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Images of crustal variations in the intermountain west

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[1] We develop a map of crustal thickness variations across the Great Basin, Colorado Plateau, Rocky Mountain, and Great Plains Provinces of the western United States using common conversion point stacking of teleseismic receiver functions. Below the Rocky Mountains and High Plains in Colorado we find the thickest crust in the region at 45–50 km thick. Beneath the Basin and Range, thinner, between 30 and 40 km, crust is found. Thin, 30 km thick, crust is present in the northern portion of Nevada and Utah despite elevations similar to those farther south. Crustal thickness across the Colorado Plateau can be characterized as a broad transitional region between the thin crust of Basin and Range to the thicker crust of the Rocky Mountains. The impedance contrast across the Mohorovicic discontinuity decreases below the Colorado Plateau, as converted arrivals recorded in this region appear weak compared to surrounding areas. Variations in V_P/V_S across the region indicate higher values along the western boundary of the Basin and Range, in the Rocky Mountains, and in the western Great Plains. We are not able to characterize V_P/V_S in the Colorado Plateau. We find that crustal thickness does not closely correlate with surface topography within each region or across the region as a whole. Differences in crustal thickness in each tectonic province indicate the need for a mantle component to support the high elevations across the western United States. *INDEX TERMS:* 7205 Seismology: Continental crust (1242); 7218 Seismology: Lithosphere and upper mantle; 8115 Tectonophysics: Core processes (1507); 8110 Tectonophysics: Continental tectonics—general (0905); 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; *KEYWORDS:* western U.S. crustal structure, Basin and Range extension, Colorado Plateau

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1. Introduction

[2] The western United States has had a varied and complex tectonic history. The combination of compressional and extensional forces in this area during the Sevier/Laramide orogeny and subsequent Basin and Range extension has provided the conditions necessary for its current tectonic state [e.g., *Dickinson*, 1979]. During the Mesozoic a volcanic arc was present at the site of the present Sierra Nevada. Volcanism ceased in the late Cretaceous, and the locus of deformation migrated eastward [e.g., *Burchfiel et al.*, 1992]. In the early Cenozoic the volcanic activity migrated westward from the Rocky Mountains [*Lipman*, 1992]. The high elevations acquired during the Laramide orogeny eventually eroded to a gentle surface [*Epis and Chapin*, 1975] and were subjected to more recent uplift. Over the past 20 Myr the Great Basin has been subjected to 100–200% extension and is characterized by fault bounded mountain ranges, sedimentary basins, and Cenozoic volcanism [e.g., *Jones et al.*, 1992]. The Colorado Plateau, positioned between the Basin and Range and Rocky Mountains, has remained relatively undeformed throughout its history [e.g., *Thompson and Zoback*, 1979; *Morgan and Swanberg*, 1985].

[3] Numerous mechanisms have been proposed for producing the diverse tectonic provinces of the western United States. Some amount of crustal thickening below the Rocky Mountains may be related to the suture zone between the Archean and Proterozoic crust [*Snelson et al.*, 1998; *Keller et al.*, 1998]. Thick crust has been found below the Rockies [see *Prodehl and Lipman*, 1989, and references therein] as well as the adjacent Great Plains. While thick crust is isostatically balanced by the high topography of the western Great Plains, the mechanism for the thickening is poorly understood. The presence of thick crust below both the Rockies and Great Plains may be a relict from crustal thickening during cratonization in the Archean [*Prodehl and Lipman*, 1989]. A portion of the thickening could also be related to magmatic processes such as those in the area of the San Juan Mountains, where locations of thick crust has been found to correlate with locations of large volumes of mid-Tertiary felsic volcanism [*Keller et al.*, 1998]. Tractions associated with the flat subducting Farallon plate in the

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western United States continuing to the Rocky Mountains have been proposed as a factor contributing to the high elevations by transport of lower crust from west to as far east as the Rocky Mountains and western Great Plains [*Bird*, 1984]. An investigation into forces responsible for deformation in the western United States suggested that pre-Laramide subsidence of the Western Interior seaway prestressed the lithosphere such that subsequent deformation was localized in the previously weakened Rocky Mountain region [*Jones et al.*, 1998].

[4] Uplift of the Colorado Plateau has also been attributed to forces originating from within the mantle. *Thompson and Zoback* [1979] found the crust of Colorado Plateau to be 40 km thick and concluded that to be insufficient to support all the elevation, requiring low-density mantle material be involved in the uplift of the plateau. *Morgan and Swanberg* [1985] concluded that the plateau was uplifted by ~2 km from thermal expansion related to magmatic crustal thickening and lithospheric thinning. Conversely, the ratio of geoid elevation to surface topography has been reported to indicate a depth of compensation near 50 km for the Colorado Plateau, which would be consistent with the uplift of the plateau resulting from effects within the crust [*Chase et al.*, 2002]. Several models have been suggested to explain its high elevation, ranging from lithospheric delamination [e.g., *Lastowka et al.*, 2001; *Spencer*, 1996] to crustal thickening due to lower crustal flow [*McQuarrie and Chase*, 2000].

[5] Identification of moderately high compressional seismic velocities (~6.8 km/s) in the lower crust of the Colorado Plateau has led to the suggestion of the presence of mafic rocks possibly associated with magmatic underplating [*Wolf and Cipar*, 1993]. Other investigators have found evidence for mafic material in the lower crust below the plateau [e.g., *Zandt et al.*, 1995]. The addition of mafic material would contribute additional crustal thickness and strength that may contribute to the limited deformation within the plateau [e.g., *Morgan and Swanberg*, 1985]. However, studies comparing seismic velocities from the southwestern portion of the Colorado Plateau to the transition zone of the Basin and Range have found uniform seismic velocities, implying that the lack of deformation within the plateau may not result from compositional variations [*Parsons et al.*, 1996].

[6] Surface wave studies describe an eastward progression of crustal thickening from the Basin and Range to the Colorado Plateau with thicknesses of 32 km in the Basin and Range, 37 km in the transition zone between the Colorado Plateau and Basin and Range, and 42 km for the Colorado Plateau [e.g., *Sheehan et al.*, 1997]. Reevaluating a portion of the data recorded by a temporary array used by *Sheehan et al.* [1997] as well as additional permanent stations, *Lastowka et al.* [2001] also detected an eastward thickening of the crust from the southeastern Basin and Range which they found to only be 35 km thick, while the Colorado Plateau thickens to 42 km. Previous studies, which have recognized thinner crust within the Basin and Range and identified similar composition between it and the Colorado Plateau, have proposed models that infer a preextension crustal structure of the Basin and Range similar to that of the current Colorado Plateau [e.g., *Benz et al.*, 1990; *Wernicke*, 1990; *Kruse et al.*, 1991; *Parsons et al.*, 1996].

[7] The region of the Basin and Range studied here is characterized by high elevations (Figure 1) and high heat flow and is generally accepted to have experienced active east-west extension over the past 15 Myr [e.g., *Wernicke*, 1992]. Seismic refraction and wide-angle reflection data sets in northwestern Nevada have been interpreted to indicate the presence of thin crust that is only 28 km thick [*Benz et al.*, 1990]. Previous investigations using a portion of the same data set presented here similarly found thin crust of only 32 km in the northeastern portion of the Basin and Range with thicker crust in the central and eastern portions of this province [*Ozalaybey et al.*, 1997]. Investigating the region of the Basin and Range studied here, *Sonder and Jones* [1999] proposed potential energy associated with crustal thickening, subsequent removal of the mantle lithosphere, and asthenospheric upwelling as a possible scenario responsible for producing extension.

[8] As is apparent from the brief sampling of previous studies mentioned above, numerous geophysical studies have examined crustal structure and crustal thickness variations within the western United States. While often providing considerable detail on small profiles, significant extrapolation is needed to view the variations across the whole of the western United States. We seek to combine receiver function data from seismic stations located across the Great Plains, Rocky Mountains, Colorado Plateau, and Basin and Range to make one coherent analysis of western United States crustal structure to constrain mechanisms of tectonic development of the region.

[9] Teleseismic receiver functions (records of *P-SV* converted phases) have been used to provide point constraints on crustal structure for three decades [e.g., *Phinney*, 1964; *Langston*, 1977, 1979; *Vinnik*, 1977; *Owens et al.*, 1984]. Recent advances in passive seismic experiment technology and data processing, along with increased data density, have led to improved techniques for determining subsurface discontinuity structure with receiver functions. Common conversion point (CCP) methods take advantage of the lateral coherence between receivers and produce reflection-style images of discontinuities in crust and mantle seismic wave speeds over a variety of scales, rather than spot estimates. By stacking receiver functions recorded by multiple stations that sample the same subsurface area, the signal-to-noise ratio is dramatically improved and small-amplitude features can be resolved. These techniques have led to high-resolution images of mantle discontinuity topography [*Dueker and Sheehan*, 1997, 1998; *Li et al.*, 1998; *Owens et al.*, 2000] and crustal structure [e.g., *Crosswhite and Humphreys*, 2003; *Wilson et al.*, 2003].

2. Data and Method

[10] Here we apply common conversion point stacking of receiver functions to seismic data available from a number of portable Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) seismic experiments in the intermountain west supplemented by data from U.S. National Seismic Network (USNSN) stations (Figure 1). The portable deployments include the Rocky Mountain Front Experiment (RMF) [*Lerner-Lam et al.*, 1998], the Snake River Plain Experiment (SRP) [*Dueker and Humphreys*, 1993], the Colorado Plateau-Great Basin experiment (CPGB) [*Sheehan*

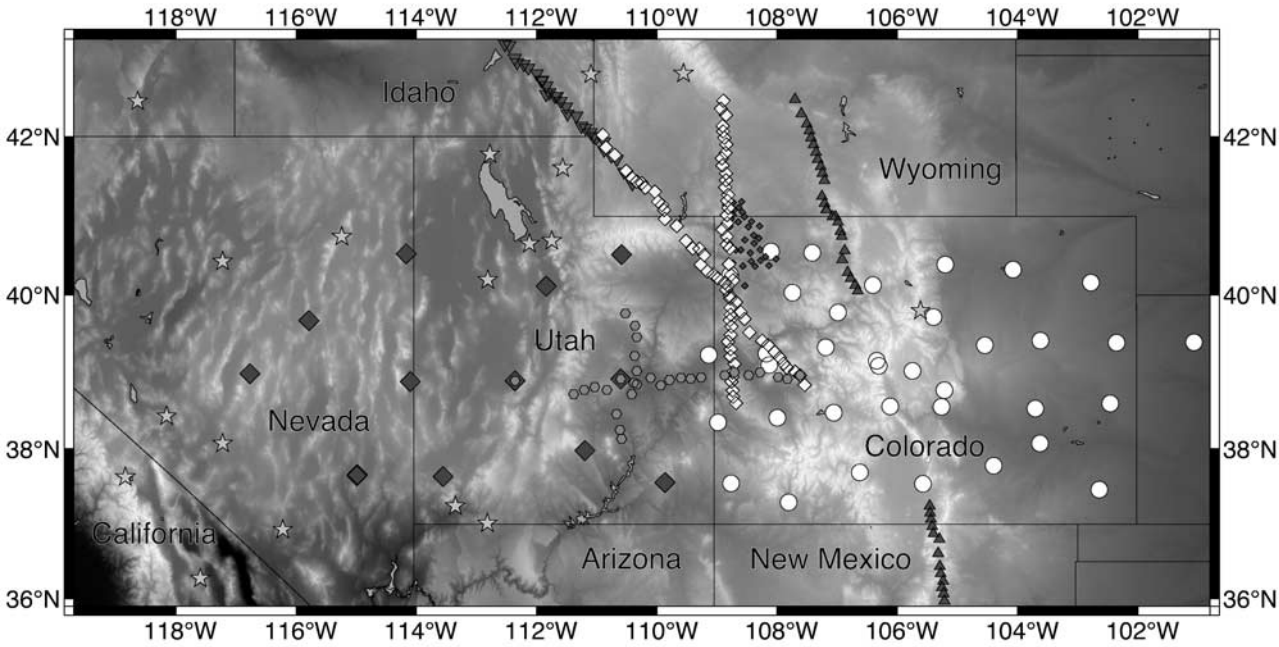


Figure 1. Map of state boundaries and seismic stations comprising arrays in the western United States used in this study. Each different PASSCAL experiment and station contributing to the USNSN network is coded by different symbols. RMF stations, circles; CPGB, large gray diamonds; DPU, hexagons; SRP, inverted triangles; Deep Probe, white diamonds, CD-ROM triangles; Lodore; small gray diamonds; and USNSN, stars.

et al., 1997], the Deep Probe Utah array (DPU) [*Bump et al.*, 1995], the Lodore array [*Crosswhite and Humphreys*, 2003], the CD-ROM experiment [*Karlstrom and CD-ROM Working Group*, 2002], and the Deep Probe experiment [*Crosswhite et al.*, 1999].

[11] Receiver function analysis can be used to constrain discontinuities in shear wave speeds in the crust and mantle. While developed mainly as a tool for examining the crust [e.g., *Owens et al.*, 1984], stacking receiver functions have also been extended to analysis of deep mantle discontinuities such as the 410 and 660 km discontinuities [e.g., *Vinnik*, 1977; *Dueker and Sheehan*, 1997]. A *P* wave impinging at an oblique angle on a discontinuity, such as the crust-mantle boundary, produces a converted *S* wave that travels slower than the original *P* wave. The timing between the direct *P* and *P*-to-*S* converted wave (referred to here as P_dS) is a function of crustal seismic velocities (V_P and V_S) and thickness. All data have been processed uniformly by using a single model to migrate converted phases arrival times to depth. This facilitates comparison between regions, a difficulty with compilations that compare results from a range of data types and processing methods.

[12] In this study, receiver functions are calculated for seismograms with clear *P* wave arrivals on both the vertical and radial components by deconvolving the vertical seismogram from the radial. Prior to deconvolution, seismograms were high-pass-filtered to frequencies greater than 0.02 Hz. The deconvolution is accomplished through an iterative approach that relies on the cross correlation of the vertical and radial component seismograms [*Ligorría and Ammon*, 1999]. During the deconvolution routine, we use a low-pass Gaussian filter width of 2 (corresponding to ~1 Hz). After each iteration the variance reduction of the calculated receiver function is related to the quality of the deconvolution. For our analysis we only used receiver functions with final variance reductions of over 70%. Observations presented here were made using over 2500 radial receiver functions.

[13] To image spatial variations in the depths to the Moho beneath the intermountain west, we geographically bin the ray set and perform CCP stacks of receiver functions. Our receiver function stacking follows the procedures described by *Gilbert et al.* [2003]. Receiver functions are projected along their ray paths at 1 km depth intervals, and piercing point locations are tabulated relative to a grid of stacking bins. Bin centers are spaced 60 km apart, and each bin has a radius of 120 km, resulting in sharing between adjacent bins (Figure 2). Amplitudes of receiver functions within each bin are weighted as a function of the distance between their piercing points and the center of the bin. Weights are assigned to each trace within a bin in a linear manner such that amplitudes of traces at the edge of a bin are weighted half as much as traces at the center. Receiver functions are stacked along moveout curves that adjust for their timing and amplitude variations with incidence angle [*Wilson et al.*, 2003]. Still, it should be noted that the stacked receiver functions represent averaged waveforms that accentuate laterally coherent features.

[14] Paths of *P* waves and converted *S* waves are traced through a model with a constant V_P of 6.4 km/s, based on compilations of previous refraction and passive seismic studies in the area [*Braile et al.*, 1989; *Pakiser*, 1989; *Prodehl and Lipman*, 1989; *Sheehan et al.*, 1995], and a constant V_P/V_S of 1.80. Sensitivity tests, as well as other studies [e.g., *Zandt et al.*, 1995], indicate that crustal thicknesses are much more dependent on the V_P/V_S value

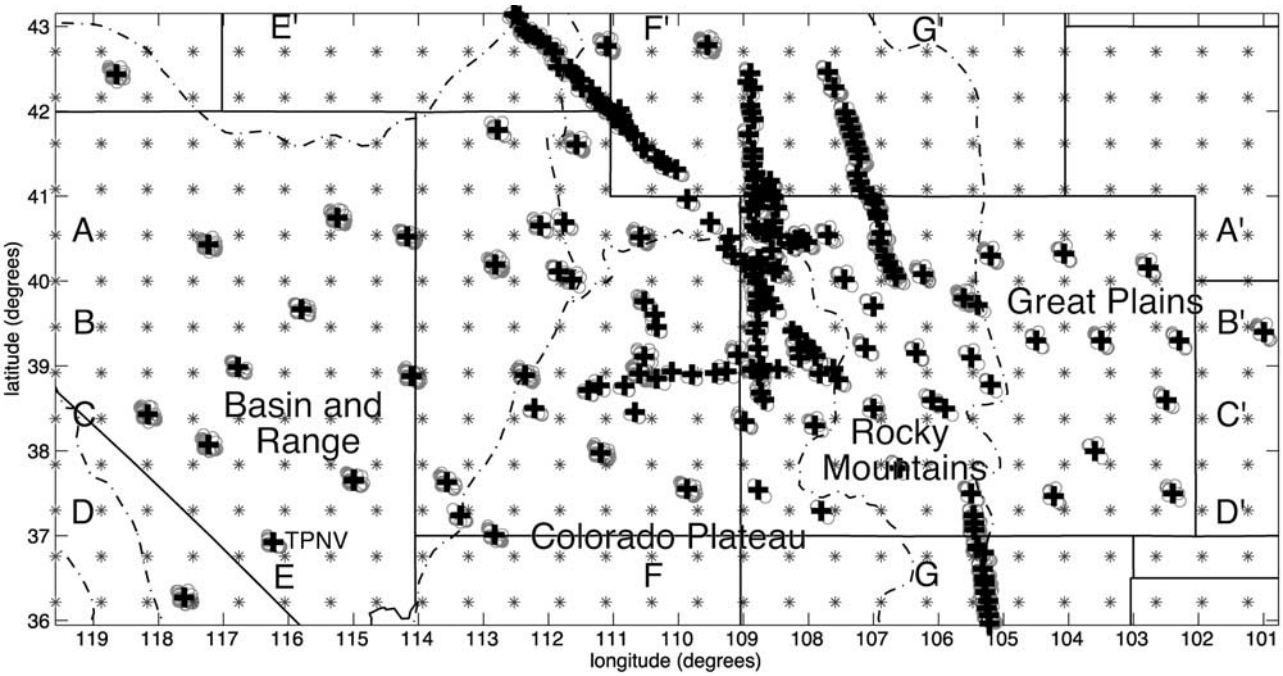


Figure 2. Map showing $P_d s$ wave piercing points (circles), which fan out away from each station with increasing depth. Points shown here correspond to the location of the $P_d s$ ray at 50 km depth. Common conversion point bin locations are shown as asterisks spaced at 60 km. Seismic stations contributing data are shown as black pluses. Boundaries between the Great Plains, Rocky Mountains, Colorado Plateau, and Basin and Range are shown as dashed lines. Also noted are locations of east-west (A-A′, etc.) and north-south (E-E′, etc.) cross sections. Note location of station TPNV in southern Nevada.

used than V_P. Stacked receiver functions for station TPNV in southern Nevada (Figure 2) using 6.4 km/s and 1.80 for V_P and V_P/V_S, respectively, display a peak corresponding to a crustal thickness of 40 km. Increasing or decreasing V_P within the range of 6.0–6.6 km/s changes the depth of the peak by nearly 4 km. Differently, changing V_P/V_S between 1.70 and 1.90 (with a constant V_P of 6.4) changes the depth of the peak over 10 km.

[15] We use a constant P wave speed and V_P/V_S rather than a regional model, such as the tectonic North American model [*Grand and Helmberger*, 1984] or interpolated refraction profiles, to avoid shifts introduced by crustal discontinuities or differences between models. Using a constant model introduces fewer artifacts and permits comparison between regions without concern of features resulting from different models. However, lateral changes in seismic wave speeds affect arrival times and accordingly migrated depths of converted phases. Better knowledge of wave speeds variations across our study area would permit more accurate determination of crustal thicknesses, but a continuous model is not presently available.

[16] A three-dimensional image of crustal structure is constructed by finding crustal thickness within each column of bins in a manner similar to that of *Gilbert et al.* [2003]. We examine the distribution of amplitudes of bootstrapped [*Efron and Tibshirani*, 1986] receiver functions in the depth range of 25–55 km and pick and record their maxima. To determine the depths of the discontinuities, we used the median in the 5 km depth range surrounding the mode (most frequently picked depth) of each distribution. The confidence limits of the pick for each column were then found by determining the depth interval containing 66% of the picks. We exclude estimated depths with broad distributions, where 66% of the picks do not lie within 5 km of the median. The remaining depth estimates are fit to a more finely sampled surface with 10 by 10 km grid spacing using the interpolation method of *Sandwell* [1987].

3. Observations and Discussion

[17] Our CCP receiver function stacks exhibit significant variations in crustal thickness beneath the western United States, both between and within physiographic provinces (Figure 3). We find the thickest crust (50 km) in this region below the Rocky Mountains of central Colorado and the Great Plains of eastern Colorado. Crust near 50 km thick below the Rockies in Colorado has previously been recognized [*Prodehl and Lipman*, 1989]. The thinnest crust (~30 km thick) lies beneath northern Nevada and northern Utah. The Basin and Range of southern Nevada and the portion of the Colorado Plateau in southern Utah possess thicker crust (40 km). Generally, our observations of the changes in crustal structure between the Colorado Plateau and Basin and Range follow the trends of westward thinning of the crust from the plateau into the Basin and Range that have previously been recognized [e.g., *Wolf and Cipar*, 1993; *Sheehan et al.*, 1997; *Lastowka et al.*, 2001]. Individual receiver functions and stacks made from single stations have been inspected and confirm the patterns of thick and thin crust seen from the common conversion point stacking.

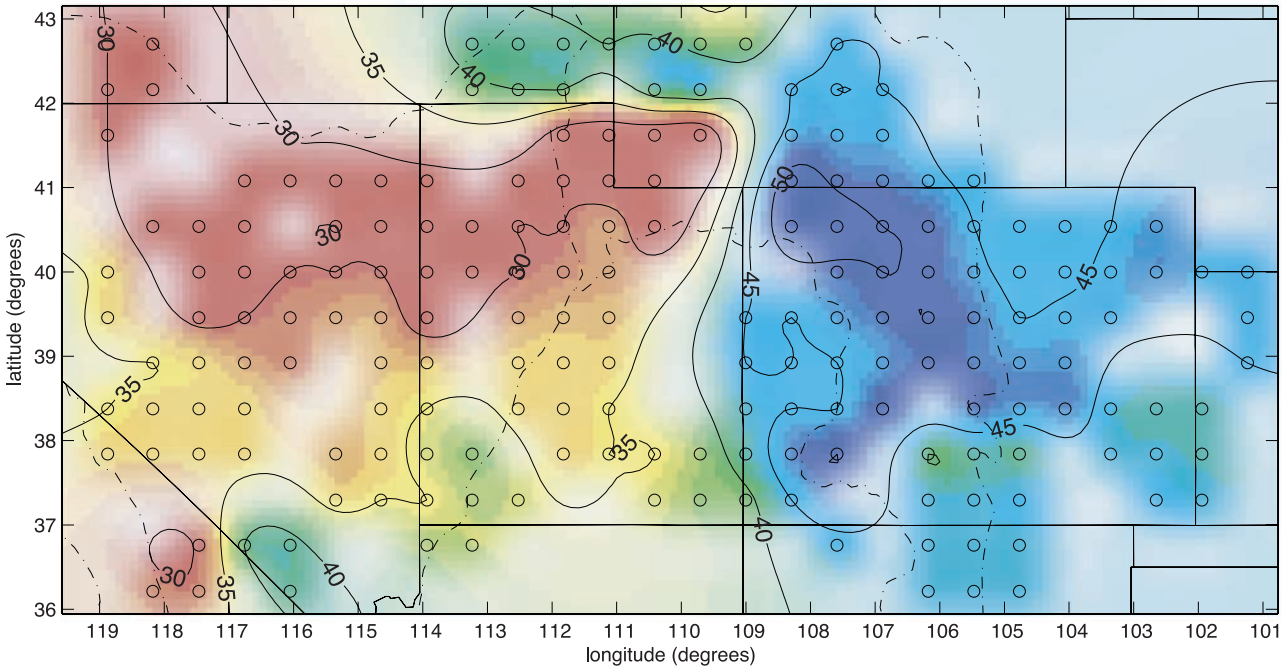


Figure 3. Color contour map of crustal thickness of the intermountain west from this study. Areas of thicker crust are shown as blue colors, while red colors show thinner crust. Thicknesses range between 30 and 50 km. Color saturation is scaled by the standard deviations (σ) of the thickness (least saturated is >5 km uncertainty; the most saturated show $\sigma \leq 1$ km). Locations of bin center points for which thickness estimates are used are shown as circles. Also shown are boundaries (dashed line) between the Great Plains, Rocky Mountains, Colorado Plateau, and Basin and Range Provinces.

[18] For comparison purposes we also present a crustal thickness map for the model CRUST2.0 [*Bassin et al.*, 2000] for this area (Figure 4). CRUST2.0 is a 2° × 2° global crustal model made from a compilation of prior refraction, reflection, and some receiver function results. This model is an updated version of the 5° × 5° CRUST5.1 model [*Mooney et al.*, 1998]. A similar pattern and amount of variations in crustal thickness are present in both our observations and the model CRUST2.0 (comparing Figures 3 and 4). The crust below the Basin and Range is close to 30 km thick in both our study and CRUST2.0; crustal thickness increases to close to 40 km thick in the Colorado Plateau; and in the Rockies, the crust thickens to 50 km. Differently, however, we observe variations in thickness of ~10 km within each the Basin and Range, Colorado Plateau, and Rocky Mountain provinces.

[19] By subtracting elevations of a U.S. Geological Survey surface elevation data set (available at http://gisdata.usgs.net/ned/default.asp) from crustal thickness we calculate the depth to the Moho for each bin that provided a reliable crustal thickness. We smoothed the surface topography data by averaging together elevations within 1° of each bin point, which is close to the size of bins used during stacking and helps remove effects from smaller features that could not be imaged in our map of crustal thickness. Qualitative comparison between Moho depth and surface elevation indicates little significant correlation for this study area as a whole (Figure 5). We observe a weak negative correlation between Moho depth and elevation within the Basin and Range (Figure 5). Significant variations in Moho depth are found below the Colorado Plateau, which does not vary greatly in elevation (black triangles on Figure 5). Although the Great Plains are on average at lower elevations than the Basin and Range, the Moho beneath the western Great Plains is as deep as that found below the high Rocky Mountains (asterisks on Figure 5). Exclusion of the Great Plains from the regression results in a positive but weak correlation coefficient, suggesting a small density contrast across the Moho if elevation differences are to be explained by lateral crustal thickness variations. For the study as a whole, large crustal thickness variations are accompanied by fairly small variations in elevation throughout the western United States. In contrast, between the Great Plains and the Rocky Mountains, large elevation variations are accompanied by very little change in crustal thickness.

[20] East-west and north-south cross sections of CCP stacks are presented in Figures 6 and 7, respectively. The prominent positive arrivals (shown as red in Figures 6 and 7) in the 30–50 km depth range show variations in thickness of the crust. These cross sections illustrate the 20 km of variation in crustal thickness across the region. To compare crustal structure and physiographic provinces, surface topography along the cross sections is plotted above each profile. Midcrustal features can also be found on these cross sections but have smaller amplitudes and are generally less laterally coherent. A midcrustal arrival can be seen on central cross sections (e.g., Figure 6, cross section B-B′) between longitudes 114°W and 112°W deepening to the west in the depth range of ~10–20 km. It is unlikely that arrivals present at this depth result from reverberations or other sources of scattering. Interestingly, these arrivals are limited in location to an area were the Sevier Desert

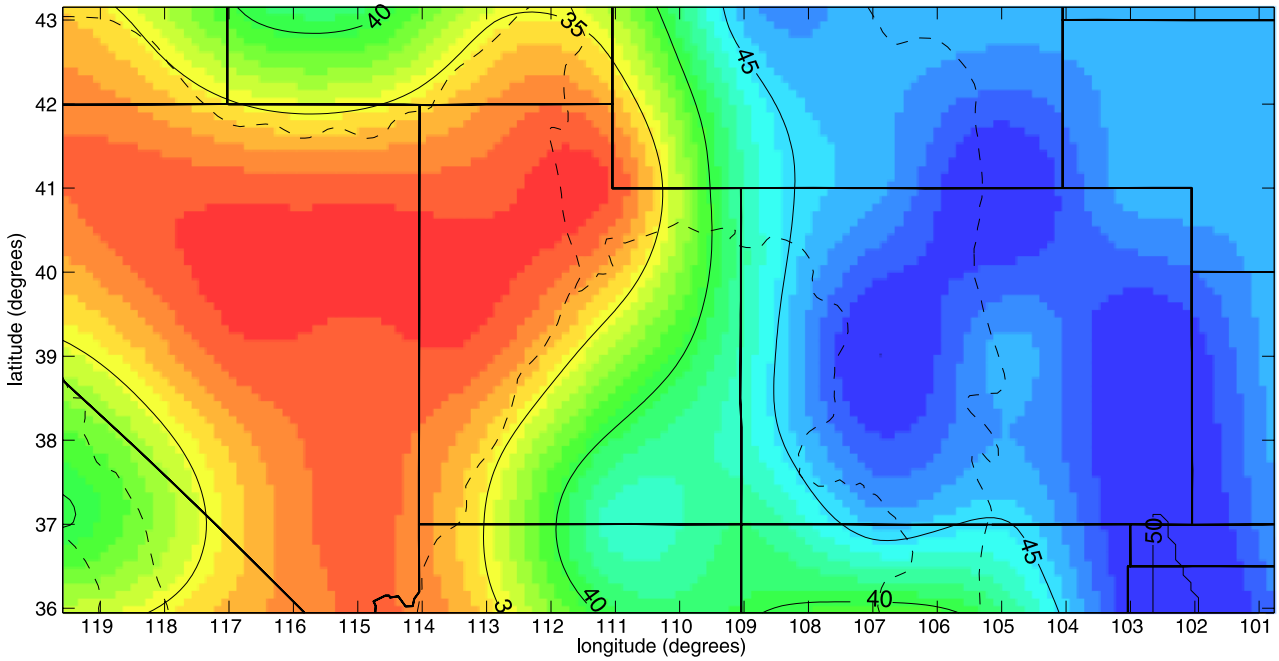


Figure 4. Color contour map of crustal thickness for CRUST2.0 model for this region. Similar to Figure 3, areas of thicker crust are shown as blue colors, while red colors show thinner crust. Thicknesses range between 30 and 50 km. Also shown are boundaries (dashed line) between the Great Plains, Rocky Mountains, Colorado Plateau, and Basin and Range Provinces.

detachment fault was imaged by Consortium for Continental Reflection Profiling (COCORP) studies [e.g., *Von Tish et al.*, 1985]. Detailed modeling of the original receiver functions is warranted to confirm whether or not these arrivals actually relate to the Sevier Desert detachment.

[21] In addition to depth variations shown in our crustal thickness map, differences in crustal structure between tectonic provinces can be seen in the receiver function profiles. High-amplitude-converted phases, indicative of a large impedance contrast, characterize the receiver functions within the Great Plains and Rocky Mountain regions (Figure 6, cross sections A-A′ to D-D′, and Figure 7, cross section G-G′). Receiver functions to the west, in the Colorado Plateau, have smaller amplitude conversions for the Moho and display variations in crustal structure within the plateau (Figure 6, cross sections B-B′ to D-D′, and Figure 7, cross section F-F′). Sharp high-amplitude Moho arrivals are present on many of the receiver functions recorded in the Basin and Range to the west of the plateau, but data recorded in the southern portion of the Basin and Range display complex structure of broad $P_d s$ arrivals varying in-depth that are not present farther north.

[22] By examining crustal structure over an extensive area, details of structural changes associated with boundaries between provinces become apparent. One such area investigated here is the transition from the thin crust in the Basin and Range to the thicker crust below the Rocky Mountains in northeastern Utah and southwestern Wyoming. In map view we find the crust changing in thickness from only 30 km thick in the Basin and Range to over 40 km to the east in less than 100 km horizontal distance (Figure 3). Significant change in crustal thickness from the thin Basin and Range style crust to the thicker crust of the Rockies has previously been reported to occur over a short distance to the east of the Wasatch front [*Braile et al.*, 1974]. The north-south cross section of this area (between latitudes 40°N and 42°N, Figure 7, cross section F-F′) shows that the structure appears to be layered with positive arrivals at depths near 30 and 50 km. Examining this same area on east-west cross sections illustrates that the layers do not extend continuously but instead only overlap for a limited extent between longitudes 112°W and 109°W (Figure 6, cross section A-A′). To better determine the existence of multiple discontinuities in the northwest portion of the Colorado Plateau, we inspected individual receiver functions from this area and found that they exhibit peaks corresponding to depths of both 30 and 50 km. This suggests that multiple discontinuities indeed exist and are not an artifact from stacking.

[23] Previous investigations into structure of the crust near the Wasatch Front have found evidence for a "double Moho" using travel times of local and near regional events [*Loeb*, 1986; *Loeb and Pechmann*, 1986; *Pechmann et al.*, 1984] (see figure describing model of *Loeb and Pechmann* [1986] in work by *Smith et al.* [1989]). A feature observed here (near 30 and 50 km depths on Figure 6, cross section A-A′, between longitudes 112°W and 109°W) appears similar to the complex crustal structure reported by others with a crust 25–28 km thick crust underlain by a second boundary, across which *P* wave speeds jump from 7.4 to 7.9 km/s at 40 km below the Wasatch Front [*Pechmann et al.*, 1984]. This region has also been discussed by *Pakiser* [1989], who reevaluated the seismic data previously used by *Pechmann et al.* [1984] and suggested that the evidence for a double Moho might actually result from

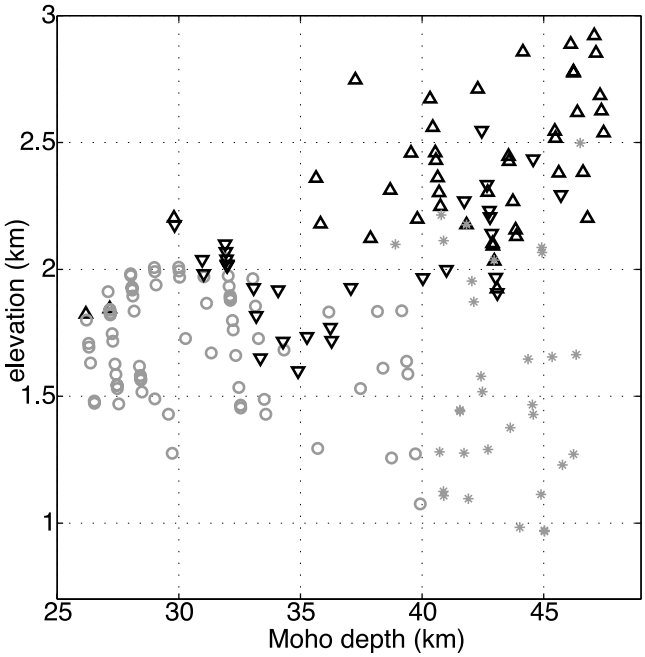


Figure 5. Plot of elevation versus Moho depth for each column of bins. Moho depth was found by subtracting surface elevations from crustal thicknesses. Coded symbols for each province: asterisks, Great Plains; triangles, Rocky Mountains; inverted triangles, Colorado Plateau; circles, Basin and Range.

complications associated with large amounts of variations in Moho depth. Here we find evidence for two discrete overlying discontinuities in shear wave speeds.

[24] The source of what appears as a double Moho remains uncertain from observations presented here. Observations of high heat flow and low Q values in the upper mantle have led previous investigators to propose that partially melted material underlies much of the western United States [*Gough*, 1984]. Possibly underplated material linked to Basin and Range extension is accumulating at its boundary and producing the observed step-like jumps in seismic wave speeds.

3.1. Rocky Mountains

[25] The crust below the Rocky Mountains appears to be between 45 and 50 km thick (Figures 3 and 6). The thickest crust found in our study area lies in northern Colorado below the Rockies. The north-south cross section below the Rocky Mountains clearly illustrates an increase in crustal thickness near latitudes 38°N–41°N (Figure 6, cross section G-G′). Interestingly, however, similarly thick crust does not underlie the Rockies across their entire extent in Colorado, as seen in southern Colorado where the crust thins to 40 km below the Rockies, possibly due to the Rio Grand Rift.

[26] Another area where crustal thickness and surface elevation vary in an uncorrelated manner is within the Great Plains of eastern Colorado (Figure 3 east of ~105°W between 38°N and 41°N) where thick crust (~45–50 km) is present below the Great Plains. The mechanism for crustal thickening below the Great Plains remains unknown. *Bird* [1984, 1988] proposed that transport of crustal material from west to east by the flat Farallon slab produced the thick crust of the plains.

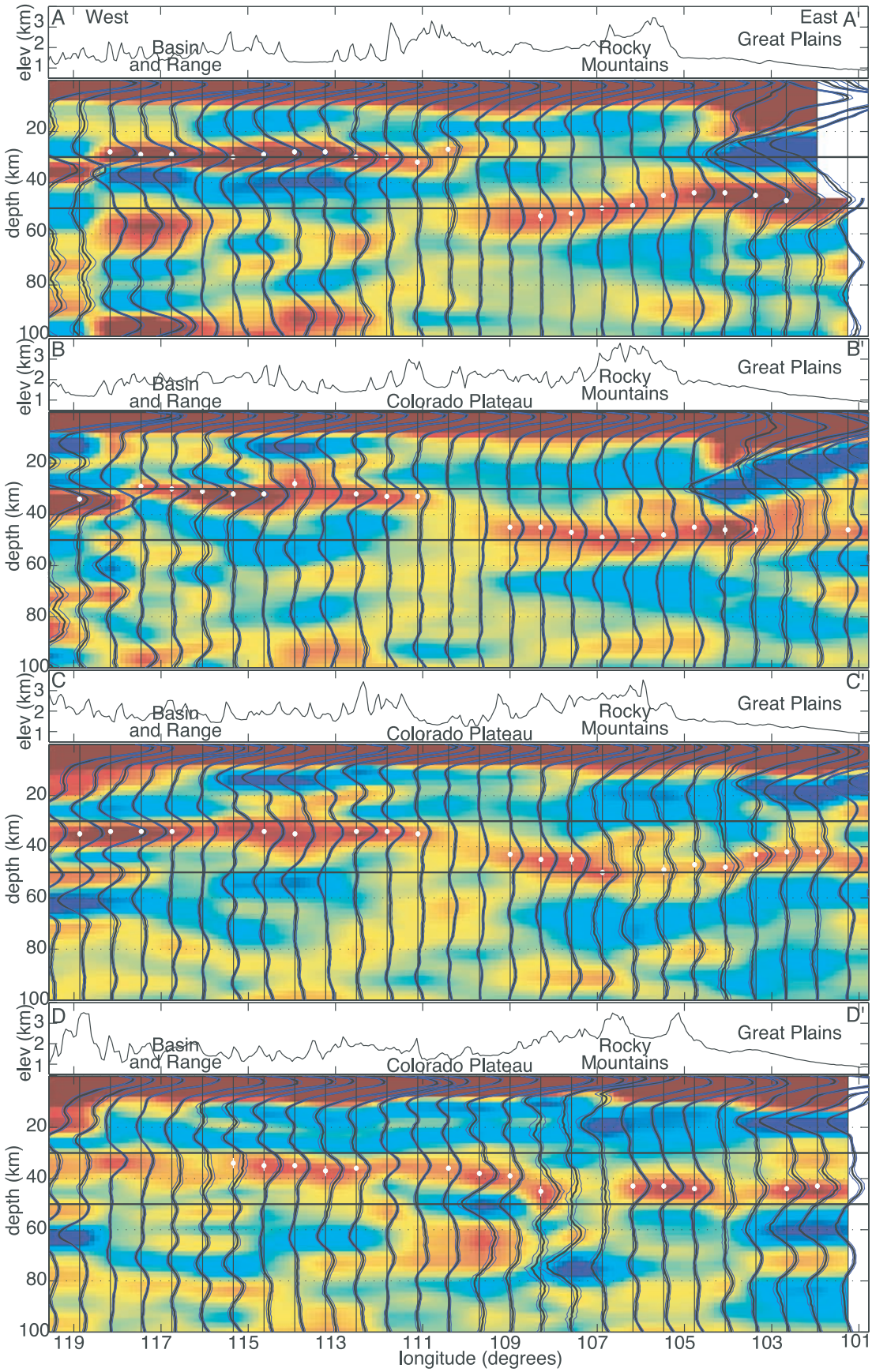
[27] Signatures of smaller-scale crustal structures that have been found within the Rio Grande Rift valley [e.g., *Dueker et al.*, 2001] are not clearly observed here. Previous active source seismic investigations of portions of the Rio Grande Rift valley south of our study area found the crust to thin within the valley and evidence for the presence of a magma body [see *Prodehl and Lipman*, 1989, and references therein]. Lack of observed variations within the rift valley may be due to their dimensions not being detectable within the large bins used here for stacking.

[28] The pulse shapes of $P_d s$ phases recorded in the Rockies are highly variable. Nonuniform widths or amplitudes of pulse shapes on receiver functions can result from lateral changes in sharpness or the conversion coefficient of the interval between two layers. In some regions the pulses appear narrow and have high amplitudes indicative of a sharp narrow interface (i.e., 104°W, Figure 6, cross section C-C′), while in other areas, arrivals appear more diffuse with lower amplitudes possibly resulting from a gradational interface (i.e., 106°W, Figure 6, cross section C-C′).

[29] Effects from sedimentary basins on receiver function stacks appear to be present in eastern Colorado, which is known to be covered by thick layers of sediments as much as 5 km thick, where we observe a delay in the arrival of the radial P arrival. Using forward modeling, we found that sedimentary basins of this thickness that possess low seismic velocities and a high V_P/V_S ratio would affect our crustal thickness estimates by nearly 3–4 km depending in the V_P/V_S ratio of the basin. We are interested in relative variations in crustal thickness of magnitudes greater than this and therefore do not correct for this effect. Comparison of our observed variations in crustal thickness below Colorado to the CRUST2.0 model shows that we find similar thicknesses below eastern Colorado without correcting for sedimentary basins.

[30] Previous studies have identified thick crust below the Rockies in northern Colorado [*Prodehl and Lipman*, 1989; *Sheehan et al.*, 1995; *Snelson et al.*, 1998; *Keller et al.*, 1998]. Comparing the pattern of variations in Moho depth observed here to surface topography, we find regions where the Moho is greater than 40 km deep are present below regions of a range of elevations between 2 and 3 km (Figure 5). Similarly, regions of shallower Moho also underlie regions with elevations between ~2.0 and 2.7 km (Figure 5). Other studies have reported a general lack of correlation between topography and crustal thickness [e.g.,

Figure 6. West to east cross sections of CCP stacked receiver functions. Locations of cross sections are indicated on Figure 2 (A-A′, etc.). Color scale ranges between ±20% (positive, red, and negative, blue) of radial P. Stacked receiver functions are shown in black. Thinner blue lines denote one sigma bounds derived from bootstrap resampling. Circles and error bars show picked depths found within each bin used to make crustal thickness and V_P/V_S maps. Lines are drawn at 30 and 50 km depth for reference.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Basin and Range
Rocky Mountains
Great Plains
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101

Figure 6.

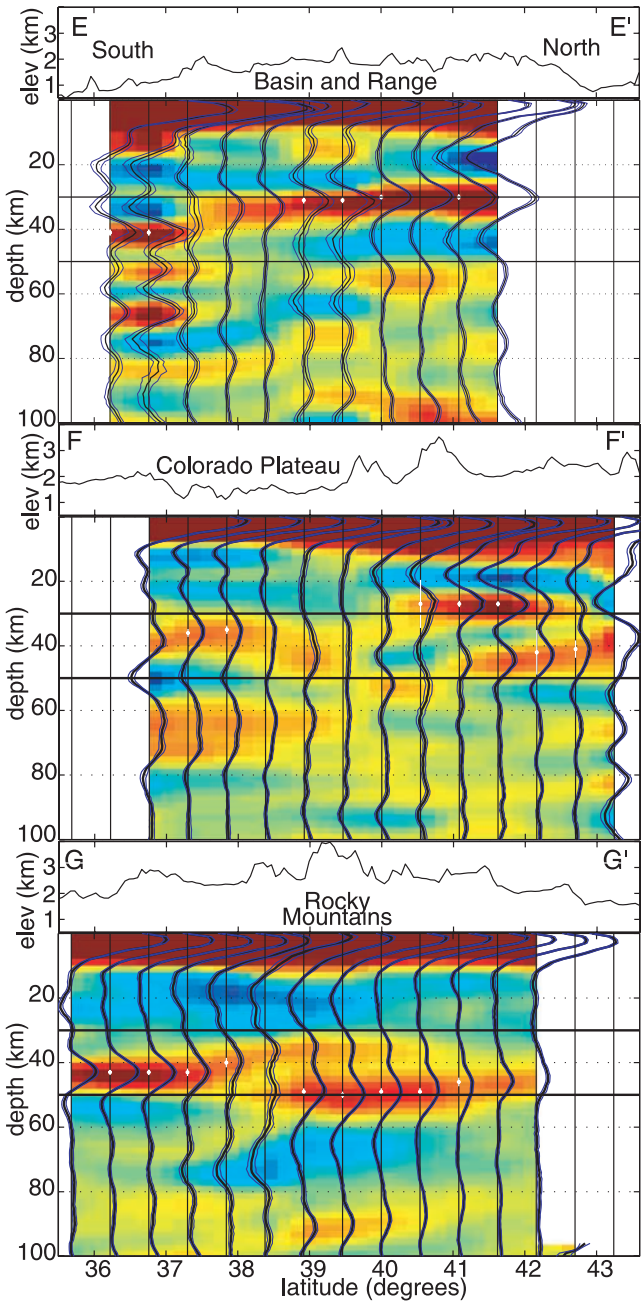

Figure 7. North to south cross sections of CCP stacked receiver functions. Locations of cross sections in the Basin and Range, Colorado Plateau, and Rocky Mountains are indicated on Figure 2 (E-E′, etc.). Color scale ranges between ±20% (positive, red, and negative, blue) of radial *P*. Stacked receiver functions are shown in black. Thinner blue lines denote 1σ bounds derived from bootstrap resampling. Circles and error bars show picked depths found within each bin used to make crustal thickness and V_P/V_S maps. Lines are drawn at 30 and 50 km depth for reference.

Keller et al., 1998; *Sheehan et al.*, 1995] and have found this to imply that the mantle must play a major role in maintaining surface topography.

[31] Detailed passive seismic studies of the Rocky Mountains have reached disparate conclusions regarding the influence of mantle buoyancy on the Rocky Mountains. A shear wave tomographic model [*Lee and Grand*, 1996] and crustal thickness study [*Sheehan et al.*, 1995] found evidence for the need for mantle buoyancy to maintain the high elevations of the Rockies. In contrast, a study using surface waves found that it is possible to construct a model of crustal thickness and shear wave speeds that satisfies observed Bouguer gravity anomalies by placing variations in shear wave speeds between ±4% within the crust [*Li et al.*, 2002], thereby negating the need for isostatic support from the mantle.

[32] The shear wave speeds found by *Li et al.* [2002] indicate at least 7% lower speeds below parts of the Rockies than the High Plains. Using lower wave speeds for the Rockies than the Great Plains instead of the constant model employed here would result in crustal thicknesses decreasing below the Rockies relative to the Great Plains, which in turn would further uncorrelate crustal thickness and elevation. Our findings argue for the mantle providing support for the high elevations; we do not find thick crust to be located solely within areas of high elevation, and some areas with high elevations do not have especially thick crust. The variability of crustal structure within the Rockies may result from the complex history of deformation within the area.

3.2. Colorado Plateau

[33] Determining crustal thickness below the Colorado Plateau becomes more difficult because of the lower amplitude and complexity of converted phases recorded in the region. The diminished amount of converted energy could result from a smaller impedance contrast across the Moho. Additional evidence for a reduced impedance contrast across the Moho below the plateau comes from the identification of a gradational Moho that could result from the presence of mafic material associated with magmatic underplating [e.g., *Wolf and Cipar*, 1993]. *Condie and Selverstone* [1999], however, found that xenolith and seismic evidence collected in the Colorado Plateau does not support the existence of magmatic underplating since its assembly during the Proterozoic. Findings of similar crustal velocities, but different thicknesses, between the Colorado Plateau and the transition zone to the Basin and Range suggest that the crust of the Colorado Plateau represents an unextended version of the crust in the Basin and Range [e.g., *Parsons et al.*, 1996]. We observe that the crust thins to the west from the Rocky Mountains into the Colorado Plateau. The Deep Probe active seismic line found that the crustal thicknesses in eastern parts of the Colorado Plateau to be near 40–45 km thick [*Snelson et al.*, 1998].

[34] Where the southern cross section transects the Colorado Plateau, we observe an arrival at 35–40 km depth with smaller amplitudes than those below the Rocky Mountains (Figure 6, cross section D-D′). The Moho dips slightly toward the east in this region of the plateau. Also visible at this latitude below the Colorado Plateau is an arrival at depths greater than 60 km (Figure 6, cross section D-D′, between longitudes 112°W and 108°W). The presence of this deeper arrival appears to be limited to the region of the Colorado Plateau at this latitude. It is unlikely that this arrival is due to a reverberation from shallower structure

because we do not observe a comparable arrival in the ~20 km depth range that could produce an arrival in this depth range.

[35] Farther north, where cross sections B-B′ and C-C′ transect the plateau, we continue to find P_ds phases to be weaker than those in the Basin and Range and Rocky Mountains (Figure 6, cross sections B-B′ and C-C′). The low-amplitude arrivals that are present in this area appear to be dipping to the east, indicative of crust thinning to the west. Amplitudes of P_ds phases in between longitudes 111°W and 108°W weaken to the degree that we cannot reliably pick crustal thicknesses.

[36] The north-south cross section within the Colorado Plateau illustrates similar complex crustal structure within the plateau and the Rocky Mountain region to the north to that imaged by the higher-frequency study of *Crosswhite and Humphreys* [2003] farther east. Within the Colorado Plateau, multiple arrivals at the base of the crust and in the upper mantle can be seen with a negative arrival between them (Figure 7, cross section F-F′, latitude 37°N to latitude 38°N). The depths of these two positive arrivals vary in an uncorrelated manner with the deeper of the two arrivals reaching its greatest depth to the south where the shallower arrival is shallowest. The negative arrival between the two positive arrivals may result from the presence of seismically slow material associated with underplating.

[37] Crustal structure below the Colorado Plateau has also been found by the Colorado Plateau/Rio Grande Rift Seismic Transect Experiment (LA RISTRA) PASSCAL array of broadband seismometers. This array extended in a line trending from the southeast to the northwest between western Texas and southeastern Utah. Receiver functions calculated from data recorded by the LA RISTRA array in the Colorado Plateau display complex arrivals that may result from crustal layering or a gradational Moho [*Wilson and Aster*, 2003]. Similar to findings presented here for southern Colorado and northern New Mexico, the LA RISTRA study reported crustal thicknesses between 46 and 50 km and the occurrence of 4 km variations in crustal thicknesses over short lateral distances of 100 km for the southern portion of the Colorado Plateau [*Wilson and Aster*, 2003].

[38] In modeling subcrustal lithospheric structure using data from the Polar Anglo-American Conjugate Experiment (PACE) experiment in the southwestern portion of the Colorado Plateau of Arizona, *Benz and McCarthy* [1994] observed evidence of a low-velocity zone in the 40–50 km depth range. The negative arrival that we observe between the positive arrivals in the 35–40 and 60 km depth range (Figure 6, cross section D-D′, between longitudes 111°W and 109°W) could result from the presence of a low-velocity zone. The source of this low-velocity zone has been interpreted to result from the presence of mafic partial melt based on the proximity of Neogene volcanism [*Benz and McCarthy*, 1994].

[39] Regional surface wave models combined with *Pn* observations for the Colorado Plateau found 42 km thick crust and the presence of a mantle lid that is characterized by normal *P* wave speeds of 8 km/s underlain by a low-velocity zone [*Lastowka et al.*, 2001]. The presence of a low-velocity zone in the mantle beneath the Colorado Plateau offers support for a thermal origin that has not yet penetrated the mantle lid contributing to plateau uplift. Observing a low-velocity zone at sublithospheric depths and a mantle lid with normal seismic velocities supports lithospheric delamination models of plateau uplift [e.g., *Spencer*, 1996].

[40] Comparisons between the geoid and topography have been used to suggest isostatic compensation of the Colorado Plateau near 50 km depth [*Chase et al.*, 2002]. This is near the depth of the Moho and would point to the need for little contribution from the mantle in maintaining the topography within the Colorado Plateau. However, we find that the crust thins in the northern Colorado Plateau in a manner that does not correlate with topography (Figure 6, cross section F-F′) allowing for the possibility that contributions from the mantle may play a role in supporting some areas of the plateau.

3.3. Basin and Range

[41] To the west of the Colorado Plateau, the crust thins in the Basin and Range. The eastern border of the Basin and Range in northern Utah is marked by an abrupt decrease in crustal thickness from east to west. Crustal thickness models based on surface wave observations also find thinner crust in northwestern Nevada and that crustal thickness increases toward the east [*Das and Nolet*, 1998; *Lastowka et al.*, 2001]. We find that crustal thickness within the Basin and Range varies between less than 30 and 40 km. The thinnest crust found in our entire study region is in northern Nevada and northern Utah (Figures 3 and 6, cross section A-A′). Across this region where the crust is thin, the crustal structure appears uniform in thickness, with only small amounts of lateral variations. In the northern cross sections (Figure 6, cross sections A-A′ and B-B′) the Moho arrival is very strong (high-amplitude) beneath the Basin and Range, with a depth of just over 30 km. In this region the amplitude of the arrival does not vary. *Benz et al.* [1990] similarly observed homogeneous thicknesses and lower crustal velocities when analyzing data from the 1986 PASSCAL experiment, leading to their assessment that the Moho and lower crust were youthful, in agreement with the post-late Tertiary ages previously suggested [e.g., *Allmendinger et al.*, 1983; *Wernicke and Burchfiel*, 1982].

[42] Our findings of thinner crust in northern Nevada concur with the findings of *Das and Nolet* [1998], who found crust of only 25 km thickness in this area. However, our findings differ in southern Nevada where we find the crust to thicken to 35–40 km thick, while *Das and Nolet* [1998] report that crust in southern Nevada that is only 25 km thick. Increases in crustal thickness from the northern to southern Basin and Range can been seen in both the east-west and north-south cross sections. In the east-west cross sections C-C′ and D-D′ the Basin and Range crustal thicknesses between 35 and 40 km thick are slightly thicker than to the north (Figure 6, cross sections C-C′ and D-D′). The north-south cross section through the Basin and Range illustrates the increase in complexity and thickness of the crust from north to south.

[43] The pulse shapes of P_ds phases in the southern Basin and Range do not appear as uniform in width and amplitude as they do to the north (compare low-amplitude variable pulses at 116°W Figure 6, cross section D-D′, to high-amplitude uniform pulses in Figure 6, cross section A-A′).

As explained earlier, variations in the impedance contrast, or the sharpness of Moho could cause such variations and are indicative of heterogeneous crustal structure. More complex structure in the southern Basin and Range may contribute to the disparity between our crustal thickness estimates and those of *Das and Nolet* [1998].

[44] Differences between crustal structure in central and northern Nevada and southern Nevada follow a pattern that may have been produced by the same factors that contributed to the observed variations in the chemistry of volcanic rocks across the region. Basalts from central Nevada have an isotopic signature similar to ocean island basalts and have been interpreted to originate from the asthenosphere. In this region we find thin crust between 30 and 35 km thick. The abrupt transition between thin and thick crust in southern Nevada coincides with the "amagmatic zone" [*Eaton*, 1982], where trace element and isotopic signatures of basalts, which have erupted over the last 10 Myr, have been attributed to the presence of older lithosphere that possibly has been preserved since the Precambrian [*Farmer et al.*, 1989]. The area of thin crust also matches the locus of mantle upwelling suggested by *Savage and Sheehan* [2000] as inferred by shear wave splitting patterns. Observed north-south variations in crustal thickness across the Basin and Range presented here also correlate with surface heat flow observations that find greater heat flow in northern Nevada where we find thinner crust [*Blackwell and Steele*, 1992]. These observations are in accordance with a closer proximity of warm convecting mantle to the surface in the northern Basin and Range than in the southern.

[45] In determining forces driving extension, *Sonder and Jones* [1999] found that different mechanisms are needed to explain extension in the northern and central Basin and Range. Variations in crustal thickness observed here across the Basin and Range may reflect diverse extensional forces present in different areas. *Sonder and Jones* [1999] favored a combination of factors acting to drive extension in the northern Basin and Range where we find thinner crust. They suggest that the potential energy from thickened crust is needed for extension but that is insufficient on its own and must be followed by the removal of mantle lithosphere and/or any attached slab that was present. Upwelling would follow the removal of material and could explain the high heat flow and asthenospheric source of basalts in the region. In the central Basin and Range where we find thicker crust and variable Moho arrivals, *Sonder and Jones* [1999] suggested that external boundary forces contributed to extension. If forces associated with extension in the northern Basin and Range pushed the Sierra Nevada away from North America, the central Basin and Range would be forced to extend, but the crust in this area need not thin as much as the crust in the northern Basin and Range. Instead, subcrustal material could have upwelled and combined with the existing crust to produce the observed nonuniform Moho structure.

3.4. Variations in V_P/V_S Across the Regions

[46] Variations in Poisson's ratio, or V_P/V_S, can be used to help infer compositional variations within the crust. Poisson's ratio is sensitive to variations in quartz and iron content, partial melt, or the presence of hydrogen. Higher values (>1.74) tend to correspond to rocks with more mafic rocks, while lower values (<1.71) are associated with rocks that contain large amounts of quartz [*Fountain and Christensen*, 1989]. The presence of fluids of partial melt have been found to reduce speeds of shear waves more than compressional resulting in high V_P/V_S values. Additionally, variations in V_P/V_S can help distinguish between mechanisms by which the crust deforms; if dense mafic blobs of lower crust are removed from the lower crust, we would expect the remaining crust to appear more felsic and accordingly possess a lower V_P/V_S.

[47] Methods have been developed using receiver functions to calculate V_P/V_S values based on the arrival times of direct P_ds phases and reverberations of converted P and S (PpP_Ms and PpS_Ms) waves within the crust [e.g., *Kind et al.*, 2002; *Zhu and Kanamori*, 2000; *Zandt and Ammon*, 1995; *Zandt et al.*, 1995]. While sampling the Colorado Plateau and Basin and Range, *Zandt et al.* [1995] found V_P/V_S values to vary between 1.65 and 1.85 with higher values in the plateau. Because calculating V_P/V_S values depends both on the arrival time of the direct and reverberation phases, any error in either will accordingly affect V_P/V_S values. Additional complications result from difficulties associated with picking low-amplitude arrivals and broad pulse widths, which can be the case for reverberation phases.

[48] With these difficulties in mind, we attempt to detect any systematic variations in V_P/V_S across our study area, or if inherent difficulties prevent such analysis. We follow the method used by *Kind et al.* [2002] to find V_P/V_S when stacking data from multiple stations. This method is based on differences in arrival times of direct and reverberation arrivals as outlined by *Zandt et al.* [1995]. Differently from *Kind et al.* [2002], however, we are able to utilize only the PpP_Ms reverberation phase but not the PpS_Ms reverberation. We found the latter to be too low amplitude to be reliably picked. Receiver function stacks made to identify the PpP_Ms reverberation arrival were filtered to lower frequencies with a Gaussian filter width of 1 (corresponding to 0.5 Hz) as compared to the Gaussian filter width of 2 used for stacking the direct arrivals. Crustal thicknesses found for each bin location using stacks of both the direct and reverberation arrivals are converted to arrival times using an average slowness of 6.4 s/km and the same V_P/V_S value of 1.80 that we used to convert time to depth. Arrival times of the direct and reverberation phases are then used to calculate a V_P/V_S ratio for each bin using the relations of *Zandt et al.* [1995].

[49] Tests of using different slownesses demonstrate that our results are not sensitive to the slowness used to convert back to time. However, the results do appear sensitive to the V_P/V_S value used. We use the value of 1.80 here because it produces similar crustal thicknesses for the P_ds and PpP_Ms phases in many locations. Using different V_P/V_S values to convert from time to depth displays greater discrepancies. While the values of the calculated V_P/V_S estimates are sensitive to the value used to convert time to depth (minimum and maximum values of 1.68 and 1.88 using 1.74, while using 1.84 produces values ranging between 1.76 and 2.0), the range in values does not vary greatly. The V_P/V_S values vary by 0.20 between minimum and maximum values when using 1.74, while using 1.84 results in a range of 0.24. Because of these issues, more attention should be paid to relative variations in V_P/V_S than absolute numbers.

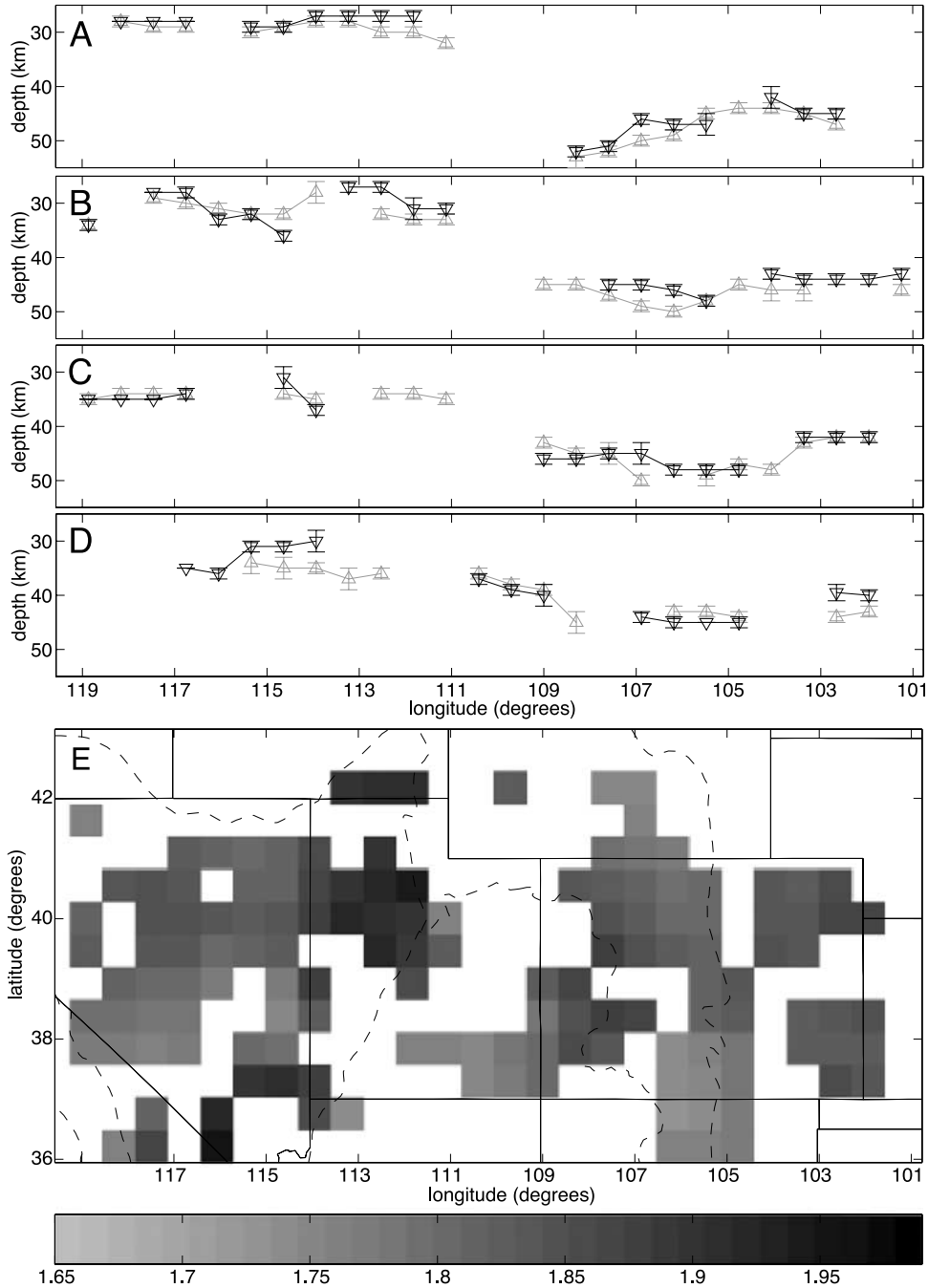

Figure 8. (a–d) Comparison of crustal thicknesses found using $P_d s$ (gray) and $P_P P_d s$ (black) for east-west cross sections A-D. Locations of cross sections A-D are the same as those shown in Figures 2 and 6. $P_d s$ picks are the same as those shown as white circles in Figure 6, cross sections A-A′ to D-D′. Regions with deeper $P_d s$ picks than $P_P P_d$ correspond to higher values and are shaded darker on the V_P/V_S map. (e) Map of V_P/V_S variations. Areas with high V_P/V_S values are shown as black, while regions with low V_P/V_S values are shown as light gray. Complications in picking the phases (as is evident from the cross sections) prevent a more complete presentation of V_P/V_S values. Also shown are boundaries (dashed line) between the Great Plains, Rocky Mountains, Colorado Plateau, and Basin and Range Provinces.

[50] The cross sections of picked depths used to determine V_P/V_S variations show that the reverberation arrivals vary considerably. Such variations would map into correspondingly short-wavelength V_P/V_S variations. It is possible that short-wavelength variations in Moho depths from $PpP_M s$ stacks do not result from actual changes in V_P/V_S or crustal thickness but instead are due to complexities associated with the longer path of the $PpP_M s$ phase. Examples of possible complexities include scattering due to surface topography, effects from nonplanar interfaces, or

velocity heterogeneities on either the P or S paths. In order to mitigate the effects of short-wavelength variations in PpP_Ms arrivals we applied a moving average filter to our V_P/V_S map. Because the P_ds arrivals, which travel a shorter path, are much simpler to pick and do not produce the same short-wavelength variations, we do not interpret the short-scale features that the PpP_Ms arrivals indicate but instead look for larger-scale variations between tectonic provinces.

[51] Crustal V_P/V_S values found here range between 1.73 and 1.95, comparable to the crustal V_P/V_S variations found globally [*Zandt and Ammon*, 1995]. As illustrated in Figures 8a–8e, regions in which P_ds arrivals migrate to deeper depths than the PpP_Ms arrivals (as in longitudes −104°W to −101°W of Figure 8b) possess V_P/V_S values greater than 1.80 (Figure 8e). Conversely, regions in which the PpP_Ms arrival maps to greater depths than the P_ds arrival possess lower V_P/V_S values (as in longitudes −114°W to −116°W of Figure 8b). Low V_P/V_S values would be predicted for regions with predominantly felsic material. The band of high V_P/V_S values trending along the border between the Basin and Range and Colorado Plateau (Figure 8e between longitudes 117°W and 112°E) could result from the accumulation of underplated mafic material. Finding a pattern of higher V_P/V_S values in the eastern Basin and Range than the western Colorado Plateau differs from findings of *Zandt et al.* [1995], who found higher values in the plateau. Thick sedimentary layers with low shear wave speeds in the Great Plains (east of 105°W on Figure 8e) and in the Basin and Range could contribute to regions of high V_P/V_S values. However, the high values present in the Colorado Rockies (Figure 8e, 107°W) may relate to deeper magmatic activity. Faint P_ds and PpP_Ms arrivals in the Colorado Plateau prevent a reliable estimate for the region.

[52] Most of the V_P/V_S variations in our study fall within between 1.75 and 1.85, indicating that using a uniform value of 1.80 during the migration from time to depth should not introduce more than 5 km shifts in crustal thickness. Large V_P/V_S variations ($\geq \sim 0.1$) over short distances mark regions where care should taken when examining crustal thicknesses. The southern Basin and Range is one area where large changes in crustal thickness coincide with large V_P/V_S variations, and it is possible that a portion of the crustal thickness changes result from V_P/V_S variations.

4. Summary

[53] Combining data from multiple seismic arrays provides an opportunity to image variations in the crustal structure below a large portion of the western United States. Receiver function stacks calculated for this study display differences in crustal thickness both within and between tectonic provinces. The thickest crust within this study area, which is close to 50 km thick, resides within the Rocky Mountains and Great Plains. Conversely, below the Basin and Range we find much thinner crust that is only 30 km thick. Between these two distinct provinces the crust below the Colorado Plateau appears to gradually thin to the west. Within each province we find that crustal thickness does not remain constant especially within the Colorado Plateau and Basin and Range where the crust varies between 35–45 km thick and 30 km thick to as much as 40 km thick, respectively.

[54] Observed differences in amplitude of converted phases produced by the Moho result from changes in the impedance contrast across the Moho, which become more apparent by studying a large area. The impedance contrast across the Moho within the Colorado Plateau appears much smaller than that below either the Rocky Mountains or the Basin and Range. Differences in impedance contrast appear to exist within the Basin and Range; a sharp Moho exists in northern portion of the study area, while the impedance contrast appears lower and the broader P_ds pulses suggests that the contrast occurs over a greater depth interval in the south. These differences may reflect different mechanisms contributing to Basin and Range extension. The crust within the Basin and Range thickens to the south, following a pattern similar to that of the impedance contrast across the Moho, which changes from north to south. The pattern of crustal thickness variations is similar to that of isotopic signatures of basaltic volcanism, lithospheric age, and lithospheric thickness.

[55] We also present variations in the V_P/V_S ratio across the intermountain west. Difficulties associated with reliably picking the arrival of reverberation phases within the crust prevent us from presenting a map of the V_P/V_S ratio of our entire study region. Instead, we are only able to discern general trends in this value. The converted arrivals observed across much of the Colorado Plateau are too weak to be able to calculate a V_P/V_S ratio. Future studies with greater sampling density may be able to put additional constraints on variations of the V_P/V_S ratio across this area.

[56] Our study indicates a broad-scale lack of correlation between crustal thickness and surface elevations. Generally, we do find thicker crust below the Rocky Mountains than the Basin and Range and Colorado Plateau, but we also find comparably thick crust below the lower Great Plains and areas of high elevations that are not underlain by especially thick crust. These findings along with observations that variations in crustal thickness within each tectonic province do correlate with topography indicate that simple Airy isostasy is not at play in the intermountain west.

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