structure could mark the limit with the Wyoming province. The Wyoming province, which is an agglom-

GSA TODAY (ISSN 1052-5173) is published monthly by The Geological Society of America, Inc., with offices at 3300 Penrose Place, Boulder, Colorado. Mailing address: P.O. Box 9140, Boulder, CO 80301-9140, U.S.A. Periodicals postage paid at Boulder, Colorado, and at additional mailing offices. **Postmaster:** Send address changes to *GSA Today*, Membership Services, P.O. Box 9140, Boulder, CO 80301-9140.

Copyright © 1998, The Geological Society of America, Inc. (GSA). All rights reserved. Copyright not claimed on content prepared wholly by U.S. Government employees within the scope of their employment. Permission is granted to individuals to photocopy freely all items other than the science articles to further science and education. Individual scientists are hereby granted permission, without royalties or further requests, to make unlimited photocopies of the science articles for use in classrooms to further education and science, and to make up to five copies for distribution to associates in the furtherance of science; permission is granted to make more than five photocopies for other noncommercial, non-profit purposes furthering science and education upon payment of a fee (\$0.25 per page-copy) directly to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923 USA, phone (978) 750-8400, <http://www.copyright.com>; when paying, reference *GSA Today*, ISSN 1052-5173. Written permission is required from GSA for all other forms of capture, reproduction, and/or distribution of any item in this publication by any means, including posting on authors' or organizational Web sites, except that permission is granted to authors to post the abstracts only of their science articles on their own or their organization's Web site providing the posting includes this reference: "The full paper was published in the Geological Society of America's news-magazine, *GSA Today*, [include year, month, and page number if known, where article appears or will appear]." GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

SUBSCRIPTIONS for 1998 calendar year: **Society Members:** *GSA Today* is provided as part of membership dues. Contact Membership Services at (800) 472-1988, (303) 447-2020 or member@geosociety.org for membership information. **Nonmembers & Institutions:** Free with paid subscription to both *GSA Bulletin* and *Geology*, otherwise \$50 for U.S., Canada, and Mexico; \$60 elsewhere. Contact Subscription Services. **Single copies** may be requested from Publication Sales. Also available on an annual CD-ROM, (together with *GSA Bulletin*, *Geology*, GSA Data Repository, and an Electronic Retrospective Index to journal articles from 1972); \$89 to GSA Members, others call GSA Subscription Services for prices and details. Claims: For nonreceipt or for damaged copies, members contact Membership Services; all others contact Subscription Services. Claims are honored for one year; please allow sufficient delivery time for overseas copies, up to six months.

STAFF: Prepared from contributions from the GSA staff and membership.
Executive Director: Donald M. Davidson, Jr.
Science Editors: Suzanne M. Kay, Department of Geological Sciences, Cornell University, Ithaca, NY 14853; Molly F. Miller, Department of Geology, Box 117-B, Vanderbilt University, Nashville, TN 37235.
Forum Editor: Bruce F. Molnia, U.S. Geological Survey, MS 917, National Center, Reston, VA 22092
Director of Publications: Peggy S. Lehr
Managing Editor: Faith Rogers
Assistant Editor: Vanessa Carney
Production Editor and Coordinator: Joan E. Manly
Graphics Production: Joan E. Manly, Leatha L. Flowers

ADVERTISING: Classifieds and display: contact Ann Crawford, (303) 447-2020; fax 303-447-1133; acrawfor@geosociety.org.

Issues of this publication are available as electronic Acrobat files for free download from GSA's Web Site, <http://www.geosociety.org>. They can be viewed and printed on various personal computer operating systems: MSDOS, MSWindows, Macintosh, and Unix, using the appropriate Acrobat reader. Readers are available, free, from Adobe Corporation: <http://www.adobe.com/acrobat/readstep.html>.

This publication is included on GSA's annual CD-ROM, *GSA Journals on Compact Disc*. Call GSA Publication Sales for details.



Printed in U.S.A. using pure soy inks.

50% Total Recovered Fiber
10% Postconsumer

IN THIS ISSUE

Probing the Archean and Proterozoic Lithosphere of Western North America 1
 Washington Report 6
 1999 Officer and Councilor Nominees 8
 New GSA Associated Society 8
 Governor Honors Fellows 8
 Student News and Views 9
 GSAF Update 10
 About People 11
 Environment Matters 12
 Penrose Conference Scheduled 14
 Letters 14
 Birdsall-Dreiss Lecturer 15
 Penrose Conference Report 18
 Selling Science 20
 Employment Service 22
 Short Courses 25
Bulletin and *Geology* Contents 26
 GSA Annual Meeting 28
 Classifieds 30
 Calendar 31

In Memoriam

John N. Adkins
St. Michaels, Maryland

Frederick W. Cater, Jr.
Lakewood, Colorado
April 13, 1998

Theodore D. Cook
Bellaire, Texas
December 28, 1997

Albert J. Depman
West Chester, Pennsylvania

Kenneth O. Emery
North Falmouth, Massachusetts
April 12, 1998

Maria C. Ledesma
Oakland, California
March 24, 1998

Vaughn C. Maley
Midland, Texas
January 6, 1998

H. Philip Raveling
Smithfield, Virginia
January 26, 1998

Frederick E. Schaeffer, Jr.
Colorado Springs, Colorado

Clement F. Shearer
Northfield, Minnesota
May 13, 1998

Thomas E. Shufflebarger, Jr.
Berkeley Springs, West Virginia

George M. Stanley
Aptos, California
May 1998

James F. Sweeney
Pittsburgh, Pennsylvania
April 15, 1998

Robert F. Walters
Wichita, Kansas
April 9, 1998

Extended Deadline!

The Penrose Conference on "Strike-slip to subduction transitions on plate boundaries: Tectonic settings, plate kinematics, and seismic hazards," Puerta Plata, Dominican Republic has extended its application deadline to **September 1, 1998.**

Lithosphere continued from p. 1

eration of back-arc basins, island arcs, and micro-continental fragments intruded by Late Archean granites, has been largely stable since 2.7 to 2.6 Ga (Houston et al., 1993). The rest of the southwestern U.S. interior consists of Proterozoic island-arc terranes accreted to the southern margin of the Wyoming province between 2.0 and 1.3 Ga (Karlstrom and Bowring, 1988). The Cheyenne belt at the southern boundary of the Wyoming province is interpreted as a Proterozoic crustal suture (Karlstrom and

Houston, 1984). The resultant continent known as Laurentia was subjected to Late Proterozoic to Early Cambrian rifting that established the limits of the modern North American craton (e.g., Hoffman, 1989).

In the Phanerozoic, the western margin of North America was uplifted and modified by a succession of tectonic events (Burchfiel and Davis, 1975; Ye et al., 1996), only some of which extended into the study area. Of those that did, the Pennsylvanian Ancestral Rockies event affected the Proterozoic terranes south of the Cheyenne belt, producing the Uncompahgre uplift. The Late Cretaceous to mid-Eocene Laramide event produced basement uplifts and deep sedimentary basins throughout the Proterozoic terranes and the southern Wyoming province. Tertiary events in the southern part of the region caused uplift of the Colorado

Lithosphere continued on p. 3

Lithosphere *continued from p. 2*

Plateau and produced Basin and Range extension (e.g., Schneider and Keller, 1994).

The goals of the seismic investigation were to determine and contrast the lithospheric structures of the relatively stable Hearne and northern Wyoming provinces with those of the southern Wyoming province and the Proterozoic terranes affected by Laramide events. The seismic data collected provide a continental-scale P-wave velocity model for the crust and upper mantle to depths of ~150 km. We describe two major lateral changes in velocity structure, one in the crust and one in the mantle, which are associated with boundaries between the geological provinces and indicate major differences in lithospheric evolution.

DEEP PROBE SEISMIC OBSERVATIONS AND INTERPRETATION

The Deep Probe experiment consisted of 10 shots detonated at seven shotpoints, recorded by 710 portable refraction seismometers deployed twice at about 1200 sites. Nominal instrument spacing was 1.25 km (Fig. 1; Gorman et al., 1997). Shot size varied from 2400 to 17000 kg of chemical explosive. The recording arrays extended from northern New Mexico to central Alberta. Just prior to our experiment, the Canadian Litho-probe program conducted the crustal-scale Southern Alberta Refraction Experiment (SAREX), coincident with the Canadian part of Deep Probe. Three shot records from SAREX are included in the analysis here (S1, S6, and S11; Fig. 1).

Seismic Observations: Three Province-Related Seismic Signatures

The fundamental experimental results are illustrated by the records from shotpoint SP43 in central Wyoming, just north of the Cheyenne belt (Fig. 3, see p. 16–17). Markedly different crustal and upper-mantle signals occur north and south of SP43, indicating profound changes in the upper 150 km of the lithosphere over a distance not exceeding 250–300 km. Primary crustal and mantle seismic waves observed include: Pg—upper crustal refractions; Pi—refracted within a lower crustal layer; PmP—reflected from the Moho; and Pn and related phases—refracted beneath the Moho. Travel times and amplitudes of these waves constrain crustal thicknesses and crustal and mantle seismic velocities. An important feature is the source to receiver offset at which Pn becomes a first arrival—the crossover distance—which increases with crustal thickness.

First-order observations on the profile south of SP43 in the Proterozoic terranes of the southern Rockies–Colorado Plateau are that Pn becomes a first arrival at ~200 km offset, has velocities of 7.9–8.0 km/s, and is very weak from the crossover at ~200 km to ~425 km (Fig. 2). Beyond 425 km, Pn amplitude

Scientific Ocean Drilling Needs YOU!

NOTICE: To all members of the earth sciences community.


The Ocean Drilling Program will end on October 1, 2003. International scientific cooperative efforts for deep-earth sampling in the marine environment will cease unless our community comes together now to plan a new program for scientific ocean drilling. We've done it before (ODP is the successor to the 1968-1983 Deep Sea Drilling Project) — we can do it again.

SPRING 1999 INTERNATIONAL CONFERENCE: To define the scientific objectives for a future, multi-platform ocean drilling program with two major vessels. This Conference will target the scientific goals of non-riser drilling and will complement the recent Conference for Cooperative Ocean Riser Drilling. CONCORD defined the scientific initiatives for use of a riser-equipped drilling vessel (the CONCORD report is available at <http://mstip1.jamstec.go.jp/jamstec/OD21/CONCORD/result.html>).

WANTED: Brief (~1-page) statements of interest that describe a scientific objective, its importance, and the necessity for drilling. Technical details are not necessary. These statements will be used to organize the Conference. This is your opportunity to influence the scientific direction of the new program and to show your support for future scientific ocean drilling.

DEADLINE: September 1, 1998.

SUBMIT TO: JOIDES Office, Department of Geology & Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA; (508) 989-3481; joides@whoi.edu.



RESPOND TODAY! THE FUTURE OF SCIENTIFIC OCEAN DRILLING IS IN YOUR HANDS

strengthens to offset distances of 800 km. This weak Pn character from 200 to 425 km also occurs on records from SP33 and SP37 in New Mexico and Colorado.

The record for the Archean Wyoming province north of SP43 is dramatically different (Fig. 2). In particular, a Pn crossover at ~260 km indicates a thicker crust, and high-amplitude and high-velocity (8.1–8.4 km/s) Pn phases to offsets of ~800–1000 km indicate a distinct upper-mantle structure. Pn with similar character is seen south of SP49 from the Canadian border to central Wyoming (Fig. 2). More subtle features seen at SP43 north and SP49 south are lower crustal refractions, Pi, with phase velocities of 7.0–7.3 km/s that are first arrivals from 180 to 260 km and clear second arrivals from 260 to 400 km (Fig. 2). Lower-crust events like these are absent in the Proterozoic terranes to the south and the Hearne province to the north.

North of SP49, in the Hearne province, Pn becomes a first arrival at ~210 km with velocities of 8.1–8.2 km/s. The shorter Pn crossover distance (210 km) is also observed on the other shots in the Hearne province, indicating a thinner crust than in the Wyoming province.

Cross Section of Western North America

To interpret the data, we used reflectivity modeling to estimate average one-dimensional velocity structures of the three

provinces (Fuchs and Müller, 1971), and two-dimensional ray-tracing and travel-time inversion to estimate two-dimensional crust and upper mantle structure from all shots (Luetgert, 1992; Zelt and Smith, 1992). Due to large distances between shotpoints (~400–600 km) travel-time modeling concentrated on the primary crustal and mantle phases identifiable from shot to shot. For two-dimensional ray-tracing, the starting model used crustal structure estimates from the one-dimensional interpretations, previous seismic studies, and other geological and geophysical data (Prodehl and Lipman, 1989; Pakiser, 1989; Schneider and Keller, 1994; Snelson, 1998). The two-dimensional modeling and inversion allow a more detailed lithospheric picture (Fig. 2), particularly where Moho depth changes by 10 km over lateral distances of ~100 km. Complex sedimentary basins along the profile generate short scale variations in arrival times which were well matched using a near-surface structure developed from published studies and velocity-depth information from 71 well logs (Snelson, 1998; Snelson et al., 1998). From the top of basement down, only small lateral velocity variations within a province were required to fit the data. Long-offset Pn and crustal arrivals allowed determination of mean velocities within a province to ± 0.1 km/s and mean depths to the Moho to ~2 km in Pn crossover regions (Fig. 2).

Lithosphere *continued on p. 4*

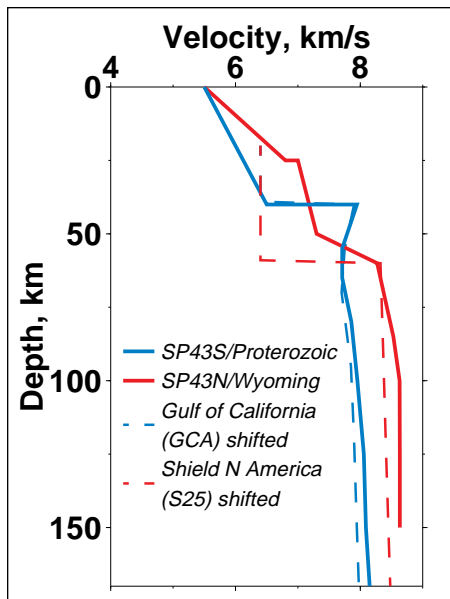


Figure 2. Top: Two-dimensional P-velocity model along Deep Probe corridor. Stars show shots used in this study, gray lines show locations of intracrustal and Moho reflection points. Model depths are best constrained by P_i and P_n refractions that arise in these locations. The one-dimensional velocity profiles derived from reflectivity modeling are superimposed. All velocities shown assume a flat Earth: At 100 km depth they are ~0.15 km/s faster than in a spherical Earth. Bottom: Record sections from SP43, SP37, and SP49 are plotted beneath the shot location with calculated traveltime curves from the model superimposed in red. The blue circles indicate the crossover where P_n becomes the first arrival.

Lithosphere continued from p. 3

The main features of the seismic data are exemplified by three simple but very different one-dimensional velocity models that explain the main amplitude relations among the seismic phases and give average crustal and mantle structure within each province (Figs. 2, 3¹). These are related through the two-dimensional interpretation (Fig. 2). In the south, the Proterozoic crust in the Rocky Mountains and Colorado Plateau is 40 to 45 km thick and shows a linear velocity increase with depth. Most variation in crustal thickness occurs near the boundary with the Wyoming province. In the Archean Wyoming province, crustal thicknesses range from ~40 km at the Cheyenne belt to an average of ~50 km farther north. A high-velocity layer ($v_p \sim 7.05\text{--}7.30$ km/s) occurs in the lower ~25 km of the crust. Crossing the Vulcan structure, Moho depth in the Hearne province shallows to ~40 km. The crust again shows a simple vertical velocity gradient, but with higher velocities than in the Proterozoic crust. Mean crustal velocity in the Southern Rockies and Colorado Plateau is 6.3 km/s, compared with 6.6 km/s in the Wyoming province, and 6.45 km/s in the Hearne province.

¹ Figure 3 is on p. 16–17.

On a global scale, the southern Rockies crust is thin and slow compared to average crustal thicknesses and velocities of 42 km and 6.4–6.5 km/s for shields and platforms, and of 46–50 km and 6.4 km/s for orogens (Christensen and Mooney, 1995; Rudnick and Fountain, 1995). The Wyoming province crust is considerably thicker and faster than that of average shields, and faster than, but similar in thickness to orogens. The somewhat thinner Hearne province crust has an average shield velocity.

Variations in amplitude and velocity of the P_n phase indicate extreme differences in the upper mantle along the profile (Figs. 2, 3). North of SP43, the mantle just below the Moho under the Archean provinces has a velocity of 8.1 km/s that increases with depth. There is no evidence of a low-velocity zone. South of SP43, the mantle under the Proterozoic province has a thin lid with velocities of 7.9–8.0 km/s that is underlain by a thick low-velocity zone with a velocity that decreases to 7.75 ± 0.1 km/s at 60 km depth. The high-amplitude P_n phase observed in the 425 to 800 km offset range is a turning or reflected phase from a depth of ~90 km or more.

Although determining the width of horizontal transitions between terranes is hampered by shot spacing, fortuitous shot positioning and geologic information allow some inferences to be made. In particular, strong asymmetry of seismic arrivals from SP43 implies a transition zone of less than ~250 km on the southern edge of the Wyoming province. On the northern edge, first-arrival refractions from the lower crust are seen from both the north and the south at SP49/S1; whereas 250 km to the north at S6, strongly asymmetric first arrivals do not include lower-crustal events. This implies that the transition zone between the Wyoming and Hearne provinces is less than 100 km wide.

IMPLICATIONS FOR NORTH AMERICAN EVOLUTION

The scale of the Deep Probe experiment permits comparison with earthquake-derived tomographic images of North America that indicate a transition from fast, cold upper mantle beneath the craton, to slow, hot upper mantle beneath the uplifted North American orogenic plateau (Grand, 1994; Grand et al., 1997; van der Lee and Nolet, 1997). The resolution of the earthquake studies is considerably less—about 500 km horizontally and 100 km vertically.

Southern Rocky Mountains—Colorado Plateau: Proterozoic Accreted Terranes

Given its location within a region of Laramide tectonism, the crust in the southern Rockies—Colorado Plateau is surprisingly simple: little lateral velocity variation and no vertical layering. Its 40 to 45 km thickness is insufficient to explain present regional elevations (e.g., Sheehan et al., 1995). Going deeper, the upper-mantle velocity profile is

comparable to that of Walck (1983) for the Gulf of California part of the East Pacific Rise spreading system (Fig. 3), in that both show low-velocity zones just beneath the Moho. The low-velocity zone beneath the southern Rockies likely represents the buoyant mantle needed to support the topography, and is deeper and thicker than its equivalent in the Colorado Plateau–Basin and Range transition zone in Arizona (Benz and McCarthy, 1994). To the east, a range of seismic methods (e.g., Sinno and Keller, 1986; Keller et al., 1990; Slack et al., 1996) indicates low velocities in the uppermost mantle of the Rio Grande Rift. Grand's (1994) teleseismic observations show low velocities in the mantle extending from the East Pacific Rise through the southwestern United States. The Deep Probe results show that regional low-velocity mantle extends northward to the Cheyenne belt.

Wyoming Province: Thick Archean Crust

The crust is thicker and faster in the Wyoming province than in the Proterozoic terranes, with a high-velocity lower-crustal layer occurring in most of the province. The transition from thin (40 km) to thick (50 km) crust occurs in the southernmost 150 km of the province. It is unclear how the Laramide tectonism that affected parts of the province modified the Archean crust. Nothing in our results indicates a Laramide influence unless the entire lower crustal layer is a Laramide feature. The seismic velocity model (Fig. 2) indicates a thick lower crust and uniform upper-mantle structure beneath Laramide uplifts in Wyoming and southern Montana as well as the plains of Montana and southern Alberta.

Although the Archean crust in this part of the Deep Probe profile is ~10 km thicker than the global average for shields and platforms (Christensen and Mooney, 1995), it is not the only cratonic region with a high-velocity lower crust (Rudnick and Fountain, 1995). High velocities like these are compatible with mafic garnet granulite or hornblende compositions, such as are found among northern Montana xenoliths (Reed et al., 1993), or with intermediate-composition crust that is mixed with eclogite, pyroxenite, or dunite.

After adjustment for crustal thickness, the upper-mantle model for the Archean Wyoming province is comparable to the average Canadian shield P-wave profile (S25 in Fig. 3) derived from teleseismic P-wave observations by LeFevre and Helmberger, (1989). The similarities of the two profiles, derived from different types and scales of seismic data, indicate a similarity between Wyoming province and Canadian shield upper mantle.

Vulcan Structure and Hearne Province

The crustal boundary between the Wyoming and Hearne provinces appears to lie close to the Vulcan structure in southern

Alberta. This structure is covered by younger sedimentary sequences, and is thus delineated by gravity, magnetic, and seismic data (Kanasewich et al., 1969). It is a target for Lithoprobe's Alberta Basement Transect (Ross et al., 1997). North of the Vulcan structure, the crust is like average Archean crust. No strong vertical or lateral variations are seen with the exception of a slight thinning to the north. Despite crustal differences with the Wyoming province, the Hearne province has a similar mantle.

Some Unanswered Questions

We are left with questions related to the development of the crust-mantle system along the profile. Is the thick high-velocity lower crust in the Wyoming province due to original Archean assembly, Laramide tectonism, or neither? If the lower crust is the result of Archean formation, why is the Hearne province different? Has its lower crust been delaminated or incorporated into the upper mantle through eclogitization (Nelson, 1991)? If the lower crust beneath the Wyoming province resulted from lower crustal flow during the Laramide, why is the crust to the south so different? A global compilation of Precambrian seismic structure (Durrheim and Mooney, 1994) shows Archean crust to be generally thinner and to have lower velocity crust than Proterozoic crust. This pattern is opposite to that seen in the Wyoming province and the Proterozoic terranes to the south.

CONCLUSIONS

The Deep Probe experiment provides a continental-scale model of crust and upper-mantle compressional velocity to depths of ~150 km along a transect crossing three distinct geologic provinces. Each province has a distinct crustal type. The Wyoming province has an unusual 25-km-thick high-velocity lower-crustal layer, whereas the Hearne province crust is more typical of an Archean shield. The crust in the southern Rockies–Colorado Plateau is relatively simple, and it is thinner than expected from its elevation and Phanerozoic contractional tectonic history.

The lithospheric mantle structure differs profoundly between the relatively stable Archean mantle in the north and a mobile, tectonically active upper mantle in the south, likely modified by Laramide and more recent tectonism. The transition between the two mantle structures is laterally abrupt, lying close to a Proterozoic-age crustal suture despite episodes of more recent tectonism.

ACKNOWLEDGMENTS

We thank the 100 volunteers who helped deploy seismographs, the IRIS/PASS-CAL Instrument Center, and the Geological Survey of Canada (GSC) Instrumentation Group, who achieved an almost perfect data collection record. We thank especially Ed Criley, Grey Jensen, and Tom Burdette of the

USGS and Tim Cartwright and Peter Carroll of Lithoprobe for assistance with shotpoints. Phelps-Dodge Tyrone, Inc., permitted use of a copper mine as a shotpoint. We thank numerous private landowners, as well as state, provincial, and federal agencies in the United States and Canada for land access, in particular the U.S. Forest Service, the New Mexico Department of the Environment, the U.S. Bureau of Land Management, and Canadian Forces Bases Suffield and Cold Lake. We thank Michael Milstein of the *Billings Gazette* for accurate coverage of the experiment. We thank reviewers Eric Erslev, Ron Bruhn, Walter Mooney, and especially *GSA Today* editor Sue Kay for many improvements to the manuscript. This research was supported by the National Science Foundation Continental Dynamics Program, EAR-94109021, EAR-9706841, AFOSR Grant F49620-J-0438, the Lithoprobe Project [funded by the Geological Survey of Canada and the Natural Sciences and Engineering Research Council of Canada (NSERC)], and NSERC research grants.

REFERENCES CITED

Benz, H. M., and McCarthy, J., 1994, Evidence for an upper mantle low velocity zone beneath the southern Basin and Range–Colorado Plateau transition zone: *Geophysical Research Letters*, v. 21, p. 509–521.

Burchfiel, B. C., and Davis, G. A., 1975, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis: *American Journal of Science*, v. 275, p. 363–396.

Christensen, N. I., and Mooney, W. D., 1995, Seismic velocity structure and composition of the continental crust: A global view: *Journal of Geophysical Research*, v. 100, p. 9761–9788.

Durrheim, R. J., and Mooney, W. D., 1994, Evolution of the Precambrian lithosphere: Seismological and geochemical constraints: *Journal of Geophysical Research*, v. 99, p. 15,359–15,374.

Fuchs, K., and Müller, G., 1971, Computation of synthetic seismograms with the reflectivity method and comparison with observations: *Royal Astronomical Society Geophysical Journal*, v. 23, p. 417–433.

Gorman, A. R., Henstock, T. J., and 9 others, 1997, Southern Alberta Refraction Experiment (SAREX) and Deep Probe Refraction Experiment 1995: Field acquisition and preliminary data processing report: Lithoprobe Report No. 52, 26 p., 11 apps.

Grand, S. P., 1994, Mantle shear structure beneath the Americas and surrounding oceans: *Journal of Geophysical Research*, v. 99, p. 11,591–11,621.

Grand, S. P., van der Hilst, R. D., and Widiyantoro, S., 1997, Global seismic tomography: A snapshot of convection in the earth: *GSA Today*, v. 7, no. 4, p. 1–7.

Hoffman, P. F., 1989, Precambrian geology and tectonic history of North America, in Bally, A. W. and Palmer, A. R., eds., *The geology of North America—An overview*: Boulder, Colorado, Geological Society of America, *Geology of North America*, v. A, p. 447–512.

Houston, R. S., Erslev, E. A., Frost, C. D., Karlstrom, K. E., Page, N. J., Zientek, M. L., Reed, J. C., Jr., Snyder, G. L., Worl, R. G., Bryant, B., Reynolds, M. W., and Peterman, Z. E., 1993, *The Wyoming Province*, in Reed, J. C., Jr., eds., *Precambrian: Conterminous U.S.*: Boulder, Colorado, Geological Society of America, *Geology of North America*, v. C-2, p. 121–170.

Kanasewich, E. R., Clowes, R. M., and McLoughlan, C. H., 1969, A buried Precambrian rift in western Canada: *Tectonophysics*, v. 8, p. 513–527.

Karlstrom, K. E., and Bowring, S. A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: *Journal of Geology*, v. 96, p. 561–576.

Karlstrom, K. E., and Houston, R. S., 1984, The Cheyenne belt: Analysis of a Proterozoic suture in southern Wyoming: *Precambrian Research*, v. 25, p. 415–446.

Keller, G. R., Morgan, P., and Seager, W. R., 1990, Crustal structure, gravity anomalies and heat flow in the southern Rio Grande rift and their relationship to extensional tectonics: *Tectonophysics*, v. 174, p. 21–37.

LeFevre, L. V., and Helmsberger, D. V., 1989, Upper mantle P velocity structure of the Canadian shield: *Journal of Geophysical Research*, v. 94, p. 17,749–17,765.

Luetgert, J. H., 1992, MacRay: Interactive two-dimensional seismic raytracing for the Macintosh: U.S. Geological Survey Open-File Report 92-356, p. 1–2.

Nelson, K. D., 1991, A unified view of craton evolution motivated by recent deep seismic reflection and refraction results: *Geophysical Journal International*, v. 105, p. 25–35.

Pakiser, L. C., 1989, Geophysics of the Intermontane system, in Pakiser, L. C., and Mooney, W. D., *Geophysical framework of the continental United States*: Geological Society of America Memoir 172, p. 235–247.

Prodehl, C., and Lipman, P. W., 1989, Crustal structure of the Rocky Mountain region, in Pakiser, L. C., and Mooney, W. D., *Geophysical framework of the continental United States*: Geological Society of America Memoir 172, p. 249–285.

Reed, J. C., Jr., Ball, T. T., Farmer, G. L., and Hamilton, W. B., 1993, A broader view, in Reed, J. C., Jr., et al., eds., *Precambrian: Conterminous U.S.*: Geological Society of America, *Geology of North America*, v. C-2, p. 597–636.

Ross, G. M., Parrish, R. R., Villeneuve, M. E., and Bowring, S. A., 1991, Geophysics and geochronology of the crystalline basement of the Alberta Basin, western Canada: *Canadian Journal of Earth Sciences*, v. 28, p. 512–522.

Ross, G. M., Eaton, D. W., Boerner, D. E., Clowes, R. M., 1997, Geologists probe buried craton in western Canada: *Eos (Transactions, American Geophysical Union)*, v. 78, p. 493–497.

Rudnick, R. L., and Fountain, D. M., 1995, Nature and composition of the continental crust: A lower crustal perspective: *Reviews of Geophysics*, v. 33, p. 267–309.

Schneider, R. V., and Keller, G. R., 1994, Crustal structure of the western margin of the Rio Grande rift and Mogollon-Datil volcanic field, southwestern New Mexico and southeastern Arizona, in Keller, G. R., and Cather, S. M., eds., *Basins of the Rio Grande Rift: Structure, stratigraphy, and tectonic setting*: Geological Society of America Special Paper 291, p. 207–226.

Sheehan, A. F., Abers, G. A., Jones, C. H., and Lerner-Lam, A., 1995, Crustal thickness variations across the Colorado Rocky Mountains from teleseismic receiver functions: *Journal of Geophysical Research*, v. 100, p. 20,319–20,404.

Sinno, Y. A., and Keller, G. R., 1986, A Rayleigh wave dispersion study between El Paso, Texas and Albuquerque, New Mexico: *Journal of Geophysical Research*, v. 91, p. 6168–6174.

Slack, P. D., Davis, P. M., Baldrige, W. S., Olsen, K. H., Glahn, A., Achauer, U., and Spence, W., 1996, The upper mantle structure of the central Rio Grande rift region from teleseismic P and S wave traveltime delays and attenuation: *Journal of Geophysical Research*, v. 101, p. 16,003–16,023.

Snelson, C. M., 1998, An integrated lithospheric study of the Rocky Mountain region along the Deep Probe seismic profile [M.S. thesis]: El Paso, University of Texas, 150 p.

Snelson, C. M., Henstock, T. J., Keller, G. R., Miller, K. C., and Levander, A., 1998, Crust and uppermost mantle structure along the Deep Probe seismic profile: *Rocky Mountain Geology* (in press).

Van der Lee, S., and Nolet, G., 1997, Upper mantle S velocity structure of North America: *Journal of Geophysical Research*, v. 102, p. 22,815–22,838.

Walck, M., 1983, The P-wave upper mantle structure beneath an active spreading center: The Gulf of California: *Royal Astronomical Society Geophysical Journal*, v. 76, p. 697–723.

Ye, H., Royden, L., Burchfiel, B. C., and Schuepbach, M., 1996, Late Paleozoic deformation of interior North America: The greater ancestral Rocky Mountains: *American Association of Petroleum Geologists Bulletin*, v. 80, p. 1397–1432.

Zelt, C., and Smith, R. B., 1992, Seismic traveltime inversion for 2-D crustal velocity structure: *Geophysical Journal International*, v. 108, p. 16–34.

Manuscript received February 20, 1998; accepted May 12, 1998 ■