Thick-Structured Proterozoic Lithosphere of the Rocky Mountain Region

Ken Dueker, Huaiyu Yuan, and **Brian Zurek**, Dept. of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071-3006, USA

ABSTRACT

A new tomographic image of the western United States shows three northeast-trending, low-velocity, upper mantle anomalies in the Rocky Mountain–Colorado Plateau region: the Yellowstone, Saint George, and Jemez lineaments. Each is characterized by small compressional wave-speed anomalies (±2% perturbations) that extend to 200–250 km depth. A fundamental question is whether they represent ongoing asthenospheric convection or old lithospheric compositional bodies. This puzzle is compounded by the observation that each is aligned with both young volcanic fields and Proterozoic crustal grain and/or sutures. We suggest that the low-velocity bodies are lithospheric anomalies and that they were derived from melting of hydrated olivine-poor lithologies (oceanic slabs, their associated sediments, and batholith residue) that were tectonically emplaced during Proterozoic suturing events. Such lithologies would be hydrated by the water in oceanic slabs and sediments trapped during the suturing processes. Our suggestion is consistent with the geochemical fingerprint of most of the young volcanics that indicate melting of an old and chemically diverse lithosphere that often contains a subduction zone trace-element signature. In addition, the sharp and dipping lateral velocity gradients bounding the low-velocity bodies, in particular where extensional deformation is small, suggest these bodies are not upwelling asthenosphere. This suggestion that the low-velocity bodies follow Proterozoic lithospheric sutures is supported by new teleseismic data from the Continent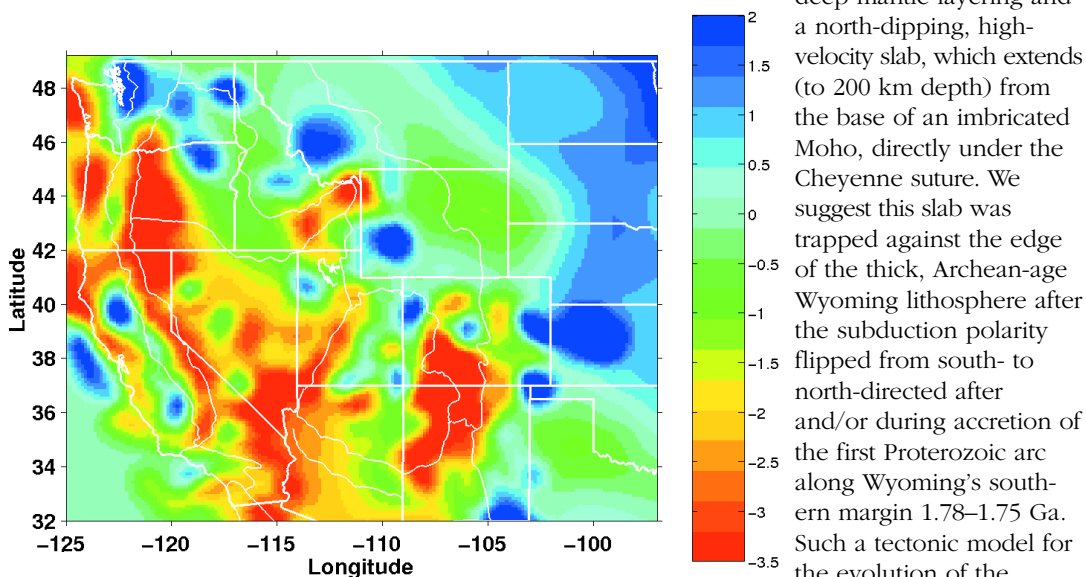al Dynamics–Rocky Mountains project that reveal a surprisingly thick continental lithosphere. In our transect across the Proterozoic Jemez suture, we find the coincidence of young lithospheric volcanism, a low-velocity mantle anomaly, and deep lithospheric layering (to 170 km). In our Wyoming-Colorado transects across the Archean-Proterozoic Cheyenne suture, we find the coincidence of deep mantle layering and a north-dipping, high-velocity slab, which extends (to 200 km depth) from the base of an imbricated Moho, directly under the Cheyenne suture. We suggest this slab was trapped against the edge of the thick, Archean-age Wyoming lithosphere after the subduction polarity flipped from south- to north-directed after and/or during accretion of the first Proterozoic arc along Wyoming's southern margin 1.78–1.75 Ga. Such a tectonic model for the evolution of the Cheyenne belt is consistent with observations along many other Archean-Proterozoic sutures worldwide. Overall, our results demonstrate that Proterozoic crustal sutures in the Rocky Mountain region extend throughout a thick chemical lithosphere and that young lithospheric melting has been focused along old suture zones.

Figure 1. Image of compressional-wave velocity structure at 100 km depth made from combined inversion of P-wave data used to construct Fig. 2 and shear-wave velocity model of van der Lee and Nolet (1997). High velocities (blue shading) on eastern side of image reflect cold, stable tectospheric root present beneath North American craton, and low velocities (yellow and red shading) on western side of image reflect the generally thin lithosphere and warm asthenosphere. In between these two "end-member" regions is average velocity (green shading) Rocky Mountain region that is actively being reworked by interactions between lithosphere and asthenosphere. More detailed results from Continental Dynamics–Rocky Mountain project (Karlstrom, 1999) presented herein attempt to determine relationship between old lithospheric architecture associated with Archean-Proterozoic accretionary history of Rocky Mountain region and today's restless underlying asthenosphere.

The coincidence of old deep structure and young tectonism supports the hypothesis that the lithospheric structure created during Proterozoic assembly provides a first-order control on the complex history of exhumation, deformation, sedimentation, and magmatism of this fascinating, tectonically active region.

INTRODUCTION

The active tectonics of the western United States represent widespread magmatic, strike-slip, and extensional activity

within a wide, deforming plate margin, where past and present tectonism is superimposed on a variety of lithospheric types. Figure 1 shows a tomographic image that depicts upper mantle P-wave velocity at 100 km depth. The high-velocity mantle on the easternmost side (beneath the western Great Plains) is the western edge of the lithospheric root of the North American plate, which extends to depths of 200–250 km (van der Lee and Nolet, 1997). This chemical lithosphere is thought to be high velocity because a buoyant, chemically differentiated root stabilizes the mantle root against convective disruption. This allows a cold, cratonic geotherm to be developed to 200–250 km depth, hence the thick chemical lithosphere coincides with thick thermal lithosphere. On the westernmost side of this image, very low velocities are found beneath the western United States plate margin and Basin and Range province (notable exceptions being the high-velocity subducting Juan de Fuca plate and the high-velocity body beneath the Sierra Nevada batholith). In this region, the thermal lithosphere is thin. In between these two velocity provinces lies a domain of average velocities beneath the Rocky Mountains and High Plains physiographic provinces (green colors on Fig. 1). This transitional domain is an important natural laboratory in which to study lithospheric evolution because it is a domain where the lithosphere is in a state of transition. We argue that in this area, the chemical lithosphere is still thick, while the thermal lithosphere is thinning.

WESTERN UNITED STATES TOMOGRAPHIC IMAGE

Western United States compressional wave images of the upper mantle (Fig. 2) demonstrate the heterogeneous nature of the velocity structure in the upper mantle. This high-quality image (i.e., 72% variance reduction) was created by inversion of ~80 000 hand-picked P-wave times from the more than one thousand short-period seismic stations operating in the western United States (Humphreys and Dueker, 1994). The majority of the velocity heterogeneity resides above 200 km depth, where lateral compositional and

thermal variations are largest and the occurrence of partial melt is possible (Goes and van der Lee, 2001; Humphreys and Dueker, 1994). This image covers the area west of the

stable North American interior and can be divided into two domains: (1) a margin-parallel domain dominated by the effects of plate subduction, and (2) an interior western United States
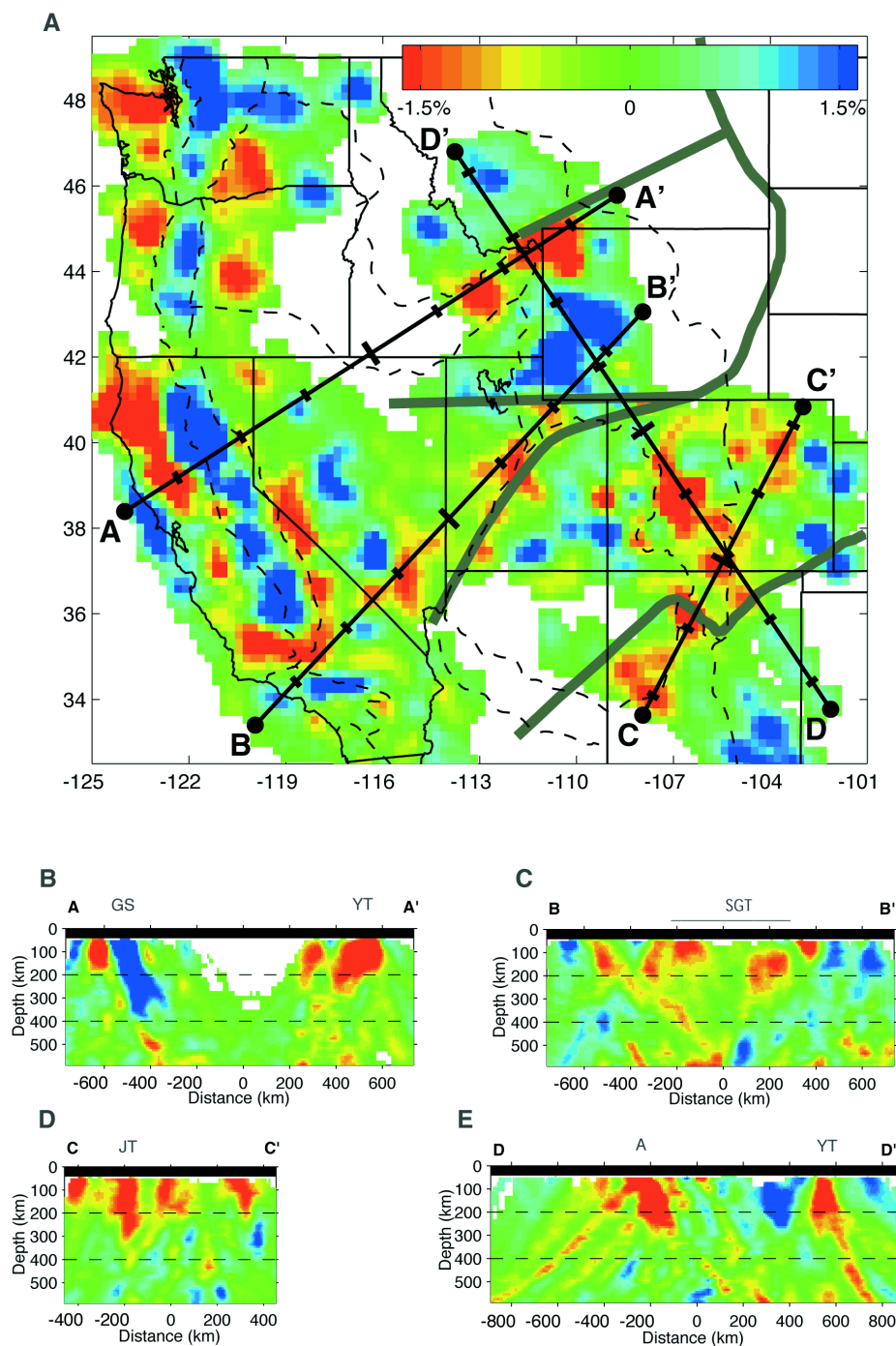
Figure 2. Tomographic P-wave velocity variations. Velocity variations are in percent P-wave velocity variations with red and blue representing slow and fast velocities respectively. Gray lines are Proterozoic lithospheric boundaries as described in text. **A:** Map view at 100 km depth with cross-sectional lines. Tic marks every 200 km along cross-section lines correspond to distance along cross sections. (Big tic mark is 0 km offset). **B:** High-velocity Gorda slab (GS) and Yellowstone trend (YT). **C:** Saint George trend (SGT). **D:** Jemez trend (JT). **E:** Yellowstone trend (YT) and Aspen anomaly (A).

domain where the effects of a thicker Archean-Proterozoic lithosphere, perhaps underlain by an organized pattern of asthenospheric activity, exist.

In the plate margin domain, the primary grain of the image is dictated by: the high-velocity slabs associated with subduction of the Juan de Fuca plate beneath Oregon, Washington, and northern California; the evolution of the low-velocity "slab window" beneath the San Andreas transform; and the high-velocity body beneath the Sierra Nevada batholith, which could be either late Cenozoic slab fragment(s) or the eclogitic facies root of the Sierra batholith (Ducea, 2001). In the interior western United States domain, the primary grain of the image is dictated by 100–200 km diameter low-velocity anomalies that line up to produce three northeast-southwest oriented, low-velocity trends associated with the Yellowstone, Saint George, and Jemez volcanic lineaments. The low-velocity body beneath central Colorado (the Aspen anomaly; Fig. 2E) being the notable exception to the northeast trends.

Do these low-velocity anomalies represent ongoing asthenospheric convection? An asthenospheric model to explain the origin of these low-velocity bodies and trends suggests they manifest the upwelling limbs of upper mantle convective rolls (Richter, 1973). Such a model would be supported in two ways: (1) When the asthenosphere is sheared by plate motion, modeling shows that convective roll axes preferentially align with their axes parallel to the shear, i.e., parallel to the southwest drift of the North American plate over the deeper mantle; (2) The preferred aspect ratio of such convective rolls is ~1, which for upper mantle processes predicts a roll spacing of 400–500 km. This would explain the anomalies (excluding the Aspen anomaly). A notable feature is the noncontinuous (i.e., blob-like) character of the low-velocity trends (e.g., the four low-velocity bodies beneath the Jemez lineament shown in Fig. 2D); this is consistent with lithosphere/asthenosphere dynamic simulations that include partial melt production and extraction (Tackley and Stevenson, 1993; Schmeling, 2000). Implicit in this asthenospheric model is that the Yellowstone hotspot is not the track of a deep mantle plume

(Humphreys et al., 2000), but instead results from the organization of asthenospheric convection predicted to develop beneath moving plates. The force driving the volcanic propagation is the interaction between an actively melting asthenosphere, the depleted residuum this creates, and the upper mantle plate shear which "drags" the depleted residuum downstream of an active melt event or "burp" (see Schmeling [2000] for two-dimensional simulations of propagating melt instabilities that move at 2–4 cm/yr rates).

Or, do the low-velocity anomalies represent compositional variations within a thick lithosphere? A lithospheric model to explain these low-velocity trends (Karlstrom and Humphreys, 1998) suggests that low melting point materials trapped in Proterozoic suture zones localize melting of the lithosphere. For example, the Jemez and Saint George volcanic lineaments (Smith and Luedke, 1984) follow the suture zones associated with the 1.75–1.70 Ga Mojave-Yavapai suturing event and the 1.65 Ga Yavapai-Mazatzal suturing event, respectively. Direct evidence that low melting point materials reside in the mantle lithosphere beneath these regions comes from mantle xenoliths (e.g., Helmstaedt et al., 1975) and geochemical study of magmatic intrusions (Carlson and Nowell, 2001). However, this lithospheric suture model may fail to explain the Yellowstone volcanic track where no suture has been documented. Yet, it has been noted that the Yellowstone volcanic track does follow a Proterozoic structural trend and is coincident with a major crustal shear zone (the Madison shear zone; Erslev, 1993) that is coincident with a prominent magnetic and gravity lineament (Lemieux et al., 2000). If this crustal shear zone penetrates the entire lithosphere, it could provide a favorable rheologic anisotropy along which a lower lithosphere convective downwelling could develop, especially when the lithosphere is extending as it is along the Yellowstone hotspot.

These are end-member models, and the suggestion that either the lithosphere or the asthenosphere fully controls the evolution of these low-velocity trends is almost certainly incorrect because of the strong feedbacks between lithospheric and

asthenospheric dynamics. For instance, to trigger the melting of low-solidus materials in suture zones requires an increase in heat input from the mantle and/or lithospheric thinning. One possible process to increase the heat input into the lithosphere would be to place the suture over the top of an upwelling asthenospheric roll. However, as the suture zone is rheologically weakened by the input of asthenospheric heat and melt, extensional deformation could localize along the upwelling, which would further enhance the asthenospheric upwelling. In the end, perhaps the young volcanic activity east of the central Basin and Range results from the parallelism between North America's absolute plate motion and the northeast-trending Proterozoic suture and/or shear zones. This scenario would favor the organization of the asthensosphere into convective rolls parallel to the dominant northeast-southwest trend of the lithospheric boundaries discussed.

CONTINENTAL DYNAMICS–ROCKY MOUNTAINS PROJECT TOMOGRAPHIC IMAGE

A critical test of the importance of the lithospheric controls is to evaluate how thick the lithosphere is in the Rocky Mountain region and whether the lithosphere changes across old boundaries. Figure 3 shows new high-resolution tomographic images of the compressional- and shear-wave velocity structure beneath the Continental Dynamics–Rocky Mountains project (CD-ROM) transects. The 73% variance reduction of these images, along with resolution tests, indicates that these are high-quality images. The P- and S-wave images are well correlated, which suggests that the large-scale features in these images are correct. These transects were designed to image the deep structure beneath two major geologic boundaries in the Rockies. The Cheyenne belt is a suture in southern Wyoming between the Archean Wyoming craton to the north and the accreted Proterozoic island arcs to the south (Karlstrom and Houston, 1984). The Jemez lineament is an alignment of young volcanic centers in New Mexico that is believed to coincide with the boundary between two of the
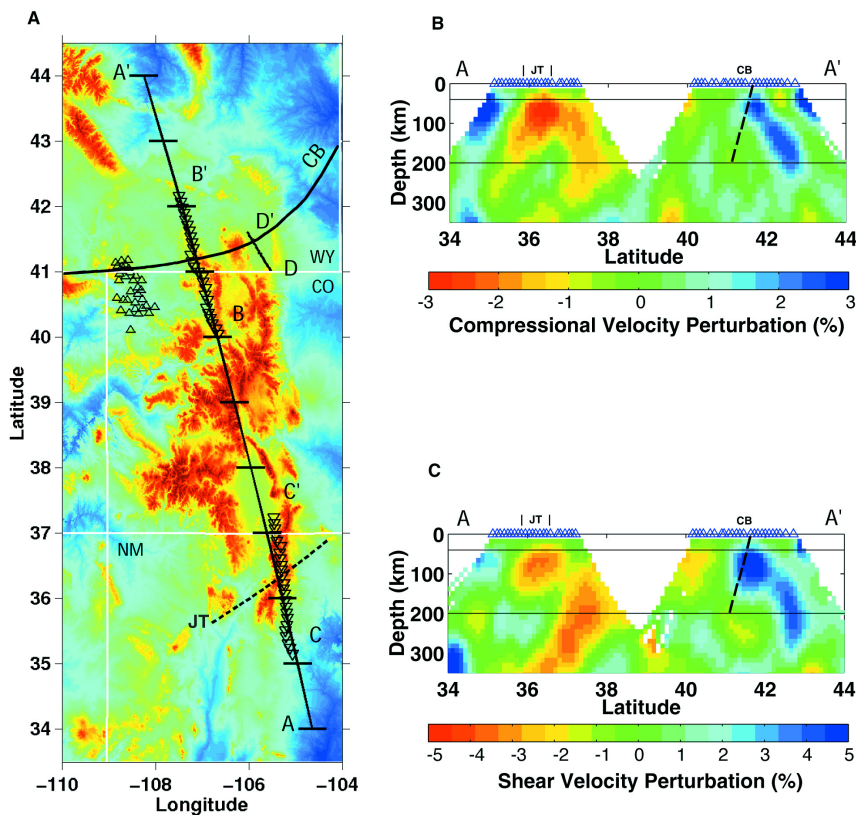
Figure 3. Tomographic image of P- and S-wave velocity variations beneath Continental Dynamics–Rocky Mountain project (CD-ROM) transects. Color bar denotes percent variation of velocity anomaly, with red and blue representing slow and fast velocities, respectively. CB—Cheyenne belt; JT—Jemez trend. Dashed black line under CB is deep expression of suture as found in Fig. 4. **A:** Topography and cross-sectional lines for Figs. 3 and 4. CD-ROM PASSCAL/IRIS broadband stations denoted as triangles. WY—Wyoming; CO—Colorado; NM—New Mexico. **B:** P-wave image. **C:** S-wave image.

Proterozoic arc terranes—the Yavapai province to the north and the Mazatzal province to the south (Karlstrom and Humphreys, 1998).

Beneath the Cheyenne belt, the primary structure seen in the tomography is a north-dipping, high-velocity "slab," which extends to 200 km depth. If this feature's velocity anomaly results from purely thermal effects, then it must be of late Cenozoic origin; otherwise, thermal diffusion would have smoothed the sharp lateral velocity variations along its margins. The two possible ways to produce a late Cenozoic thermal anomaly here would be either a convective instability of the lower lithosphere (Schott et al., 2000) or the stalling of a subducting slab. We dismiss the first possibility because the anomaly has features inconsistent with dynamical modeling of convective instabilities, i.e., the anomaly extends all the way to the base of the crust (see

Fig. 4), and it has a 45° dip. The second possibility is dismissed because this feature is more than 1000 km inboard of the western United States plate margin and orientated at a high angle to the Cenozoic plate boundary. Therefore, because the velocity anomaly is correlated directly with an old suture, we interpret it to be a fossil oceanic slab dating back to the time of suturing along the Cheyenne belt at 1.78–1.75 Ga. Of course, the thermal signature of such an old slab would be long gone, thus the slab's velocity anomaly must result from some combination of a compositionally fast structure (e.g., a garnet-rich eclogite "slab" juxtaposed against a pyrolitic mantle) and/or an anisotropically fast structure where the seismically fast crystallographic A-axis of olivine is steeply plunging. We note that a sharp change in shear-wave splitting fast-axis orientation across the Cheyenne suture (Fox and Sheehan,

2001) supports the notion that sharp lateral variations in the lithospheric fabric are present. Given the geologic constraint that the accretion of the first Proterozoic arc along the Archean margin involved long-lived south-dipping subduction (Karlstrom and Houston, 1984), a tectonic model to emplace a north-dipping slab would require a polarity flip of the subduction zone during late stages of accretion of the first Proterozoic arc. In a recent review of the deep structure of Archean-Proterozoic margins, Snyder (2002) reports that cratonic margins, with outward-facing subduction zones, commonly flip subduction polarity during collision; furthermore, he cites the ongoing collision of the Banda arc with Australia as a modern-day example of an arc-continent collision in the process of flipping subducting polarity.

The primary velocity feature beneath the Jemez transect (JT in Fig. 3) is a low-velocity body that extends to 120 km. From a regional context (Fig. 2), this low-velocity body is one of a series of northeast-southwest–trending, upper mantle, low-velocity bodies that reside beneath the Jemez trend. A potential complication with this interpretation would be the adjacent Rio Grande rift. However, Figure 2 shows that the northeast-southwest–trending low-velocity bodies under the Jemez lineament dominate the upper mantle structure of this region, not the north-south–trending Rio Grande rift. This lack of an upper mantle seismic signature is consistent with the quite modest (<30 km) total net dilatation across the Rio Grande rift. Thus, our tomographic images in tandem with the lithospheric geochemical fingerprint of the Jemez volcanics (McMillan, 1998) suggest that the Jemez lineament is the dominant upper mantle structure here, not the Rio Grande rift. Finally, we note the south-dipping low-velocity "pipe" between 150 and 350 km depth (strongest in the S-wave image; Fig. 3C). Interestingly, the projection of this anomaly toward the surface connects it to the low-velocity Aspen anomaly beneath central Colorado (label A in Fig. 2E). One interpretation of this anomaly is as a mantle plume; yet, the 45° dip of the pipe is inconsistent with plume models. Another interpretation, given its strong dip, is as a
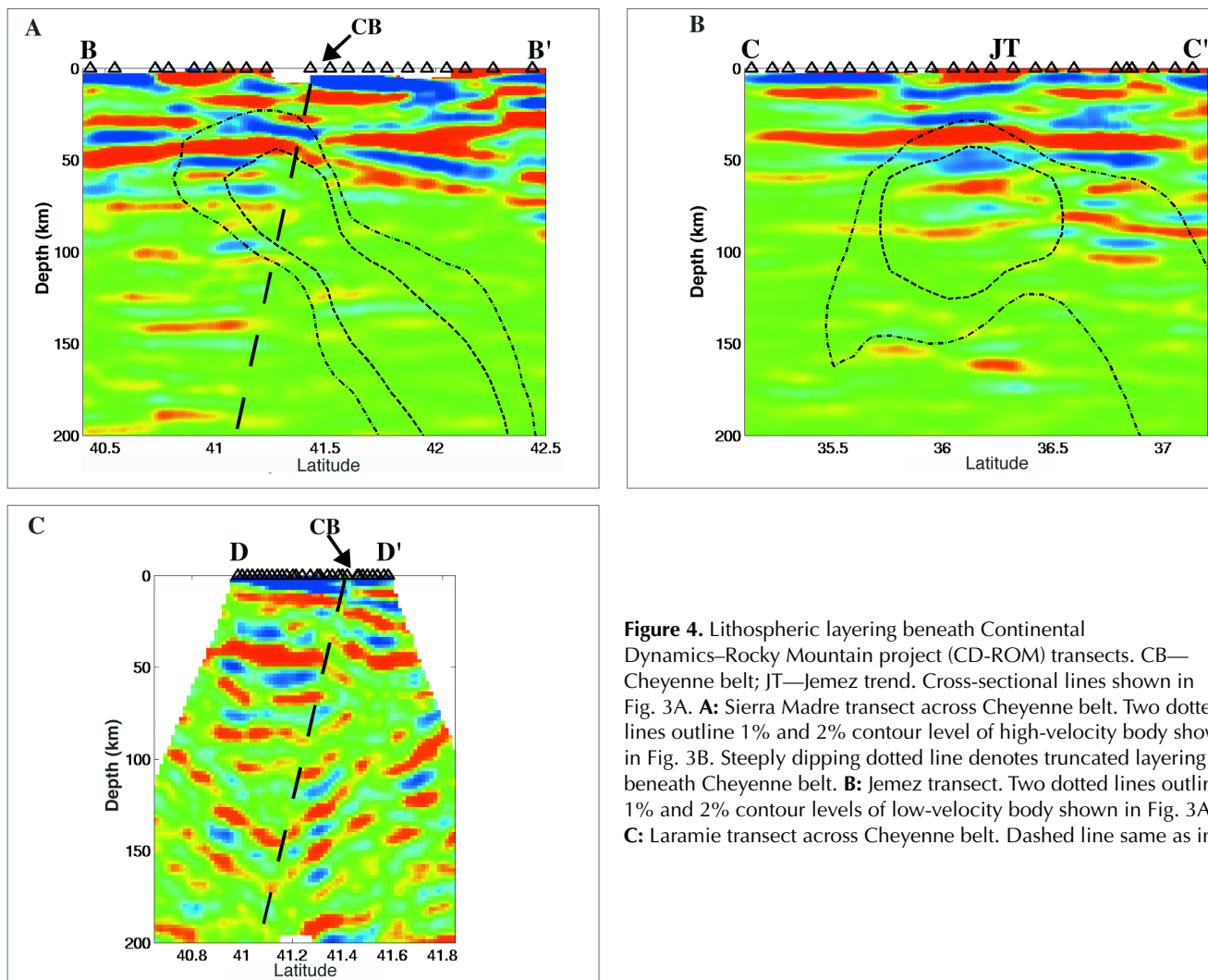
Figure 4. Lithospheric layering beneath Continental Dynamics–Rocky Mountain project (CD-ROM) transects. CB—Cheyenne belt; JT—Jemez trend. Cross-sectional lines shown in Fig. 3A. **A:** Sierra Madre transect across Cheyenne belt. Two dotted lines outline 1% and 2% contour level of high-velocity body shown in Fig. 3B. Steeply dipping dotted line denotes truncated layering beneath Cheyenne belt. **B:** Jemez transect. Two dotted lines outline 1% and 2% contour levels of low-velocity body shown in Fig. 3A. **C:** Laramie transect across Cheyenne belt. Dashed line same as in A.

lithospheric zone of low-solidus material that is partially molten. However, this interpretation would require a 350-km-thick chemical lithosphere, which conventional wisdom would say is too thick for this region. Thus, the best answer is: We do not know what this feature is.

LITHOSPHERIC LAYERING IMAGES

In Figure 4, images of shear-wave velocity discontinuities (called reflectors in active source seismology) from the surface to 200 km depth are shown. These images are constructed from earthquake recordings and consequently have much lower resolution than reflection data, but they can be used to image layering to much greater depths. To suppress unwanted reverberations in the image, velocity analysis has been used to identify direct arrivals and their associated reverberations. The red and

blue shading represent significant interfaces with an increase in velocity (red) or decrease in velocity (blue) with depth. For example, in both transects at 40–50 km depth, the Moho is clearly imaged as a velocity increase (red). Given that velocity gradients reflect changes in the composition and/or fabrication of lithosphere, these images provide a snapshot of lithospheric layering or stratigraphy.

Two images of the lithospheric stratigraphy beneath the Cheyenne belt transects show a disrupted Moho directly beneath the surface exposure of the Cheyenne belt (Fig. 4A and 4C). In both transects the Proterozoic lower crust is underthrust beneath the Archean Moho, and mantle layering between the Moho and 100–190 km depth is truncated by the downward projection of a steeply south-dipping Cheyenne suture. In the Sierra Madre

transect (B–B′), the Proterozoic mantle layering appears to truncate at the north-dipping, fossil slab imaged by tomography. Whereas in the Laramie basin transect (Fig. 4C), a lithospheric-scale "chevron fold" is observed between 100 and 170 km depth. This structure may be a fold or just a series of oppositely dipping, truncated reflections that match up. This structure is broadly consistent with the complex shortening history across the Cheyenne belt (Chamberlain, 1998) and further supported by the crustal wedging imaged by the CD-ROM reflection line (Morozova et al., 2001). The occurrences of diamond-bearing kimberlite pipes (McCallum et al., 1975) of Devonian age at the southernmost end of the Laramie transect (near label D in Fig. 3A) are good evidence that the lithosphere extended into the diamond stability field (i.e., 170 km depth). We

suggest that the sharp variations in mantle stratigraphy across the Cheyenne belt are good evidence that the arc-continent collision that formed the Cheyenne belt was a thick-skinned tectonic event with a signature that is still preserved in a 200-km-thick lithosphere.

The New Mexico transect (Fig. 4B) shows some difference with respect to the Cheyenne belt transects. Most notably, the Moho is relatively flat with no break in structure across the Proterozoic-Proterozoic Jemez suture, and there is less coherent structure below 90 km depth. We suggest these observations result from the thermal lithosphere being thinner (i.e., <120 km) and hotter than the lithosphere beneath the Cheyenne belt. However, the observation that horizontal mantle layering exists within the core of the low-velocity body, and the lithospheric geochemical fingerprint of the overlying Ocate volcanic field (McMillan, 1998), suggest that the low-velocity body is lithospheric, not asthenospheric. Further, the weak south-dip of the anomaly is in agreement with a set of south-dipping lower crustal reflectors (Magnani et al., 2001), which suggests an overall southerly dip for a Proterozoic paleosuture in this region. Whether the lithosphere is thinner here because the collisional processes that make continental lithosphere did not thicken the lithosphere as much as beneath the Cheyenne belt, or because there is warmer, low-velocity mantle beneath this region (Fig. 1) that has eroded and/or disrupted the preexisting lithosphere is unknown at this time.

CONCLUSIONS

Our foremost conclusion is that the chemical lithosphere, defined as the material that has been moving as part of the North American plate since the times of lithospheric formation, is thick for both Proterozoic and Archean lithosphere east of the Basin and Range province. This statement is supported by numerous xenolith and geochemistry studies. Thus, even though the subcrustal lithosphere is generally hot beneath the western United States, this mantle has been moving with the North American plate since it formed. To speculate what makes this possible,

we note three outstanding observations: (1) The event that made the Transcontinental Proterozoic provinces (of which the lithosphere of the American Southwest is just a small part) was one of the largest crustal formation events in the history of the planet and suggests a massive interchange of mass and heat between the upper and lower mantle (Van Schmus et al., 1993); (2) The curiously slow cooling of the Proterozoic lithosphere in the southwestern United States (~1 °C/Ma; Bowring and Karlstrom, 1990) requires that a thick chemical lithosphere was constructed by the Proterozoic accretionary event; (3) The juxtaposition of this region next to one of the planet's largest tectospheric roots may shield it from the asthenosphere's convective forces.

ACKNOWLEDGMENTS

REFERENCES CITED

Bowring, S.A., and Karlstrom, K.E., 1990, Growth, stabilization, and reactivation of Proterozoic lithosphere in the southwestern United States: Geology, v. 18, p. 1203–1206.

Carlson, R.W., and Nowell, G.M., 2001, Olivine-poor sources for mantle-derived magmas: Os and Hf isotopic evidence from potassic magmas of the Colorado Plateau: Geochemistry, Geophysics, and Geosystems, v. 2., paper number 2000GC000128.

Chamberlain, K.R., 1998, Medicine Bow orogeny: Timing of deformation and model of crustal structure produced during continent-arc collision, ca. 1.78 Ga, southeastern Wyoming: Rocky Mountain Geology, v. 33, p. 259–277.

Ducea, M., 2001, The California arc: Thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups: GSA Today, v. 11, no. 11, p. 4–10.

Erslev, E.A., 1993, Archean rocks: Beartooth Mountains and southwest Montana, in Reed, J.C., Jr., et al., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 123–132.

Fox, O., and Sheehan, A.F., 2001, Shear wave splitting beneath the CD-ROM transects: American Geophysical Union, Fall Meeting, Abstracts (in press).

Goes, S., and van der Lee, S., 2001, Structure of the North American lithosphere-asthenosphere: Journal of Geophysical Research (in press).

Helmstaedt, H.H., and Doig, R., 1975, Eclogite nodules from kimberlite pipes of the Colorado Plateau; samples of subducted Franciscan-type oceanic lithosphere: Physics and Chemistry of the Earth, v. 9, p. 95–111.

Humphreys, E.D., and Dueker, K.G., 1994, Physical state of the western U.S. upper mantle: Journal of Geophysical Research, v. 99, p. 9635–9650.

Humphreys, E.D., Dueker, K.G., Schutt, D.L., and Smith, R.B., 2000, Beneath Yellowstone: Evaluating plume and nonplume models using teleseismic images of the upper mantle: GSA Today, v. 10, no. 12, p. 1–7.

Karlstrom, K.E., 1999, Introduction to special issues; Part II: Natural tectonic boundaries in lithosphere of the Rocky Mountains: Rocky Mountain Geology, v. 34, no. 1, p. 1–4.

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.

Karlstrom, K.E., and Humphreys, E.D., 1998, Persistent influence of Proterozoic accretionary boundaries in the tectonic evolution of southwestern North America; interaction of craton grain and mantle modification events: Rocky Mountain Geology, v. 33, no. 2, p. 157–159.

Lemieux, S., Ross, G.M., and Cook, F.A., 2000, Crustal geometry and tectonic evolution of the Archean crystalline basement beneath the southern Alberta Plains, from new seismic reflection and potential-field studies: Canadian Journal of Earth Sciences, v. 37, p. 1473–1491.

Magnani, M.B., Levander, A., Eshete, T., and Miller, K., 2001, CDROM structure of the Jemez lineament and Sangre de Cristo Laramide thrusts in northern New Mexico: Geological Society of America Abstracts with Programs, v. 33, no. 5, p. A41.

McCallum, M.E., Eggler, D.H., and Burns, L.K., 1975, Kimberlitic diatremes in northern Colorado and southern Wyoming: Physics and Chemistry of the Earth, v. 9, p. 149–161.

McMillan, N.J., 1998, Temporal and spatial magmatic evolution of the Rio Grande rift: New Mexico Geological Society, 49th Field Conference, Guidebook, p. 107–116.

Morozova, E., Wan, X., Chamberlain, K.R., Smithson, S.B., Johnson, R., and Karlstrom, K.E., 2001, Interdigitizing (Inter-wedging) nature of the Cheyenne belt suture from seismic reflection data: Geophysical Research Letters (in press).

Richter, F.M., 1973, Dynamical models for sea floor spreading: Reviews of Geophysics and Space Physics, v. 11, p. 223–287.

Schmeling, H., 2000, Partial melting and melt segregation in a convecting mantle, in Bagdassarov, N., et al., eds., Physics and chemistry of partially molten rocks: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 567–589.

Schott, B., Yuen, D.A., and Schmeling, H., 2000, The diversity of tectonics from fluid-dynamical modeling of the lithosphere-mantle system: Tectonophysics, v. 322, p. 35–51.

Smith, R.L., and Luedke, R.G., 1984, Potentially active volcanic lineaments and loci in western conterminous United States, in Explosive volcanism: Inception, evolution, and hazards: Washington, D.C., National Academy Press, p. 47–65.

Snyder, D.B., 2002, Lithospheric growth at margins of cratons: Tectonophysics (in press).

Tackley, P.J., and Stevenson, D.J., 1993, A mechanism for spontaneous self-perpetuating volcanism on the terrestrial planets, in Stone, D.B., and Runcorn, S.K., eds., Flow and creep in the solar system: Observations, modeling, and theory: Norwell, Massachusetts, Kluwer Academic Press, p. 307–322.

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.

Van Schmus, W.R., Bickford, M.E., Anderson, J.L., Bender, E.E., Anderson, R.R., Bauer, P.W., Robertson, J.M., Bowring, S.A., Condie, K.C., Denison, R.E., Gilbert, M.C., Grambling, J.A., Mawer, C.K., Shearer, C.K., Hinze, W.J., Karlstrom, K.E., Kisvarsanyi, E.B., Lidiak, E.G., Reed, J.C., Jr., Sims, P.K., Tweto, O., Silver, L.T., Treves, S.B., Williams, M.L., Wooden, J.L., 1993, Transcontinental Proterozoic provinces, in Reed, J.C., Jr., et al., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 171–334.