Evidence for shallow isostatic compensation of the southern Rocky Mountains from Rayleigh wave tomography

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ABSTRACT

In the past decade, seismologists have found that the topography in Colorado correlates with seismic velocities in the upper mantle, not with crustal thickness, and postulated that isostatic compensation of the southern Rocky Mountains takes place largely in the mantle. To test the validity of this hypothesis, we use Rayleigh wave phase and amplitude data recorded in the Rocky Mountain Front PASSCAL Experiment to obtain crustal thickness and shear-wave structure in the crust and upper mantle. The thickest crust in the model is beneath one of the two most elevated regions, the San Juan volcanic field. The other most elevated region in central Colorado, the Sawatch Range, is underlain by crust of anomalously low velocity. The seismically defined mantle lithosphere is thicker beneath the Great Plains than beneath the Colorado Plateau and is largely absent beneath the southern Rocky Mountains, but the correlation of topography with mantle velocities is weaker than the correlation with crustal anomalies. We construct a model that matches the observed Bouguer gravity anomaly primarily with variations in crustal thickness and density by assuming that density anomalies are proportional to the observed velocity anomalies. The anomalous mantle may also contribute to maintaining regional isostasy in Colorado, but its contribution may be much less important than the crust.

Keywords: southern Rocky Mountains, crust, lithosphere, isostasy, Rayleigh wave.

INTRODUCTION

The southern Rocky Mountains have the highest regional elevations and the lowest Bouguer anomalies in the conterminous United States. Locally, the highest elevations in Colorado, centered on the Sawatch Range and the San Juan volcanic field (Fig. 1A), correspond to the most negative Bouguer gravity anomalies (Fig. 1B), suggesting that local isostatic compensation is only moderately affected by the flexure of a relatively thin lithosphere (Bechtel et al., 1990; Lowry et al., 2000). In addition, the relatively short wavelengths present in the Bouguer map suggest that much of the compensation is shallow (Isaacson and Smithson, 1976). However, seismological investigators since 1995 have suggested that isostatic compensation of the southern Rockies occurs largely in the mantle.

A compilation of crustal thickness estimates (Keller et al., 1998) from seismic refraction experiments and receiver function studies shows that although the crust is generally thick beneath the Colorado Rockies, there is no apparent correlation of crustal thickness with elevation (Fig. 1C). For example, the thickest crust is reported in a band east of the Front Range, beneath the high plains. In addition, both P and S wave tomography (Lee and Grand, 1996; Lerner-Lam et al., 1998) reveal lower velocities in the mantle beneath the southern Rocky Mountains than beneath the Great Plains or Colorado Plateau, implying thermal buoyancy and possibly partial melt in the asthenosphere. Because the highest topography apparently correlates with the inferred hottest mantle, not the thickest crust, most recent seismological investigators (e.g., Karlstrom and Humphreys, 1998) have concluded that much of the isostatic compensation of the southern Rocky Mountains occurs in the mantle, not within the crust or at the Moho.

In this study we measured Rayleigh wave dispersion in the Colorado Rocky Mountain region and surrounding terranes and inverted this data set for a model of crustal and upper mantle structure that sheds new light on the compensation mechanism of the southern Rockies. Rayleigh waves are sensitive primarily to shear-wave velocity structure over a range of depths with peak sensitivity at a depth of about one-third of a wavelength. Measuring phase velocities over a range of periods provides better vertical resolution than teleseismic body-wave tomography for velocity structure shallower than 100 km, given the station spacing available in the Rocky Mountain Front experiment (Fig. 1A), although unlike receiver function analysis, Rayleigh waves do not directly resolve velocity discontinuities. The wide distribution of stations and the horizontal propagation of surface waves ensures a more uniform horizontal sampling of structure than was previously possible. We have found that topography and Bouguer gravity anomalies correlate much better with crustal structure than with mantle velocity variations, suggesting that the crust makes significant contributions to compensating the high topography of the southern Rocky Mountains, and mantle compensation may be relatively unimportant.

DATA ANALYSIS AND INVERSION METHODS

We used Rayleigh wave data from teleseismic earthquakes with body-wave magnitudes larger than 5.0 and epicentral distances from 30° to 120°, which were recorded by 35 broadband seismic stations from the Rocky Mountain Front PASSCAL Experiment (Fig. 1A). The ray paths from the earthquake sources to the receivers are dense enough in Colorado (Fig. 1D) to resolve velocity structure in a region with a radius of ~80 km. After correcting instrument responses, we filtered seismograms in 11 frequency bands with center periods ranging from 20 to 100 s, corresponding to wavelengths of 70–450 km. The first

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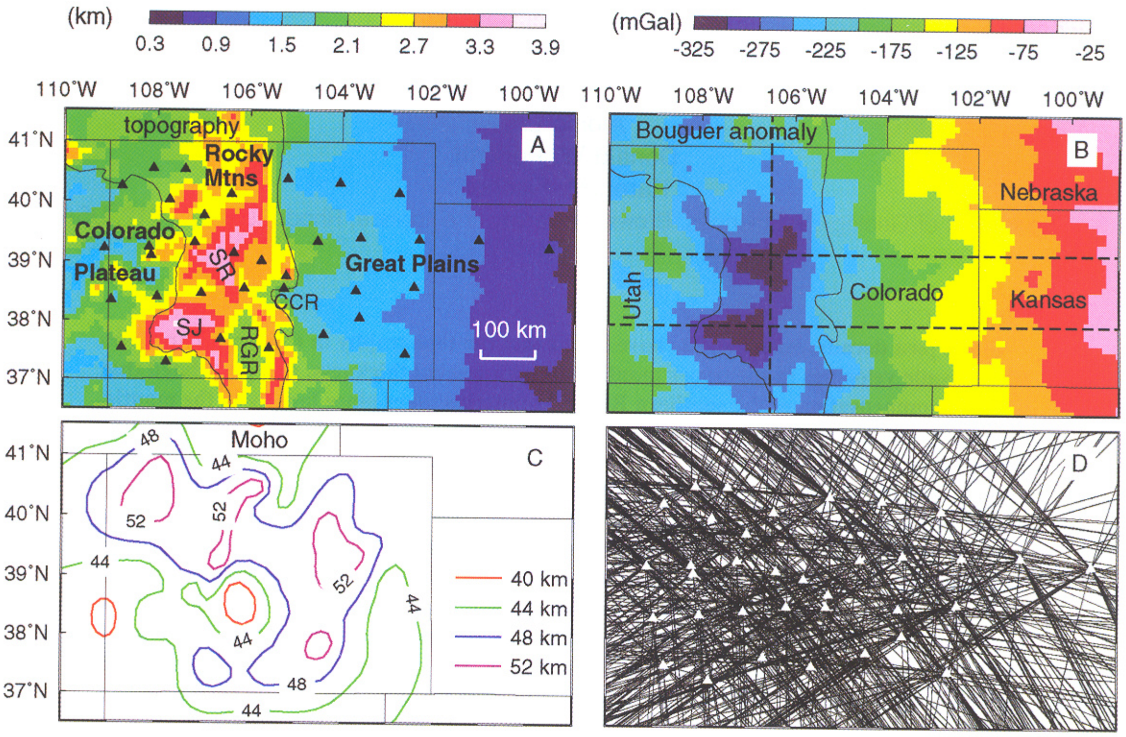

Figure 1. A: Topography of study area. Black triangles represent seismic stations of Rocky Mountain Front PASSCAL Experiment (Lerner-Lam et al., 1998). Black curved lines mark tectonic boundaries, which separate Colorado Plateau, Colorado Rocky Mountains, and Great Plains. CCR is name of station used as reference for starting model. SR—Sawatch Range, SJ—San Juan volcanic field, RGR—Rio Grande rift. B: Bouguer gravity anomaly map. Dashed lines are locations of profiles D–F shown in Figure 2. C: Contour of Moho depth from refraction and receiver function studies (after Keller et al., 1998). D: Great-circle ray paths for Rayleigh waves in vicinity of array from 72 events at period of 40 s. White triangles indicate seismic stations.

step of the inversion is to solve for phase velocities from Rayleigh wave phase and amplitude data. To account for wave-propagation effects, such as focusing and multipathing that occur between the sources and the array, each incoming wave field is represented as the sum of two plane waves with amplitude, initial phase, and propagation direction to be determined in the inversion (Forsyth et al., 1998; Li, 2001). The study area is described by a grid of nodes. Phase velocity at any point in the study area is represented as a weighted average of values at neighboring nodes on the grid. The spatial resolution is controlled by adjusting the characteristic length of the two-dimensional Gaussian weighting function, which is 80 km in this study.

To obtain three-dimensional shear-wave velocity structure, we inverted the 11 phase velocities at each point on the map. Model parameters are crustal thickness and shear velocities in ~20-km-thick layers extending to a depth of 200 km; thicker but ultimately irresolvable layers extend to 600 km. As a starting model, we used the AK135 structure, a global model derived by Kennett et al. (1995), and modified it to agree with the receiver function estimate of crustal thickness (Sheehan et al., 1995) beneath station CCR (Fig. 1A) and to satisfy the phase velocities at that point. In this improved reference model, the S-wave velocity is 3.32 km/s in the upper crust, 3.73 km/s in the lower crust, and 4.47–4.50 km/s in the upper mantle above 200 km. P-wave velocities were coupled to S-wave variations with the same Poisson's ratio in each layer as in the starting model. Because there is some trade-off between crustal thickness and the velocities of the lowermost crust and uppermost mantle, we adjusted the relative damping of crustal thickness and velocity variations to maximize agreement between Rayleigh wave and receiver function data (Fig. 1C), although the latter were not explicitly employed as constraints in the inversion. The resulting model is illustrated in Figure 2. There are three well-resolved, independent pieces of information about the vertical velocity structure: the average velocity in the crust; the Moho depth and/or average velocity from 40 to 70 km; and average velocity from 70 to ~150 km. The three map views in Figure 2 are chosen to represent the best-resolved horizontal layers within each of these depth ranges.

CRUSTAL STRUCTURE

The pattern of crustal thickness beneath the Colorado Rockies from this uniform surface-wave data set (Fig. 2A) is different than the combined refraction and receiver function observations (Fig. 1C), although the variation of crustal thickness is about the same range (40–54 km). We found that the crust beneath the southern Rockies is thicker than beneath the Great Plains or Colorado Plateau, and the crustal thickness correlates well with the topography. The thickness of crust in the northeastern Colorado Plateau in the model increases northward from 42 to 48 km, consistent with the transition of crustal structure from the plateau to the craton observed in seismic refraction profiles (Keller et al., 1998). The crust becomes gradually thinner, from 48 km near the Rocky Mountain Front to 40 km in the Kansas Great Plains, over a distance that is much greater than can be attributed to smoothing and averaging. The thickest crust in the model is beneath one of the two highest regions, the San Juan Mountains in southwestern Colorado.

Two caveats must be borne in mind when interpreting these results. First, the inversion attempts to find the least and smoothest variations that can fit the data, then averages the results with a Gaussian weighting function. Second, surface waves cannot resolve discontinuities, just average velocity over a depth range. Thus, a trade-off is possible between crustal thickness and shear velocity. The crustal thickness beneath the San Juan volcanic field and the northern Rio Grande rift, for example, could be exaggerated if there are strong, low-velocity anomalies associated with melt in the uppermost mantle or lower-

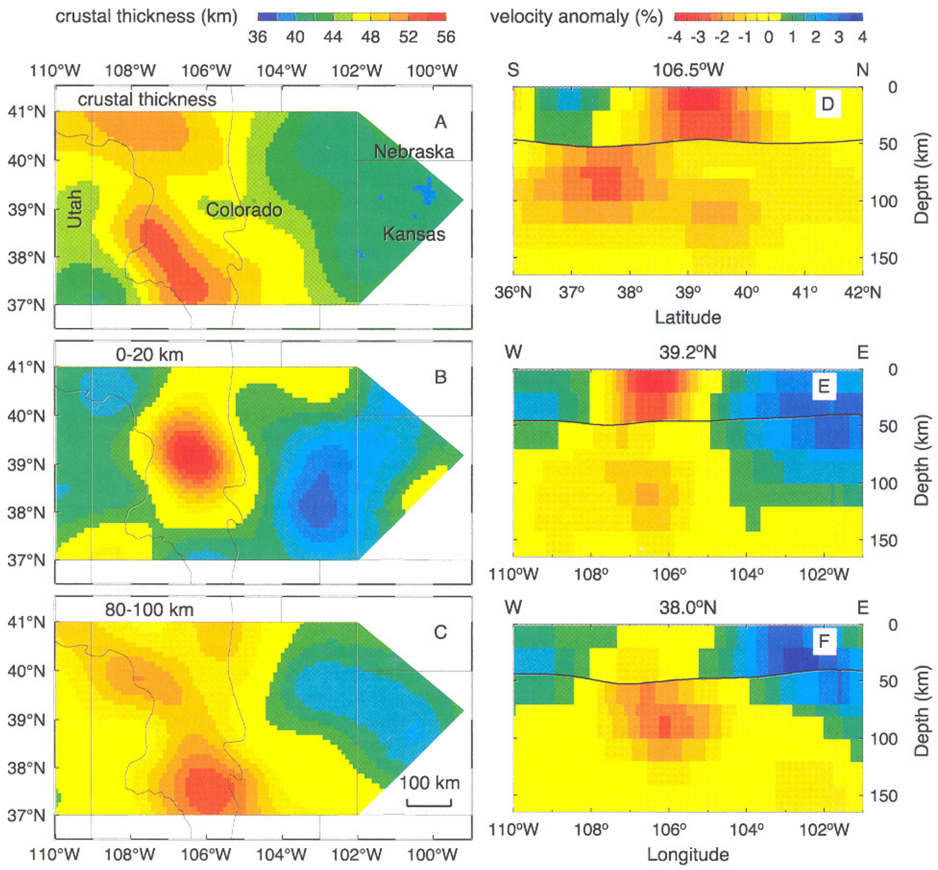

Figure 2. A: Variation of crustal thickness obtained from inversion of phase velocities. B: Shear-wave velocity anomaly in upper crust from 0 to 20 km. C: Shear-wave velocity anomaly in uppermost mantle from 80 to 100 km. In A–C, maps show only area where good model resolution is expected. Even in this selected area, crustal thickness and velocity are less well defined at edges and corners. D: Shear-wave velocity anomaly profile along 106.5°W. Thick black line denotes crustal thickness as shown in A. E: Same as D; profile along 39.2°N. F: Same as D; profile along 38.0°N. Velocity anomalies are calculated relative to improved reference model at station CCR.

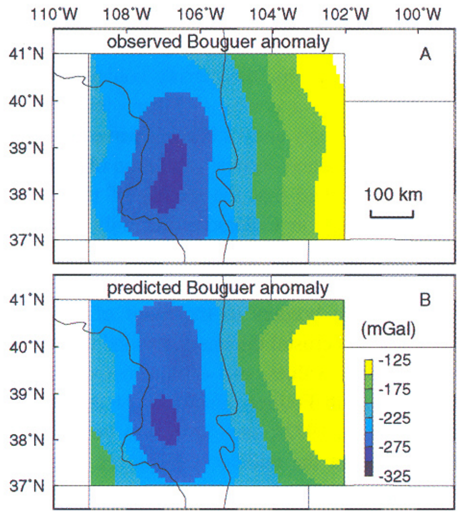

Figure 3. A: Smoothed Bouguer gravity anomaly using Gaussian weighting function with characteristic length of 80 km. B: Predicted Bouguer gravity anomaly calculated from velocity anomalies and Moho variation.

most crust. A 5 km increase in crustal thickness has roughly the same effect as a 3% reduction in shear velocity over a depth range of 40–70 km. A more conservative description of the results in Figure 2A is that there is a good correlation between elevation and average shear velocity in this depth range centered on the Moho.

The poorest correlation between topography and crustal thickness variation is in central Colorado in the vicinity of the Sawatch Range, where relatively thin crust is imaged beneath one of the two most elevated areas of the southern Rockies (Figs. 2A and 1C). This is consistent with the previous observations summarized by Keller et al. (1998). Here we found, however, a pronounced velocity anomaly within the crust (Fig. 2, B, D, and E). The shear velocity is at least 7% lower than beneath the Great Plains. The extremely low velocity crust beneath the Sawatch Range is consistent with the very high heat flow and more felsic composition in this area (Decker et al., 1988), which could be associated with young (10–1 Ma) intrusions in a late Cenozoic rhyolitic complex in the upper crust (Decker et al., 1988).

UPPER MANTLE STRUCTURE

In the 70–150 km depth range, shear-wave velocity is generally low beneath the southern Rocky Mountains, high in the Great Plains, and intermediate in the Colorado Plateau (Fig. 2, C–F). It is interesting that the lowest velocities are not beneath the highest elevations, but instead are found beneath the northern Rio Grande rift in south-central Colorado (Fig. 2, C and D). This low-velocity anomaly continues northward along the extension of the rift into central Colorado (Eaton, 1986; Keller and Baldridge, 1999). Both west-east profiles at 39.2°N and 38.0°N show a fast (>4.5 km/s) lid extending to a depth of ~120 km beneath the Great Plains and slow upper mantle beneath the southern Rocky Mountains (Fig. 2, E and F). This transition from cratonic to tectonic lithosphere near the Rocky Mountain Front agrees with results from body-wave tomography (Lee and Grand, 1996; Lerner-Lam et al., 1998). A relatively fast lithosphere is imaged beneath the Colorado Plateau, but the mantle portion of the lid is thin, supporting the model that nearly horizontal subduction of the Farallon slab mechanically thinned the lithosphere (Humphreys and Dueker, 1994). At depths of 50–120 km, the velocity is ~6% lower beneath the southern Rockies than beneath the Great Plains. Depending on the importance of the anelastic effect (Goes et al., 2000), there could be a 200–600 °C variation in temperature from the southern Rocky Mountains to the Great Plains.

Within the Colorado Rockies, the pattern of anomalies in our model is distinctly different from the shear-wave tomographic image of Lee and Grand (1996). They found the lowest velocities at depths of 50–100 km in central Colorado in a pattern highly correlated with our crustal anomaly (Fig. 2B). We suggest that some of the crustal anomalies may have been inadvertently mapped into the mantle in the Lee and Grand inversion. We find that mantle anomalies correlate generally with the average elevations of different provinces, but the topography within provinces correlates better with crustal velocity and crustal thickness.

BOUGUER GRAVITY ANOMALY AND ISOSTATIC COMPENSATION

To quantitatively estimate crust and upper mantle contributions to isostatic compensation in the Colorado Rockies, we compared the observed the Bouguer anomalies to synthetic Bouguer anomalies based on the velocity structure model. We adopted a simple model in which lateral variations in density within each layer are directly proportional to velocity anomalies. The proportionality constants were chosen to minimize the difference between observed and synthetic anomalies in a least-squares sense. We matched the Bouguer anomalies rather than the topography directly, because the Bouguer anomalies are directly sensitive to subsurface structure and avoid the problem of flexural support of topography. There are only four free parameters in the model: $\partial\rho/\partial Vs$ for crustal layers, $\partial\rho/\partial Vs$ for upper mantle layers, the density contrast across the Moho, and a constant or zero level term, where ρ is density and Vs is shear-wave velocity. The horizontal and vertical resolution of velocity structure dictated that the quality of the fit be measured only in Colorado, and only velocity anomalies shallower than 165 km were considered. We applied a cosine taper 1° wide outside the Colorado borders to the maps of velocity anomaly and crustal thickness, padded the edges with average values, and estimated the gravity signature with Fourier transforms of the anomalies (Parker, 1972); each layer was treated as a mass sheet at the middle of the layer. In order to compare the predicted with the observed Bouguer anomalies, we smoothed the observed anomalies using a Gaussian weighting function with the same characteristic length of 80 km that was employed in the velocity inversion (Fig. 3A).

The inversion yielded $\partial\rho/\partial Vs$ values of 207 $\pm$ 9 kg m^{-3}km^{-1}s^{-1} in the crust and 17 $\pm$ 23 kg m^{-3}km^{-1}s^{-1} in the upper mantle, and the density contrast of 380 $\pm$ 19 kg m^{-3} across the Moho. The Bouguer anomalies calculated with these parameters match the observed pattern in Colorado remarkably well (Fig. 3); the root-mean-square deviation from the mean decreases from 44.9 mGal in the smoothed Bouguer anomaly to 3.4 mGal in the residual. Because the coefficient $\partial\rho/\partial Vs$ in the crust is $>$10 times larger than that in the mantle, it indicates that the mantle contribution to the predicted gravity is smaller, even though it applies to a greater depth range. The solution clearly shows that the variations in crustal thickness and density make significant contributions to regional isostatic compensation.

In the crust, $\partial\rho/\partial Vs$ is two to three times as large as would be predicted for thermal variations alone. In addition, large (200–500 °C) lateral variations in temperature would be required to match the 7% crustal velocity anomaly in central Colorado if they are purely thermal in origin. Thus, it is likely that there is a compositional component to the variation, in keeping with previous suggestions that granitic batholiths in the vicinity of the Sawatch Range are responsible for the gravity signature (Isaacson and Smithson, 1976; Decker et al., 1988). According to Rudnick and Fountain (1995), $\partial\rho/\partial Vs$ is much greater for a change to a more felsic composition than for an increase in temperature; therefore, if part of the crustal velocity variation is due to this composition change, the density variation associated with it could be significant.

Despite the small $\partial\rho/\partial Vs$ of the mantle, we expect there to be some contribution from variations in mantle density. The reason that there is no apparent density anomaly inferred for the mantle probably stems from the pronounced velocity anomaly associated with the Rio Grande rift (Fig. 2, C and D). Locally, the rift forms a topographic low that correlates with low mantle velocities and a small, local Bouguer high, which is opposite in sign to the longer wavelength trend from low elevation and high velocities in the Great Plains to high elevation and low velocities in the southern Rockies. Given two strong correlations of opposite sign, there is no one coefficient that will significantly improve the prediction of Bouguer anomalies from mantle velocity anomalies. No single proportionality constant can describe equally well the relationship between velocity and density for all processes. Variations in temperature, pressure, composition, and the presence of melt will all have different effects on density and seismic velocities. In our simple model, we assumed a single coefficient for the crust and another for the mantle because any other approach would be purely ad hoc, but it is nothing more than a demonstration of the plausibility of crustal compensation, and any individual feature should be interpreted with caution.

Although the low-velocity upper mantle beneath the southern Rockies is presumably hotter and therefore expected to be less dense, the cratonic lithosphere under the Great Plains may be more depleted (Jordan, 1978) than the tectonic lithosphere and asthenosphere beneath the southern Rocky Mountains and the Colorado Plateau, reducing the density contrast expected from the thermal variation alone. Partial melting in the mantle may be responsible for the velocity anomalies in the Rio Grande rift. If the melt is distributed in pockets with low aspect ratio, there can be a pronounced effect on shear velocity accompanied by very little density anomaly. Therefore, it is likely that the mantle $\partial\rho/\partial Vs$ is smaller than that in the crust, as found in our simple model. We conclude that the compensation of the Colorado Rocky Mountains is largely completed in the crust.

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REFERENCES CITED

Bechtel, T., Forsyth, D., Sharpton, V., and Grieve, R., 1990, Variations in effective elastic thickness of the North American lithosphere: Nature, v. 343, p. 636–638.

Decker, E.R., Heasler, H.P., Buelow, K.L., Baker, K.H., and Hallin, J.S., 1988, Significance of past and recent heat-flow and radioactivity studies in the southern Rocky Mountains region: Geological Society of America Bulletin, v. 100, p. 1851–1885.

Eaton, G.P., 1986, A tectonic redefinition of the southern Rocky Mountains: Tectonophysics, v. 132, p. 163–193.

Forsyth, D.W., Webb, S., Dorman, L., and Shen, Y., 1998, Phase velocities of Rayleigh waves in the MELT experiment on the East Pacific Rise: Science, v. 280, p. 1235–1238.

Goes, S., Govers, R., and Vacher, P., 2000, Shallow mantle temperatures under Europe from P and S wave tomography: Journal of Geophysical Research, v. 105, p. 11 153–11 169.

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.

Isaacson, L.B., and Smithson, S.B., 1976, Gravity anomalies and granite emplacement in west-central Colorado: Geological Society of America Bulletin, v. 87, p. 22–28.

Jordan, T.H., 1978, Composition and development of the continental tectosphere: Nature, v. 274, p. 544–548.

Karlstrom, K.E., and Humphreys, E.D., 1998, Persistent influence of Proterozoic accretionary boundaries in the tectonic evolution of southwestern North America: Interaction of cratonic grain and mantle modification events: Rocky Mountain Geology, v. 33, p. 161–179.

Keller, G.R., and Baldridge, W.S., 1999, The Rio Grande rift: A geological and geophysical overview: Rocky Mountain Geology, v. 34, p. 121–130.

Keller, G.R., Snelson, C.M., Sheehan, A.F., and Dueker, K.G., 1998, Geophysical studies of crustal structure in the Rocky Mountain region: A review: Rocky Mountain Geology, v. 33, p. 217–228.

Kennett, B.L.N., Engdahl, E.R., and Buland, R., 1995, Constraints on seismic velocities in the Earth from traveltimes: Geophysical Journal International, v. 122, p. 108–124.

Lee, D.K., and Grand, S.P., 1996, Upper mantle shear structure beneath the Colorado Rocky Mountains: Journal of Geophysical Research, v. 101, p. 22 233–22 244.

Lerner-Lam, A.L., Sheehan, A.F., Grand, S.P., Humphreys, E.D., Dueker, K.G., Hessler, E., Gao, H., Lee, D.K., and Savage, M., 1998, Deep structure beneath the southern Rocky Mountains from Rocky Mountain Front Broadband Seismic Experiment: Rocky Mountain Geology, v. 33, p. 199–216.

Li, A., 2001, Crust and mantle discontinuities, shear wave velocity structure, and azimuthal anisotropy beneath North America [Ph.D. thesis]: Providence, Rhode Island, Brown University, p. 168–213.

Lowry, R., Ribe, N.M., and Smith, R.B., 2000, Dynamic elevation of the Cordillera, western United States: Journal of Geophysical Research, v. 105, p. 23 371–23 390.

Parker, R.L., 1972, The rapid calculation of potential anomalies: Royal Astronomical Society Geophysical Journal, v. 31, p. 447–455.

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

Sheehan, A.F., Abers, G.F., Lerner-Lam, A.L., and Jones, C.H., 1995, Crustal thickness variations across the Rocky Mountain Front from teleseismic receiver function: Journal of Geophysical Research, v. 100, p. 20 291–20 304.

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