Lower Crustal Composition in the Southwestern United States

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The composition of the lower continental crust is well-studied but poorly understood because of the difficulty of sampling large portions of it. Petrological and geochemical analyses of this deepest portion of the continental crust are limited to the study of high grade metamorphic lithologies, such as granulite. In situ lower crustal studies require geophysical experiments to determine regional-scale phenomena. Since geophysical properties, such as shear wave velocity (Vs), are nonunique among different compositions and temperatures, the most informative lower crustal models combine both geochemical and geophysical knowledge. We explored a combined modeling technique by analyzing the Basin and Range of the United States, a region for which plentiful geochemical and geophysical data is available. By comparing seismic velocity predictions based on composition and thermodynamic principles to ambient noise inversions, we identified three compositional trends in the southwestern United States that reflect three different geologic settings. The composition of the lower crust depends heavily on temperature because of the effect it has on rock mineralogy and physical properties. In the Basin and Range, we see evidence for a lower crust that overall is intermediate-mafic in composition (53.7 +/- 7.2 wt.% SiO2), and notably displays a gradient of decreasing SiO2 with depth.

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Key Points:

- A 3D composition model for the lower crust of the southwestern United States by combing seismological and geochemical datasets
- Composition displays lateral variations that follow geologic province boundaries
- Lower crustal composition transitions gradually from more felsic to more mafic with increasing depth

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Abstract

The composition of the lower continental crust is well-studied, but poorly understood because of the difficulty of sampling large portions of it. Petrological and geochemical analyses of this deepest portion of the continental crust are limited to the study of high grade metamorphic lithologies, such as granulite. In situ lower crustal studies require geophysical experiments to determine regional-scale phenomena. Since geophysical properties, such as shear wave velocity (Vs), are nonunique among different compositions and temperatures, the most informative lower crustal models combine both geochemical and geophysical knowledge. We explored a combined modeling technique by analyzing the Basin and Range and Colorado Plateau of the United States, a region for which plentiful geochemical and geophysical data are available. By comparing seismic velocity predictions based on composition and thermodynamic principles to ambient noise inversions, we identified three compositional trends in the southwestern United States that reflect three different geologic settings. Identifying the composition of the lower crust depends heavily on its temperature because of the effect it has on rock mineralogy and physical properties. In this region, we see evidence for a lower crust that overall is intermediate-mafic in composition (53.7 ± 7.2 wt.% SiO_2), and notably displays a gradient of decreasing SiO_2 with depth.

1 Introduction

The composition of the lower continental crust, despite its influence over crust formation and geologic hazards, remains a mystery. Though as thin as 10 km in some regions (Rudnick & Gao, 2003), the lower crust contributes critically to the temperature, structure, and stress state of the continent. Lower crustal deformation models are heavily informed by deep crust silica content, water, and mineralogy (Jackson, 2002). However, because of the relative scarcity (<1% of all samples listed on `http://www.EarthChem.org/`) and the compositional heterogeneity of deep crustal samples, it is difficult to constrain the bulk composition of the lower crust purely through geochemical or petrological measures.

Because the lower crust resides at depths >20 km, its composition can only be sampled indirectly. Granulite facies lithologies serve as metamorphic analogues for the lower crust due to their appearance in exposed crustal cross-sections (Rudnick & Gao, 2003). High grade metamorphic terrains, which have been tectonically emplaced in areas such as the Ivrea-Verbano Zone in Italy or the Fraser Range in western Australia (Fountain & Salisbury, 1981), and granulite facies xenoliths serve as two geochemical windows to the lower crust. As a metamorphic facies, characterized by the dehydration of hydrous minerals (Semprich & Simon, 2014), granulites span a confounding range of mafic (< 52 wt. % SiO_2) to felsic (> 68 wt. % SiO_2) compositions. Such wide variation leads to competing models for the lower crust's composition and density structure, as outlined recently by Dumond et al. (2018).

Combined modeling of high resolution geophysical and geochemical data can place tighter constraints on lower crustal composition. Seismic velocity measurements help differentiate among possible lower crustal compositions when compared to laboratory experiments (Holbrook et al., 1992). We us seismic inversions in conjunction with petrological data in an effort to form less biased lower crustal composition model. In this study, we target the southwestern United States (Fig. 1) as a demonstration of such joint modeling efforts because of the variety of data available for the Basin and Range and Colorado Plateau physiographic provinces.

Global scale models (Laske et al., 2013; Bassin et al., 2000) predict seismic velocities in the Basin and Range that are 10% slower and densities 5% lower than those of adjacent tectonic regions. Slower seismic velocities could suggest that the Basin and Range

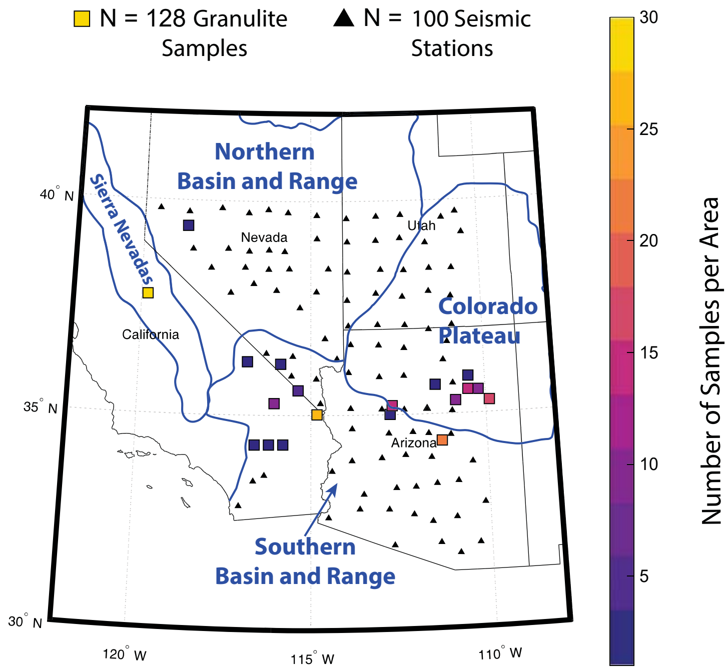

Figure 1: The southwestern United States has been sampled at high resolution through geochemical analyses and ambient noise seismology. The black triangles represent the placement of 100 Earthscope Transportable Array stations whose data were used in this study. Colored squares indicate the location of 128 granulite xenolith and terrain samples used as possible chemical compositions for the lower crust. The color of the squares indicates how many samples were collected from the area covered by the square. The overlaid blue lines demark three geologically distinct sub-regions within the study area.

has a more felsic lower crust than surrounding areas and stands in contrast to local velocity studies (Gao & Lekić, 2018; Shen et al., 2013; Olugboji et al., 2017; Plank & Forsyth, 2016). Both mafic and felsic granulite facies terrains and xenoliths have been extensively characterized in the southwestern US, providing us with a geochemical dataset of 128 samples (http://www.EarthChem.org/). We incorporate high resolution, ambient noise, dispersion measurements (Olugboji et al., 2017; Ekström, 2014) from the Earthscope US-Array (http://www.usarray.org/) project; Moho temperature models from Pn velocities (Schutt et al., 2018); and thermal gradient calculations to derive a distribution of compositions and compositional trends for the lower crust, addressing current model discrepancies.

2 Background

2.1 Compositional Modeling of the Lower Crust

The depth and thickness of the lower continental crust varies regionally and in the context of different studies. The Conrad discontinuity defines the lower crust seismically (Conrad, 1925), but it is not ubiquitous. When the continental crust is split into thirds, the average lower crustal composition is typically $\sim$ 53 wt.% SiO_2 (Rudnick & Gao, 2003). In some areas, however, the "lower crust" may refer to the bottom half of the continental crust, in which case the average SiO_2 becomes more felsic (Hacker et al., 2015). The abundance of SiO_2 in the lower crust is not only a function of lower crustal composition, but also of one's definition of the lower crust. For the purposes of this study, we define the lower crust as simply the bottom half of the crust between 11 km and the Moho (after Schmandt et al., 2015). For example, if the Moho depth were 31 km, the lower crust would have a thickness of $\frac{(31-11)}{2} = 10$ km, and range from 21 km - 31 km depth. We designate 11 km as the thickness of the upper crust because of changes seen in regional Rayleigh wave models from Lin et al. (2014). Though 11 km of upper crust and sediment throughout the entire southwestern United States is a sweeping generalization, it is similar to Roy et al. (1968) 7-11 km thick heat producing layer and Rudnick and Gao (2003)'s 12 km thick upper crust. Keep in mind that our compositional trends are more consequential than our somewhat arbitrary layer thicknesses.

Petrological and geochemical studies of the deep continental crust have sought to define composition through analysis of granulite facies xenoliths and terrains where available, usually analyzing in detail a small (5 - 20) set of samples. Similar practices have been used by many (for example Rudnick & Taylor, 1987; Halliday et al., 1993; Schaaf et al., 1994; Parsons et al., 1995; Al-Safarjalani et al., 2009) to determine the deep crustal structure in regions where samples are available, but it is hard to gauge if these isolated samples are representative of the whole lower crust. While studies of xenoliths provide insight into specific areas of the lower crust, limited sample sets and even smaller sample sizes prove to be recurring obstacles for geoscientists who seek to uncover the composition of the deep crust as it relates to global processes. Seismological crust models, on the other hand, are typically used to describe wide scale crustal phenomena. The use of seismic models for determining lower crust composition requires a conversion between seismic wave velocities and bulk rock compositions, typically achieved through laboratory experiments (for example, Christensen & Fountain, 1975; Holbrook et al., 1992; Christensen & Mooney, 1995). Recent studies (Hacker et al., 2015) give comprehensive assessments of shear and compressional waves velocities of granulite facies lithologies through thermodynamic modeling (calculations are based on empirical, composition-pressure-temperature relationships derived from rock mechanics and mineral physics experiments, and thermodynamic theory).

2.2 Geologic Setting

The southwestern United States has undergone multiple episodes of compression and extension since the Mesozoic (Coney & Harms, 1984). The elevated Colorado Plateau remains relatively undeformed despite being sandwiched between North American Cordillera and the Basin and Range. The Basin and Range province, on the other hand, is characterized by abruptly alternating basins and narrow mountain chains that arose from tensional stress and normal faulting in the Early Miocene (17 Ma) (Coney, 1980). The Basin and Range extended crust, in conjunction with the Colorado Plateau, houses Cenozoic volcanics that are thought to be linked to changes in plate interactions after the conclusion of the Laramide Orogeny (McKee, 1971). The deep crustal xenoliths delivered through Cenozoic volcanic eruptions provide one of our sources of geochemical data. A second data source are the Basin and Range's metamorphic core complexes - a belt of medium- to high-grade metamorphic terrains exhumed through crustal extension (Crittenden et al., 1980). A suite of crust deformation models have been proposed to produce these core complexes (Cooper et al., 2010), each model a different combination of brittle faulting and ductile extension.

3 Methods

We used a three-step joint geochemical-geophysical modeling process to constrain composition. Figure 2 provides a schematic walk-through of the inputs and outputs of each step.

First, we calculated physical properties over a range of pressures and temperatures for local granulite facies samples through the thermodynamic Gibbs free energy minimization software Perple_X (Connolly, 2005). Second, we determined pressure-temperature conditions at 1 km intervals within the lower crust, making the assumption that pressure uniformly increases 1 GPa per 35 km depth, or roughly 28.6 MPa (286 bars) per kilometer. Temperature inputs at the top and base of the crust allowed us to calculate a geothermal gradient and therefore a temperature for each kilometer within the crust, assuming that the top of the crust resides at $5\pm5^{\circ}$C and temperature at the Moho follows Schutt et al. (2018). Third, we compared the Perple_X-calculated shear wave velocities (Vs) of each sample to seismic inversions for Vs. We calculated the probability of each sample producing the observed seismic signal by convolving the two datasets.

In general, we favored the simplest parameter space that could explain the geochemical observations in our dataset. A full explanation of the Perple_X parameters we used and our rationale is given in the Supplement. Olugboji et al. (2017) and Ekström (2014) explain the inversion techniques that produced our seismic profiles.

We evaluated the uncertainties associated with each step of our combined model, allowing for variations in lower crustal thickness, temperature, and seismic velocity (Table 1). Moho depths were assigned a 2 km uncertainty (Shen & Ritzwoller, 2016), and Moho temperature uncertainties range from 50 to 80°C depending on location (Schutt et al., 2018). Combined variations in Moho temperature and depth, and a linear extrapolation of temperature through the crust (Blackwell, 1971) gave us variable temperature gradients throughout the area of study, which we calculated via Monte Carlo simulation. The result is a distribution of possible lower crustal pressure-temperature conditions, which translated to a probability distribution of compositions. Convolving the distribution of Perple_X generated velocities with the seismic shear wave velocities produced our final distribution.

Systematic uncertainties may exist if our fundamental assumption of a dry, granulite facies lower crust is inaccurate. The accuracy of Perple_X's velocity calculations depends largely on this assumption, as a lack of water restricts our compositions to an-

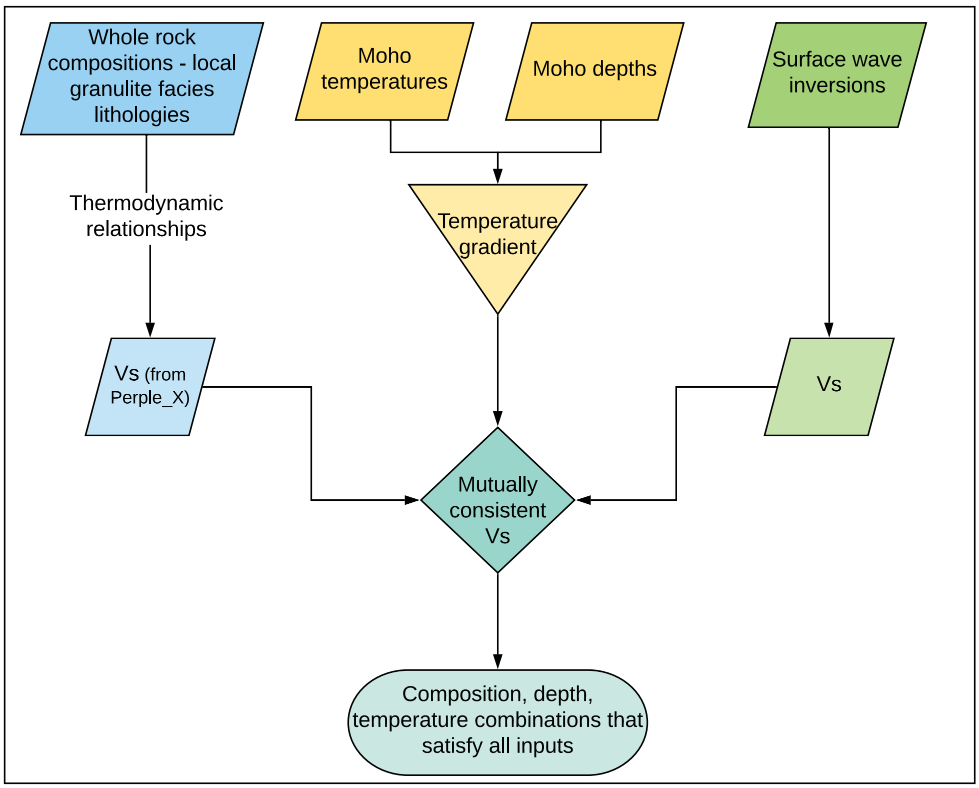

Figure 2: Crust modeling flowchart showing our procedure for finding consistent models based on Vs, temperature, depth, and composition. Seismic velocity map from Olugboji et al. (2017); Moho temperatures based on Schutt et al. (2018); Moho depths from CRUST1.0 (Laske et al., 2013).

Table 1: Uncertainties Associated with Methods

Parameter	Uncertainty
Seismic velocity inversions	full distribution compared to geochemical results, uncertainties on seismic inversion methods given from Gao and Lekić (2018)
Perple_X calculations	$<$ 1% uncertainty from calculations, but subject to unknown systematic uncertainty
Moho temperature	5%-10% (Schutt et al., 2018)
Lower crustal thickness	13% - 25%, assuming absolute uncertainty of 2 km (Buehler & Shearer, 2017)

hydrous minerals. Connolly (2005) offers an overview of the software's free energy minimization technique for calculating mineral assemblages.

4 Results

Overall, the hot lower crust of the southwestern United States trends towards intermediate and mafic compositions. When investigating sub-regional scale variations, however, three separate trends of composition emerge. Joint modeling of surface wave velocities and geochemical and petrological data yields a variety of compositions that depend on temperature. An iterative approach allows us to construct a distribution of probable compositions at each of 100 seismic stations, to account for uncertainties in temperature and composition. Any granulite compositions that were duplicates (i.e. samples whose Vs's or compositions were indistinguishable from another sample's) were removed to avoid artificially weighting our results towards redundantly-sampled lithologies.

Similar velocities and compositions are evident among three sub-provinces of the study area: the Colorado Plateau to the east, the beginnings of the Northern Basin and Range in the northwest, and the Southern Basin and Range in the southwest. As a whole, the shear wave velocities of all three regions range from 3.8 km/s to 4.2 km/s, with about half of the lower crust being faster than 4.0 km/s (Fig. 3). Vp, calculated from Perple_X, often exceeds 7.0 km/s in the Southern Basin and Range and in deeper portions of the Northern Basin and Range and Colorado Plateau. The Southern Basin and Range, which has experienced the most recent tectonic activity, is marked by the thinnest, hottest crust, while the Colorado Plateau has the thickest, coolest crust. Despite comparatively slow Vs in the Southern Basin and Range (3.9 ± 0.1 km/s), its high temperatures (often $>$ 800°C) require a Vp of 7.1 ± 0.1 km/s and a density of 3000 ± 190 kg/m^3 at the base of the crust to satisfy the geophysical model (Fig. 3). The Vp/Vs ratio remains poorly constrained, with uncertainties upwards of 10% encompassing most lithologies (Brocher, 2005). Figure 3 illustrates a change in the median Vp/Vs from ~ 1.79 to ~ 1.72 separating the Colorado Plateau from the Basin and Range, a shift that reflects compositional variation.

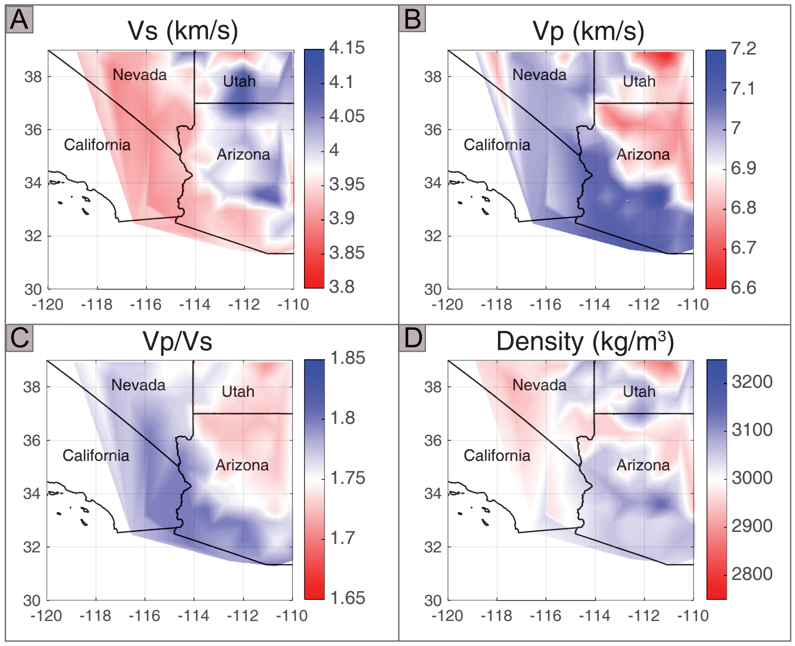

Figure 3: Joint geophysical-geochemical predicted median Vs, Vp, Vp/Vs, and density (3A - 3D, respectively) over all depths for the southwestern United States. The Colorado Plateau is clearly differentiated from the Basin and Range in Vp and Vp/Vs. Hotter temperatures in the south lead to slower Vs but faster Vp and higher densities in the Southern Basin and Range. Blue regions in B, C, and D correspond to more mafic compositions.

Not surprisingly, compositional trends follow velocity trends, forming three distinct compositional provinces. Figure 4 shows representative distributions of SiO_2 content that result from our inversions. The Colorado Plateau, which has the coolest crust and the lowest Vp/Vs ratio, also has the widest distribution of possible compositions (Fig. 4A), which range from 45 to roughly 75 wt.% SiO_2. The Basin and Range favors narrower, more mafic distributions (Fig. 4B and C). Regardless of location, though, mafic lithologies can explain the lower crust's seismic profile more frequently with increasing depth, as shown by the increasing blueness with depth of Figure 4. Figure 5 (and Figure S3) maps reveal clear compositional distinctions among the three sub-provinces. The differences between the intermediate SiO_2 Colorado Plateau, intermediate-mafic Northern Basin and Range, and mafic Southern Basin and Range are most apparent in the shallow lower crust. Both the Colorado Plateau and the Northern Basin and Range increase in MgO and FeO content and decrease in SiO_2 content at greater depths, but the Colorado Plateau does not reach truly mafic compositions until 35 - 40 km depth.

Six mineral groups dominate the modeled lower crustal mineralogy. Clinopyroxene and garnet grow at the expense of quartz and plagioclase and K-feldspars in deeper portions of the crust. Orthopyroxene abundances also decrease by a few weight % with depth. The high abundance (∼3.5 - 16 wt.%) of K-feldspars (which primarily manifests sanidine under simulated pressure and temperature conditions) reflects the alkali-rich, latite-like compositions of crystalline rocks from the southwestern United States (Tyner & Smith, 1986). At shallower pressures and colder temperatures, minerals such as kyanite, sillimanite, or ilmenite can comprise anywhere from 5 - 15 wt.% of the "lower crust".

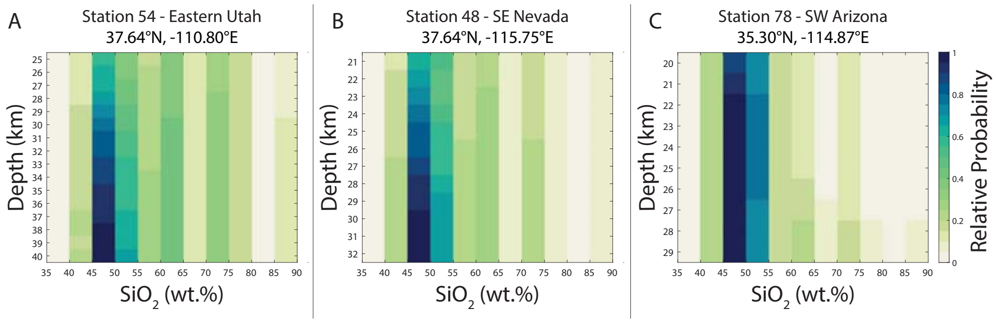

Figure 4: Representative histograms (A-C) of the three "sub-provinces" within the study area show increasing probability of a mafic crust with increasing depth. Color indicates the relative probability of a given SiO_2 abundance explaining the seismic signal at a given depth. The thicker, cooler Colorado Plateau (A) can, on average, accommodate a higher percentage of SiO_2 than the Northern (B) or Southern (C) Basin and Range.

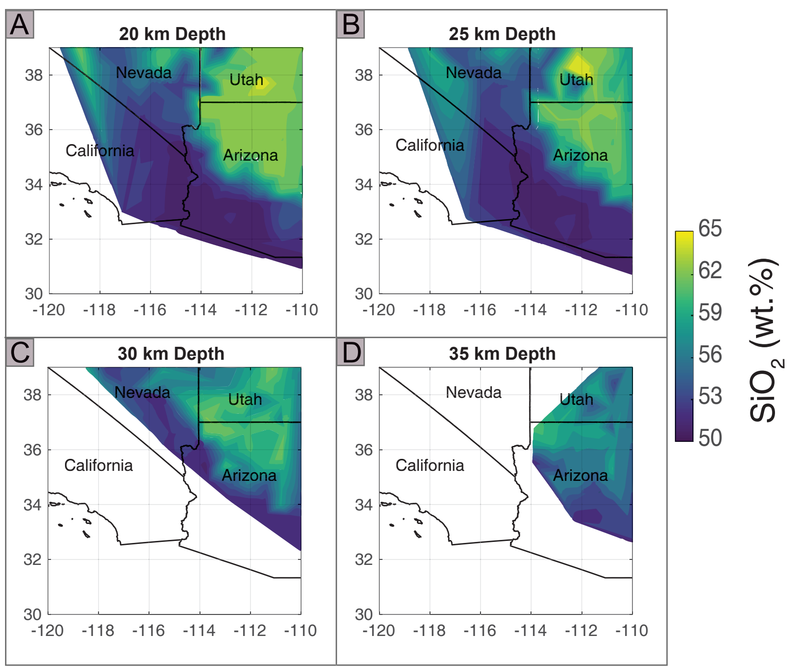

Figure 5: Variability in median SiO_2 abundance in the southwestern United States tracks the Colorado Plateau (high SiO_2), Northern Basin and Range (medium SiO_2), and Southern Basin and Range (low SiO_2). SiO_2 abundance overall decreases with increasing depth (A - D). Color scale indicates wt.% SiO_2. Mantle compositions are not shown in this figure, and therefore deeper profiles (e.g. C - D) show only regions with greater crustal thickness.

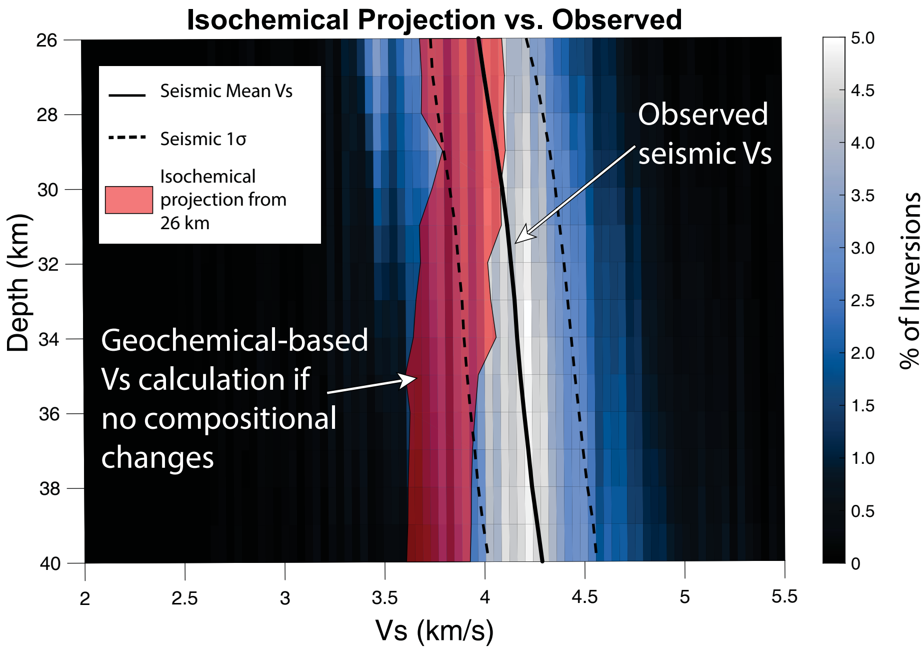

Figure 6: An example of granulite lithologies fitting the seismic signal at the top of the lower crust projected to higher temperature and pressure conditions (red field). This isochemical predicted Vs projection deviates substantially from the mean seismic Vs to the extent that by 38 km depth the distributions are distinguishable at 1σ. (For comparison, seismic Vs is typically reported as mean $\pm$ 1 standard error of the mean. Using this metric, the distributions become distinguishable at 30 km.)

Mineral assemblages simplify at greater depths, with clinopyroxene, garnet, plagioclase, and quartz often controlling >80% of the mineralogy.

Though it is convenient to report one number and an uncertainty as representative for composition, we must be mindful that the shapes of these major oxide and mineral distributions are non-normal and cannot be fully described by simple summary statistics. That being said, whether reporting mean or median value as representative of the lower crust, the trend of vertical change in composition holds true for the Colorado Plateau and Northern Basin and Range (see Tables 2 - 3). The Southern Basin and Range mean composition shows this gradient to a lesser extent, while the median is homogeneously mafic. For the sake of convenience, our interpretations will reference the median $\pm$ $\frac{1}{2}$ the inter-quartile range (IQR) compositions unless stated otherwise. We favor the median and IQR because they are more resistant to outliers than the mean.

5 Discussion

5.1 Lower Crust Composition

One value, one composition, is insufficient for describing the entirety of the continental lower crust. We can describe the lower crust more accurately by reporting changes in velocity, density, and composition as a function of depth and location. The lower continental crust, though less than 8 km thick in some sections of the southwestern United States (Buehler & Shearer, 2017), undoubtedly displays lateral and vertical heterogene-

Table 2: Colorado Plateau SiO_2 Content

Depth	Mean	Median	Standard Deviation	1st Quartile	3rd Quartile
26	60.0	58.8	11.6	50.0	69.7
27	59.8	58.6	11.8	49.5	69.9
28	59.6	58.3	11.7	49.5	69.5
29	59.3	57.8	11.7	49.3	69.2
30	59.0	57.4	11.7	49.1	68.7
31	58.8	56.8	11.8	48.8	68.6
32	58.6	56.2	11.8	48.6	68.1
33	58.3	55.8	11.8	48.5	67.3
34	58.1	55.2	11.7	48.4	66.8
35	57.9	54.7	11.7	48.3	66.4
36	57.7	54.3	11.7	48.3	65.9
37	57.5	53.7	11.6	48.2	65.3
38	57.3	53.4	11.6	48.1	64.8
39	57.1	53.1	11.5	48.1	64.4
40	56.9	52.8	11.5	48.0	64.0

Oxide abundances reported in wt.%.

Table 3: Northern Basin and Range SiO_2 Content

Depth	Mean	Median	Standard Deviation	1st Quartile	3rd Quartile
22	58.3	55.1	10.8	49.9	65.7
23	58.3	55.1	10.9	50.0	65.4
24	58.1	54.7	10.9	49.7	65.0
25	58.0	54.4	11.0	49.7	64.9
26	57.7	54.0	10.9	49.5	64.3
27	57.7	53.9	11.1	49.2	64.2
28	57.4	53.6	11.0	49.1	63.8
29	57.4	53.6	11.1	48.9	64.0
30	57.2	53.4	11.2	48.8	63.6
31	57.0	52.9	11.2	48.6	63.4
32	57.0	52.8	11.4	48.3	63.7

Oxide abundances reported in wt.%.

Table 4: Southern Basin and Range SiO_2 Content

Depth	Mean	Median	Standard Deviation	1st Quartile	3rd Quartile
19	54.6	51.2	10.0	48.0	58.1
20	54.3	51.1	9.9	48.0	57.6
21	54.1	51.1	9.8	47.9	57.0
22	54.0	51.2	9.7	47.9	56.8
23	54.0	51.2	9.7	48.0	56.6
24	53.9	51.1	9.6	47.9	56.3
25	53.9	51.2	9.6	47.8	56.4
26	53.8	51.3	9.6	47.9	56.2
27	54.0	51.4	9.7	47.9	56.7

Oxide abundances reported in wt.%.

Table 5: South Western United States Lower Crust Major Oxide Content

	Mean	Median	Standard Deviation	1st Quartile	3rd Quartile
SiO_2	56.9	53.7	10.6	49.1	63.5
Al_2O_3	16.7	16.1	4.3	14.1	19.5
MgO	5.4	3.8	4.2	2.5	7.3
FeO	8.6	7.7	4.1	5.5	11.4
CaO	7.0	5.6	4.9	2.2	10.6
K_2O	1.6	1.3	1.5	0.4	2.2
Na_2O	2.7	2.7	1.4	1.6	3.8
TiO_2	1.1	0.9	0.8	0.5	1.4

Overall lower crust oxide abundances for the southwestern United States.

Table 6: Summary of Lower Crust Seismic Properties and Mineralogy

	Mean	Median	Standard Deviation	1st Quartile	3rd Quartile
Vs*	3.62	3.61	0.36	3.30	3.64
Vs**	4.02	3.99	0.23	3.86	4.15
Vp	6.94	6.91	0.44	6.59	7.27
Vp/Vs	1.73	1.75	0.07	1.68	1.78
Density	3010	3000	220	2820	3190
Clinopyroxene	17.5	13.3	16.6	3.4	31.5
Garnet	13.0	11.8	8.7	6.5	18.1
K-feldspars	10.9	8.2	6.7	3.4	16.0
Kyanite	3.5	2.5	4.1	0.5	5.3
Olivine	1.3	0.03	5.8	0	0.3
Orthopyroxene	3.0	1.5	4.3	0.2	5.0
Plagioclase	30.3	27.6	14.0	15.5	43.5
Quartz	12.7	10.9	16.1	0.7	27.0

*Vs from surface wave inversions
**Vs from combined surface wave and geochemical model

ity (Fig. 5 and S3). Temperature plays a crucial role in determining lower crustal composition. Both cold intermediate and hot mafic granulites can produce the shear wave velocities of >3.9 km/s observed across the southwestern United States (Christensen & Mooney, 1995). The thicker, cooler crust of the Colorado Plateau (average Moho temperature 700°C, constant gradient of 17.5°C/km) and Northern Basin and Range (average Moho temperature 740°C, constant gradient of 22.4°C/km) can therefore accommodate 55.8 ±9.4 and 53.9 ±7.5% SiO_2, respectively. The Southern Basin and Range, in contrast, must have a predominantly mafic composition of 51.2 ± 4.3% SiO_2 to reach similar Vs because of its thin crust and 800°C temperatures.

The temperature gradient in the lower crust also necessitates a vertical gradient in mineralogy and composition. The crust becomes increasingly mafic with increasing depth. This trend is observed most prominently in areas of thicker crust. The increase in Vs cannot be explained by isochemical chemical changes in the lower crust - that is, we cannot explain the observed Vs by simply projecting mid-crustal compositions to higher pressures and temperatures (Figure 6). As noted by Christensen and Mooney (1995), we must invoke a compositional gradient within the lower crust to explain the increase in seismic velocity.

In the topmost portions of the Colorado Plateau's lower crust, our model can accommodate over 59 wt.% SiO_2 (Table 2). However, such intermediate-felsic material cannot reach high enough velocities to match the seismic signal deeper in the crust, where temperatures increase above 700°C (Schutt et al., 2018). Furthermore, our set of granulites can explain the seismic signal at the base of the crust more often than at the top, whereas we might expect equal probabilities at all depths if the lower crust were compositionally uniform (shown by the colors of Fig. 4). The Northern Basin and Range and Colorado Plateau (Fig. 5) show 3 – 6 wt.% decrease in SiO_2 and an increase in MgO, FeO, and CaO with increasing depth. The Southern Basin and Range, though, seems to lack this trend, the lower crust remaining consistently at 51 wt.% SiO_2. This is possibly due to removal of more felsic material from the top of the crustal column, which we discuss in section 5.1.1.

The specific mineralogy of the lower crust is trickier to constrain than the bulk composition because of its strong dependence on our initial assumptions. Provided that our lower crust is dry and equilibrated in the granulite metamorphic facies, we expect to see mineral assemblages that are rich in clinopyroxenes, garnets, and plagioclase feldspars (Rudnick & Fountain, 1995). Few studies that characterize the whole rock compositions of granulite quantitatively report mineralogy. This makes comparison between our results and petrological studies of our samples difficult. Though Perple_X builds bulk rock velocities from mineral constituents, many mafic rock forming minerals have similar Vs under lower crustal pressure and temperature conditions (e.g. at 650°C and 0.85 GPa diopside: 4.60 km/s; almandine: 4.57 km/s; spessartine: 4.65 km/s; anorthite: 3.65 km/s; sanidine: 3.49 km/s). A sample may therefore change mineralogy without drastically changing its bulk rock properties or composition. In addition, our model's mineralogy predictions are more sensitive to temperature than its seismic velocity predictions are, due to the abrupt and complete phase changes implemented by Perple_X. We do not have the seismic resolution to see such sharp changes in reality (Olugboji et al., 2017), if they exist at all.

However, retrograde metamorphism is unlikely to occur due to the thermodynamic barrier of rehydration (Semprich & Simon, 2014), and the base of the lower crust must be mafic in our model no matter *which* mafic minerals specifically are present. Broadly speaking, the abundance of garnet and clinopyroxene increases with depth, driving the increase in Vs. Mineral assemblages simplify with increasing depth and temperature, leaving little room for accessory phases, such as ilmenite and kyanite, at the base of the crust.

Further seismic constraints could reduce the uncertainty on our compositions. The Vp/Vs ratio can often distinguish mafic from felsic compositions (Holbrook et al., 1992). A Vp/Vs of >1.65 would reduce the probability of lower crustal compositions >65 wt.% SiO_2 (Holbrook et al., 1992) (or, conversely, Vp/Vs of <1.65 would indicate that geochemical studies over-sample mafic compositions). Given that most crystalline rocks exhibit Vp/Vs between 1.6 - 1.9 at standard experiment conditions (Brocher, 2005), the ratio would have to be tightly constrained at $< \pm$ 7% variation. Future quantitatively robust modeling efforts of the southwestern United States should also investigate the presence of hydrous minerals (Valentine & Perry, 2007; Dixon et al., 2004) and melt (Rey et al., 2009) in the lower crust. The presence of fluids could lower the deep crust's Vs, requiring compositions that are even more mafic than those reported here. Alternatively, melt could cause the temperatures implemented in this study to be over-predicted (Schutt et al., 2018).

5.1.1 Implications for Crust Formation

Ductile spreading and uplift of the lower crust could explain the correlation between crustal thickness and composition. Brittle thinning of the upper and/or middle crust through normal faulting allows for isostatic uplift of ductile, deeper crust with little change in lower crustal thickness (Cooper et al., 2010), illustrated by Figure 7. Because the thinnest regions of the southwestern United States are also the most mafic, what was once "lower crust" now likely comprises a greater volume of the 25-28 km thick crustal column. Crustal thickness was lost as intermediate and felsic material was removed from the top, rather than through lower crustal delamination (Rudnick & Gao, 2003). The composition of the deepest layers of Northern Basin and Range are similar to the deep Colorado Plateau 53 wt.% SiO_2, further suggesting that the extended crust has not lost a mafic root relative to the thicker crust. Had crustal thinning been caused by delamintaion, the thinnest Southern Basin and Range crust would be the most felsic rather than the most mafic. Based on the lower crust's mafic composition, the eclogitization process required for de-

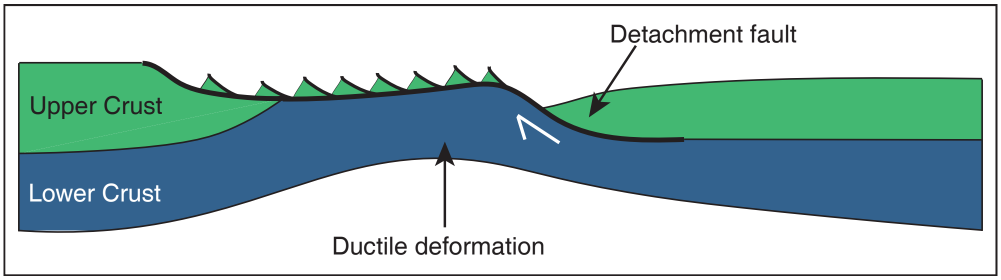

Figure 7: The west-east schematic cross-section of the southwestern United States deformation that our model supports. Crustal extension is accommodated primarily through brittle faulting in the upper crust, which is separated from the lower crust by a rolling hinge detachment Cooper et al. (2010).The ductilely deformed lower crust is uplifted but not substantially thinned.

lamination would likely only be triggered at high pressures (Semprich & Simon, 2014). While the Basin and Range is certainly hot enough to undergo delamination (Jull & Kelemen, 2001), it would have had to occur during a time of crustal thickening (for instance, during the Laramide Orogeny (Bird, 1984; Livaccari, 1991), not during extension.

6 Conclusion

Joint modeling of geophysical and geochemical properties of the lower crust can help constrain lower crustal composition. As an example, in the southwestern United States, seismic velocities, when paired with Moho temperatures and thermodynamic calculations, indicates that the lower crust transitions from intermediate to mafic composition, SiO_2 content decreasing by up to 6% with increasing depth. Temperature gradients cause compositional distinctions to arise among the relatively cool Colorado Plateau, the warm Northern Basin and Range, and the hot Southern Basin and Range. The predominantly mafic composition of the lower crust reflects the tectonic history of this region and can help distinguish between different crust deformation mechanisms.

Though global-scale models give a generalized view of the lower crust, nonunique solutions to composition can be better constrained in regional-scale studies by combining high resolution local datasets and compositional proxies. Combining seismological, petrological, and thermodynamic data opens avenues for future detailed investigation into deep crust composition and structure.

7 Author Contributions

L.G.S. wrote this text and modeled the lower crustal compositions with help from C.G. C.G. provided ambient noise inversions. W.F.M. contributed significantly to data analysis and text. The authors would also like to thank the University of Maryland - University of California, Santa Barbara joint crust discussion group for fruitful insights on model development and interpretation of results. All authors have read and approved this manuscript.

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JOURNAL OF GEOPHYSICAL RESEARCH

Supporting Information for "Lower Crustal Composition in the Basin and Range"

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Additional Supporting Information (Files uploaded separately)

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1. Perple_X Modeling Parameters

Parameter - *Value* - Justification

Thermodynamic data file - *Hpha02ver.dat: Holland and Powell thermodynamic database, augmented by Hacker and Abers (2004)* - Holland and Powell (2004) presents a self-consistent thermodynamic database. Hpha02ver is similar to hp02ver but is augmented by Hacker and Abers (2004) to be consistent with the α - β quartz transition. Another option, Hp11ver.dat, does not include shear moduli and thus cannot be used to calculate Vs. The Stx11ver.dat database uses the Stixrude and Lithgow-Bertelloni (2011) method for calculating elastic moduli, but only considers major mantle phases.

Solution models - *N/A* - All default solution models were included.

Pressure - *1,500 - 15,000 bars (0.15 - 1.5 GPa)* - This range translates to depths from about 5km to 50km, a range that encompasses the granulite stability field and expected deep crustal depths.

Temperature - *300 - 1300 K (27 - 1,027°C)* - 800 K - 1300 K encompasses the stability field for granulite. 300 K - 800 K covers all possibilities from near-surface temperatures to the granulite wet solidus. Granulites existing in this range would be at thermodynamic disequilibrium, but retrograde metamorphosis is unlikely. Granulite facies metamorphosis is marked by the dehydration of hydrous minerals. Rehydration is difficult, making rehydration unlikely to occur (Semprich & Simon, 2014).

Volatiles - *0 wt.%* - Granulite is characterized by the dehydration of hydrous minerals.

2. Suggested Updates to CRUST 1.0

High resolution, local crustal models inform their global counterparts. A mafic overall lower crustal composition, as constrained by Vs, encouragingly agrees with local petrological studies of the Basin and Range (Hanchar et al., 1994; Chen & Arculus, 1995; Dodge et al., 1986; Kempton et al., 1990; McGuire, 1994). The average compositions of all three sub-provinces of the southwestern United States agree with a R. Rudnick and Gao (2014) global lower crustal model within uncertainty. The lower crust, though, might more accurately be considered a gradient of compositions, as many of its physical properties, including density, velocity, and rheology, differ between its mafic base and intermediate to intermediate-mafic top (R. L. Rudnick & Fountain, 1995; Shinevar et al., 2018). While such details may seem trivial on the global scale, they can contribute significantly to interpretations of continental crust formation processes (Hacker et al., 2015), heat producing element distribution (Hacker et al., 2015; Huang et al., 2013; Artemieva et al., 2017), and deep lithosphere earthquakes (Jackson, 2002; McKenzie et al., 2000).

Global model refinement is not reserved for compositional models only; regional analyses can also augment geophysical models. The CRUST family (Laske et al., 2013) of global models and their derivatives predict anomalously slow seismic velocities and low densities for the entirety of the Basin and Range. Their Vp and Vs velocities of 6.6 and 3.6 km/s, respectively, imply a lower crust that is felsic to intermediate. In contradiction, regional velocity models (Parsons et al., 1995; Olugboji et al., 2017; Shen et al., 2013), along with our results, indicate the Basin and Range has fast, dense lower crust. Figures S1 - S3 show that the Basin and Range is more similar to surrounding tectonic provinces than current models suggest. A simple update in CRUST's classification of the Basin and Range from "extended crust" to "fast extended crust" (lower crust Vp = 7.0 km/s, Vs = 3.82 km/s, density = 3030 kg/m^3) would put the model in better agreement with regional-scale assessments. While this adjustment might again seem semantical, CRUST1.0 and similar models have broad impacts on various geophysical applications, including seismic tomography, lithospheric structure and thickness, mantle gravity(Herceg et al., 2015), and neutrino geoscience (Wipperfurth et al., 2019).

Figures S1- S3: reclassification of the Basin and Range from CRUST 1.0's "extended crust" to "fast extended crust", which is in closer agreement with ours and other local studies' findings.

3. Compositional Maps and Uncertainties

Figures S5 - S11

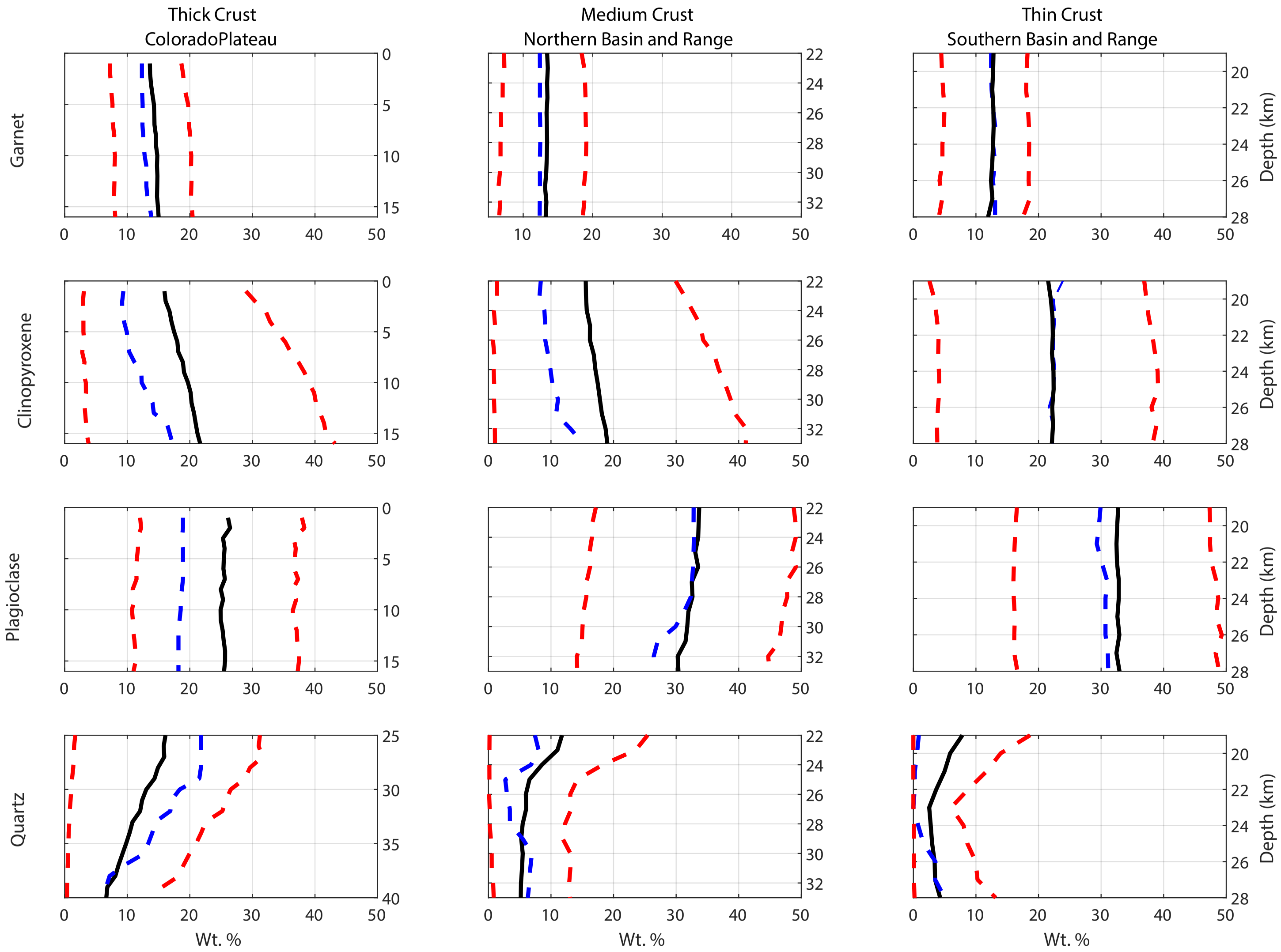

Figure S4: Changes in physical properties with depth and location control changes in predicted mineralogies. Large uncertainties mask slight increases in garnet and decreases in plagioclase feldspar. Clinopyroxene abundance increases with depth while quartz generally decreases. The thin Southern Basin and Range crust shows comparable mineralogies throughout, though could have minimal increase in quartz abundance due to the growth of *beta*-quartz.

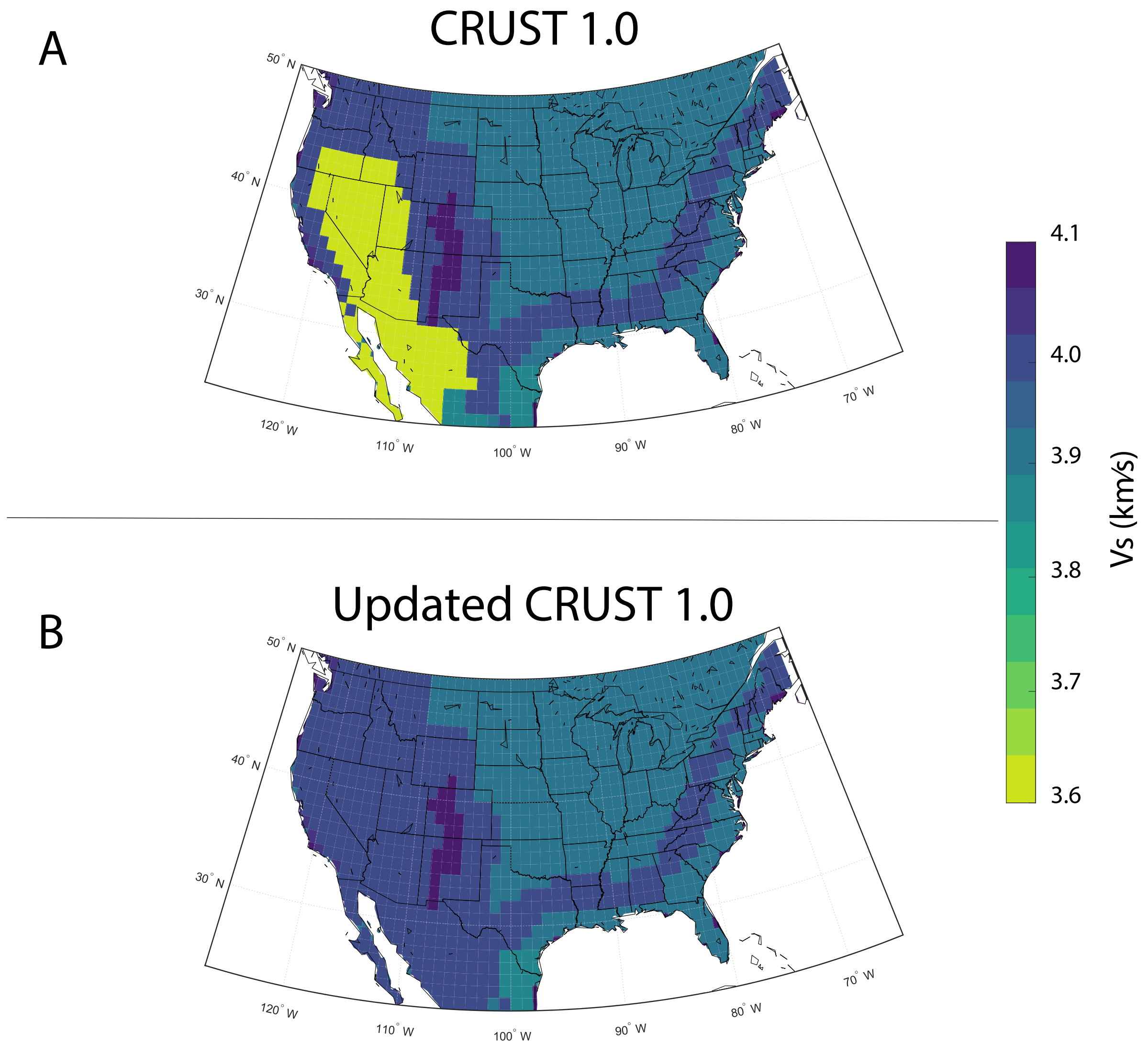

Figure S1: Shear wave velocities from CRUST 1.0 (A) updated to match our local model's Basin and Range results (B). For Figures S1 - S3: the perceptually uniform color scale shows the CRUST predicted anomaly is inconsistent with our results; (B) assigns "fast extended crust" values to all extended crust in the western United States and Mexico.

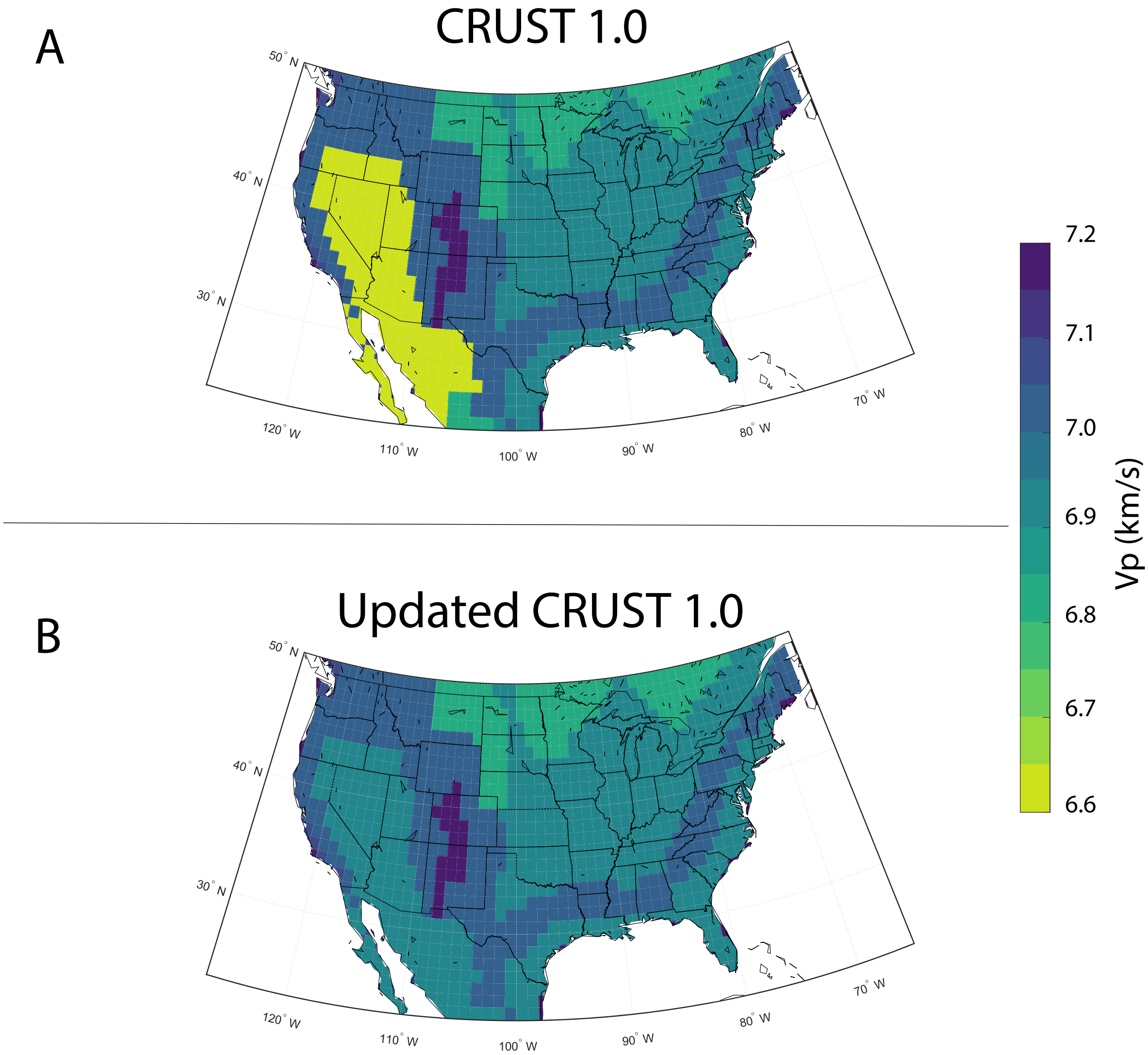

Figure S2: Compressional wave velocities from CRUST 1.0 (A) updated to match our local model's Basin and Range results (B).

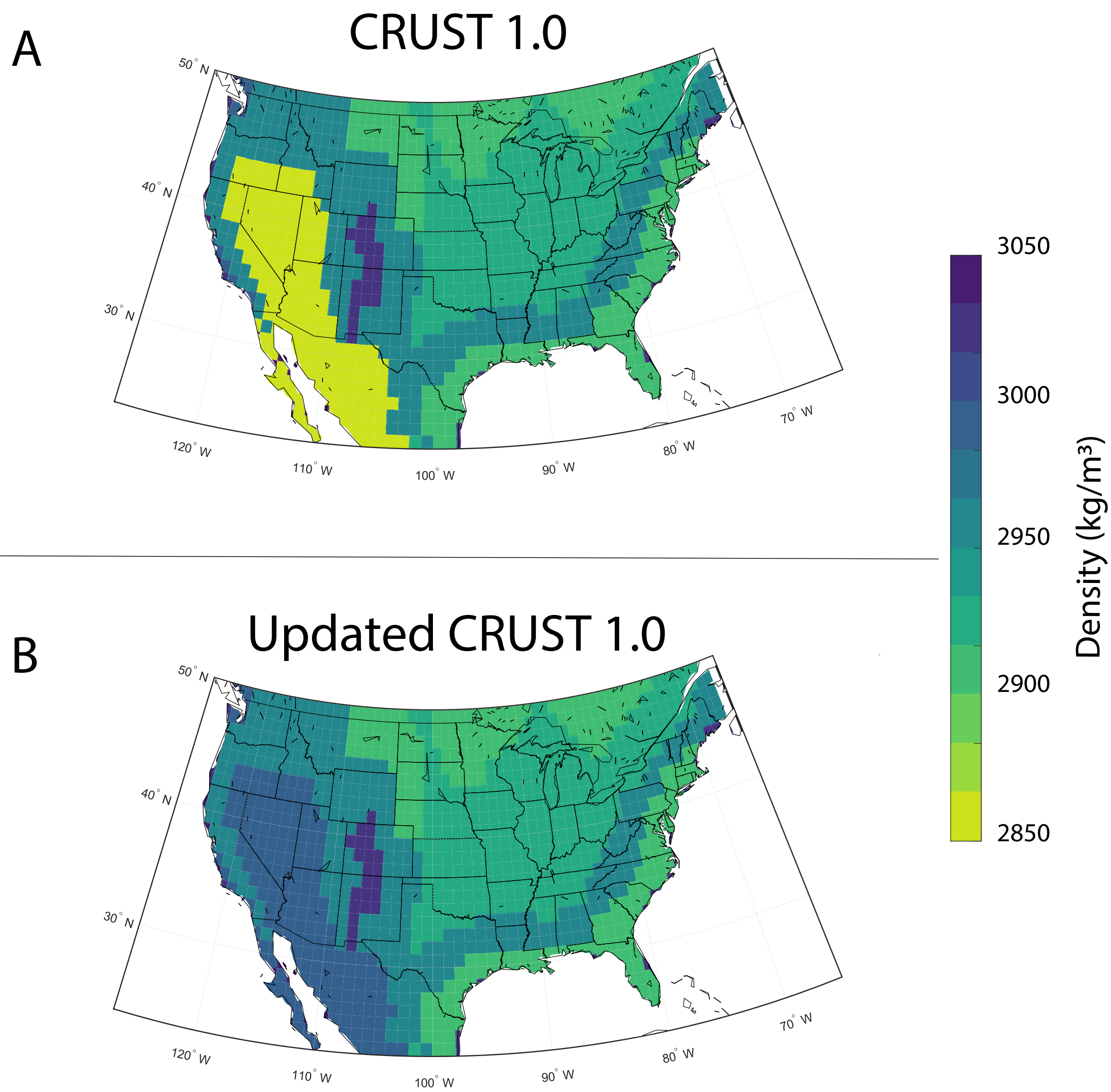

Figure S3: Densities from CRUST 1.0 (A) updated to match our local model's Basin and Range results (B).

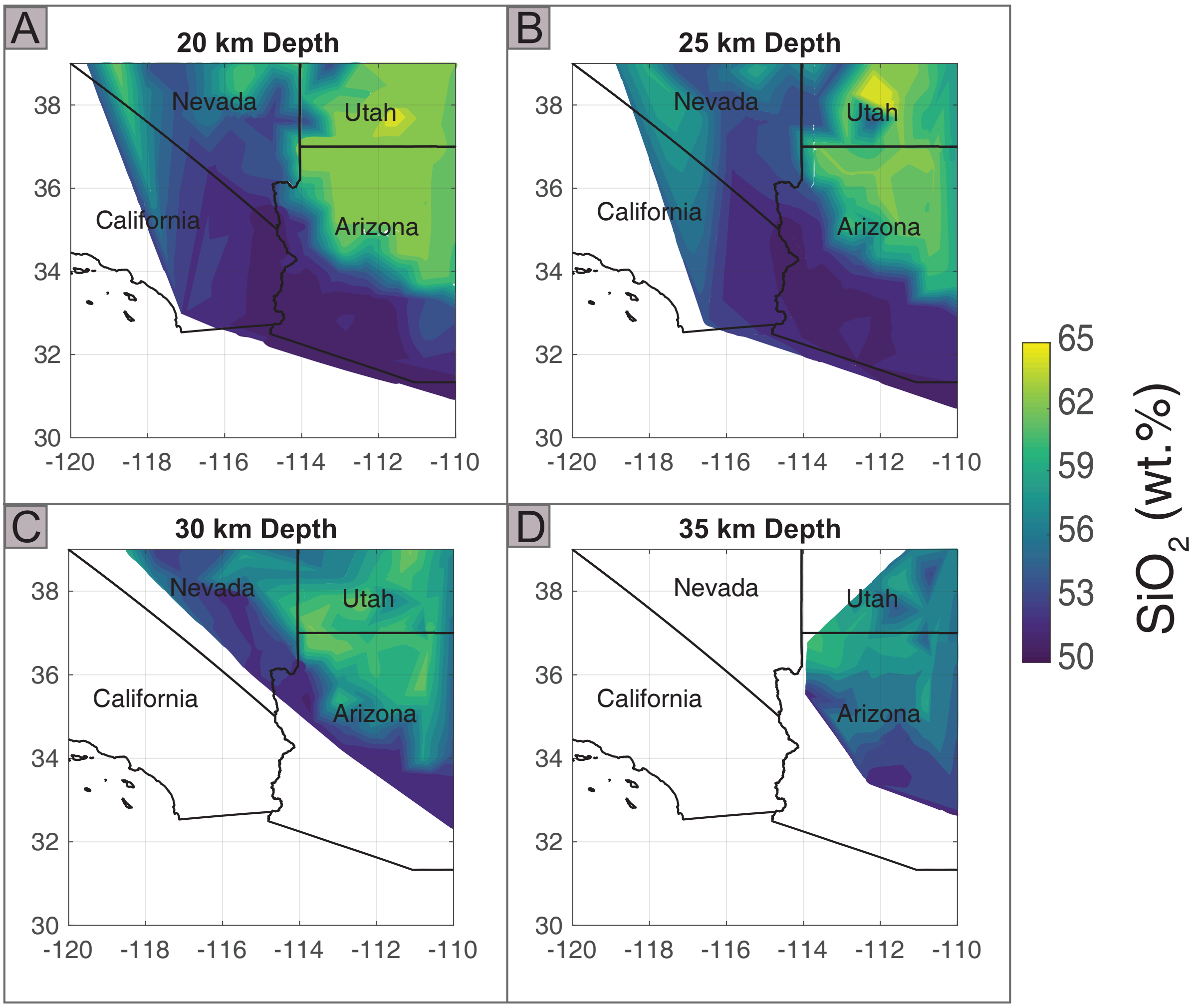

Figure S5: (From main text) Variability in median SiO_2 abundance in the southwestern United States tracks the Colorado Plateau (high SiO_2), Great Basin (medium SiO_2), and Southern Basin and Range (low SiO_2). SiO_2 abundance overall decreases with increasing depth (A - D). Color scale indicates wt.% SiO_2. Mantle compositions are not shown in this figure, and therefore deeper profiles (e.g. C - D) show only those regions which have greater crustal thickness.

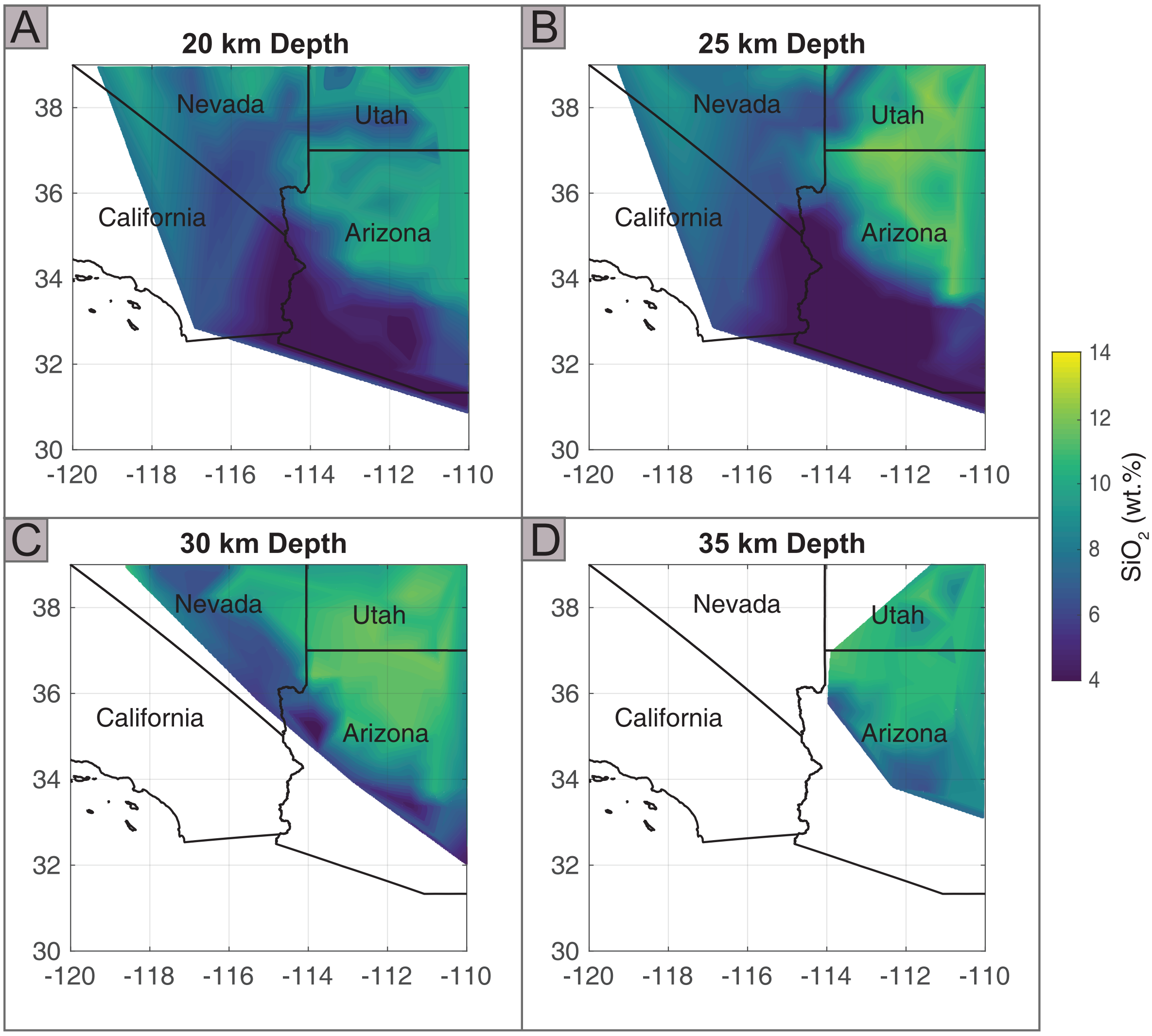

Figure S6: Uncertainty in wt.% associated with our SiO_2 calculations. Uncertainty is calculated as $\frac{1}{2}$ the inter-quartile range at various depths. Uncertainty is lowest in the Southern Basin and Range and remains relatively consistent with depth.

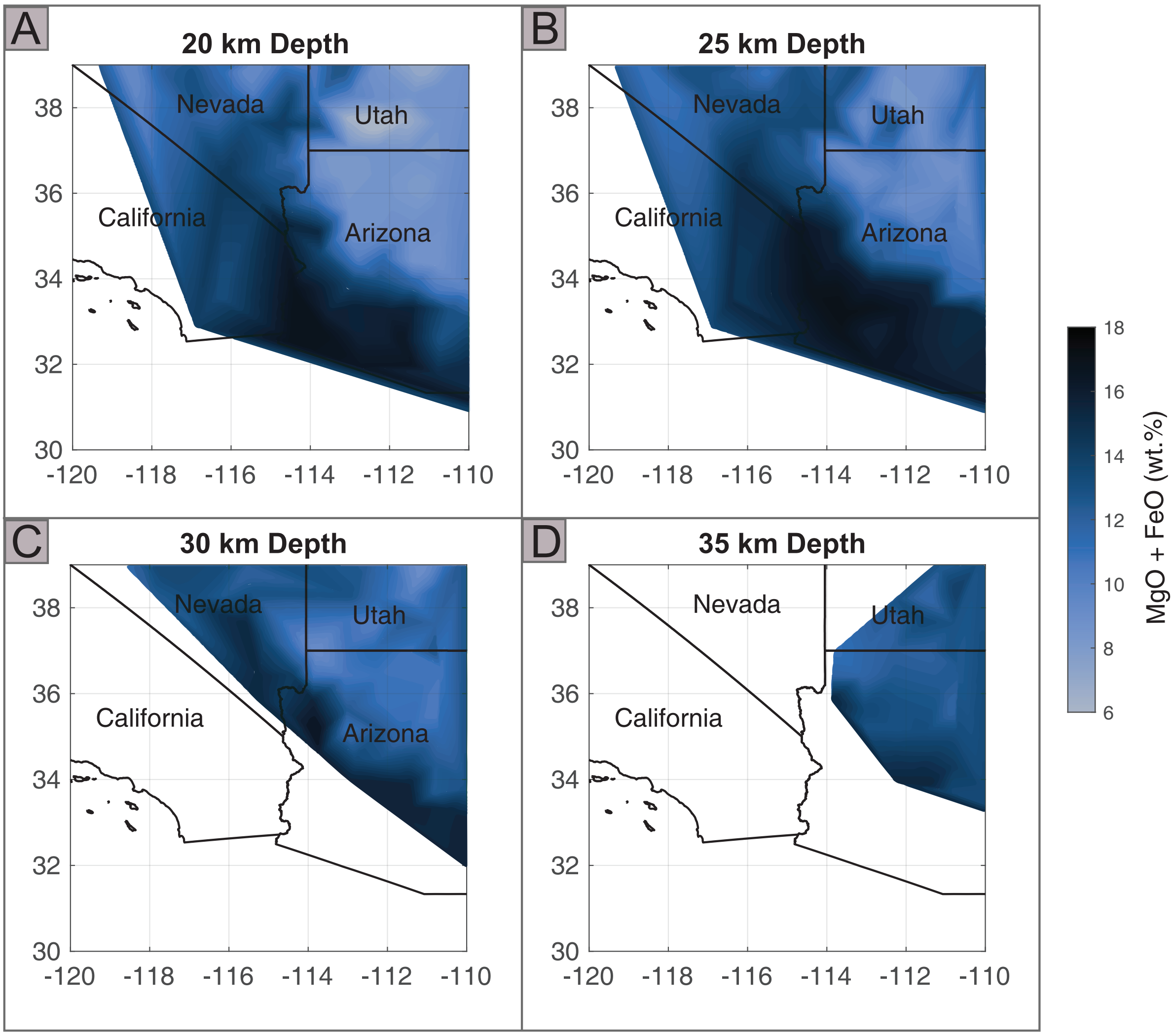

Figure S7: Variations in median MgO + FeO abundance across the Basin and Range and Colorado Plateau. Where SiO_2 abundance in Figure S5 decreased, amount of mafics increases with depth. The Southern Basin and Range has a consistently high mafic content while the Colorado Plateau is more intermediate.

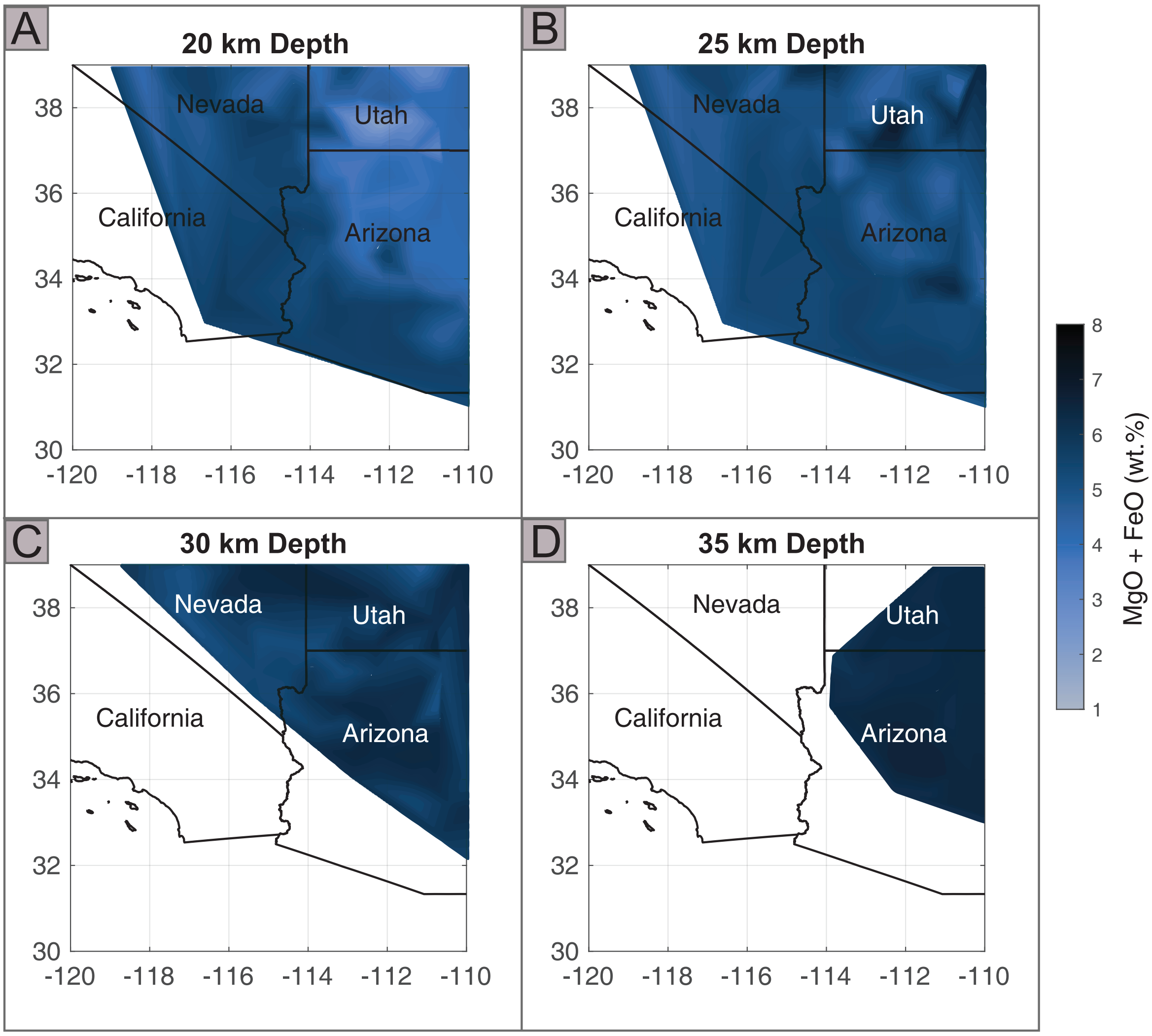

Figure S8: Uncertainty in wt.% associated with our MgO + FeO calculations. Uncertainty is calculated as $\frac{1}{2}$ the inter-quartile range at various depths, and increases by a few wt.% with increasing depth.

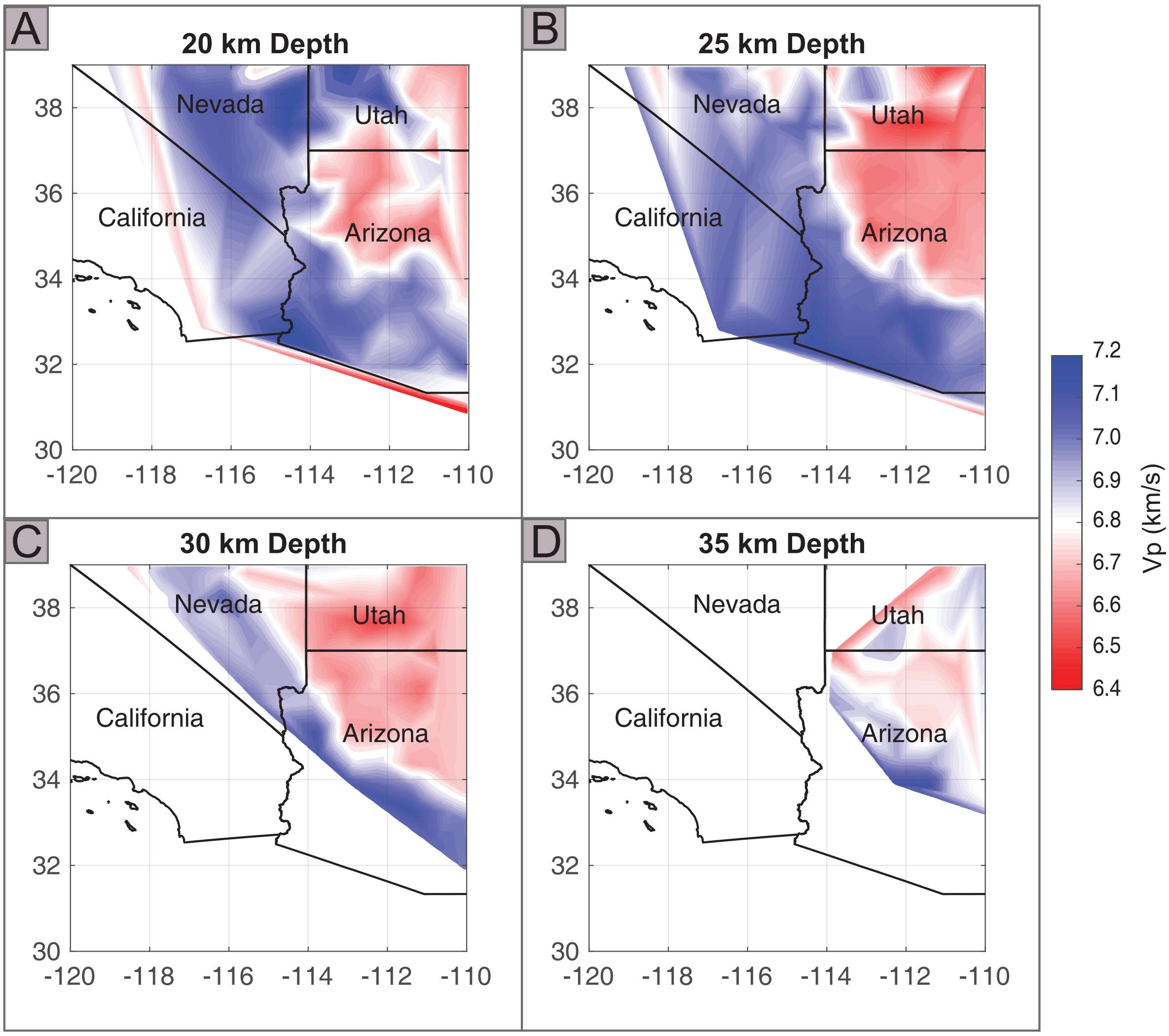

Figure S9: Median Vp calculated from the joint geochemical-geophysical model. Original Vp's were calculated in Perple_X. The Colorado Plateau is clearly visible as a slower Vp region to the east.

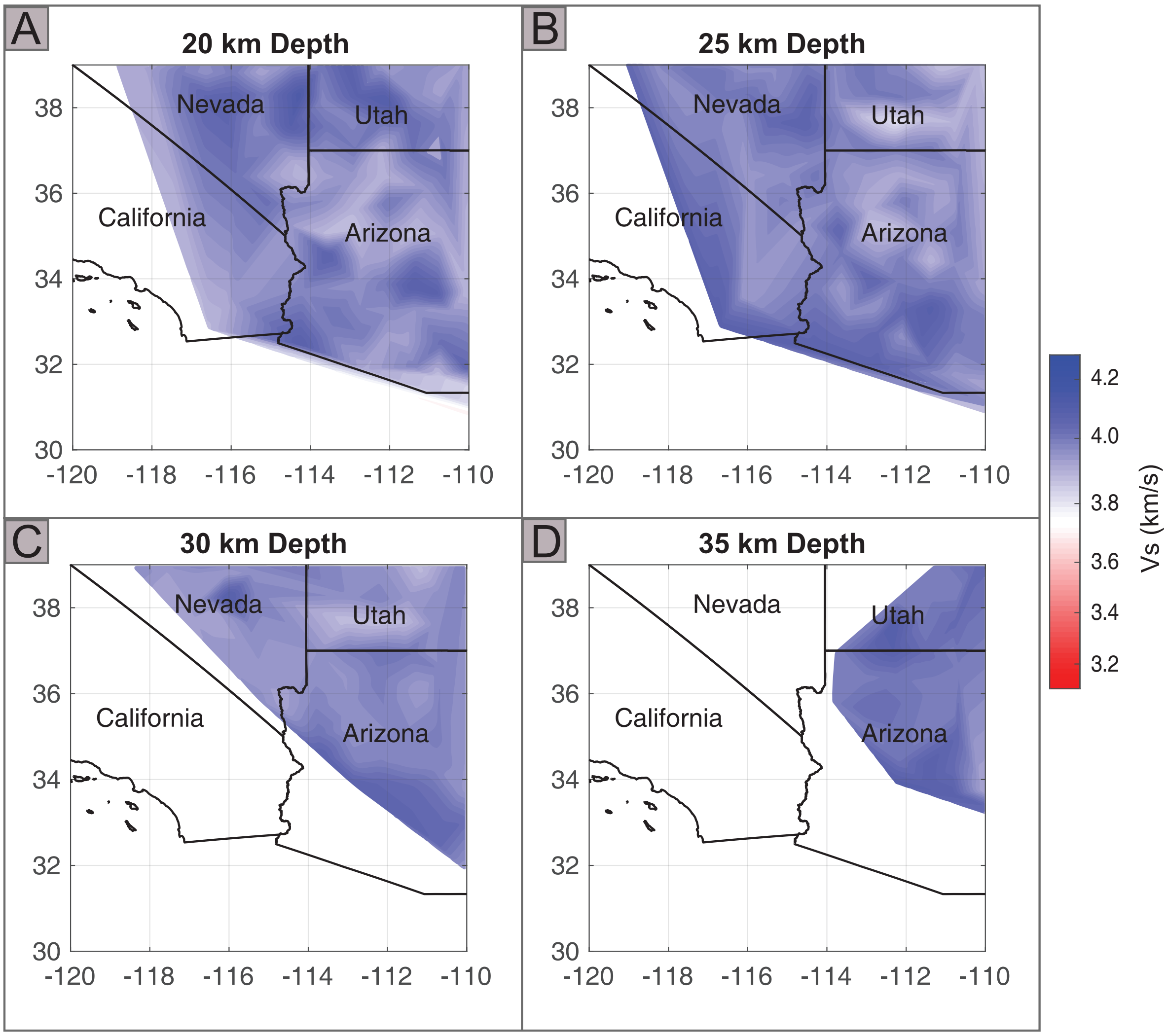

Figure S10: Joint model selections of median Vs. The geochemical data favor faster Vs solutions and therefore weight the model.

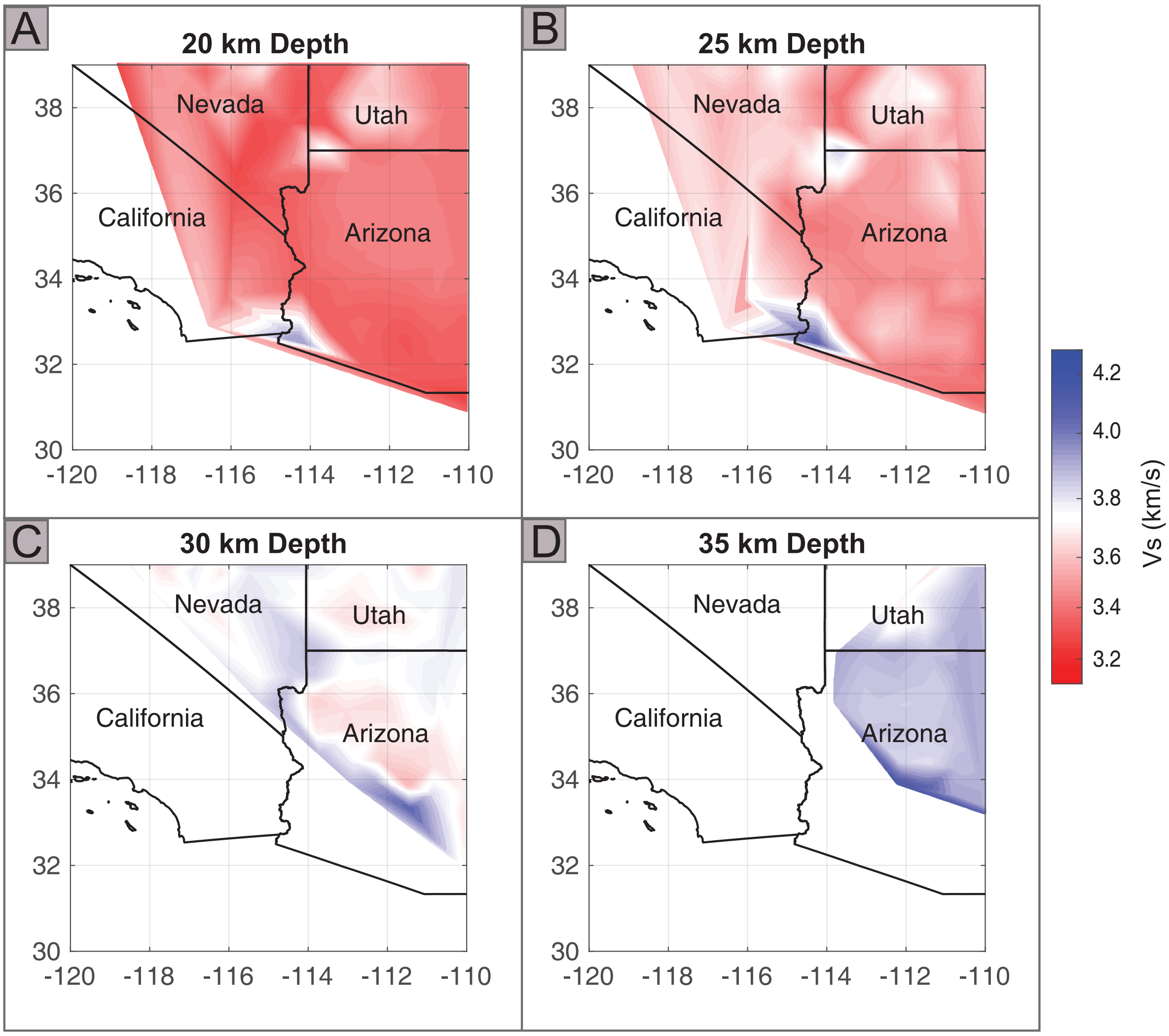

Figure S11: Median Vs from inversion of Earthscope USArray seismic data at various depths. Vs increases noticeably with increasing depth.

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