Investigating the Seismic Constraints on the Crustal Composition and Strength of Southern California: A report

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1.Introduction: Scientific Objective and Tasks

An accurate, high-resolution model of the chemical composition of the crust plays an important role in measuring the strength of the crust, constraining the strain rate, deciphering the seismicity, and assessing the seismic hazards (Bürgmann and Dresen, 2008; Karato, 2012). Geological models that bring in petrological and mineralogical information usually sample near the surface, and rely on extrapolation from excumed crustal sections or xenolith data scattered across the region (Hearn et al., 2020), thus lacking high-resolution composition at a greater depth. Seismic properties, such as Vp and Poisson's ratio, are often used to infer the deep crustal chemical composition, but usually in a qualitative way (e.g., Zandt, 1995), in which different types of seismic data are often used separately. A recent examination of the petrological database of a variety of crustal rocks reveals chemical composition (i.e., SiO2 wt%) of crust perhaps depend on both the shear velocity (Vs) and Vp/Vs ratio (shown in Fig. 1, data from Hacker et al., 2015; Christensen, 1995), indicating that crustal SiO2 wt% can perhaps be uniquely determined when both of the seismic properties (Vs and Vp/Vs) are utilized.

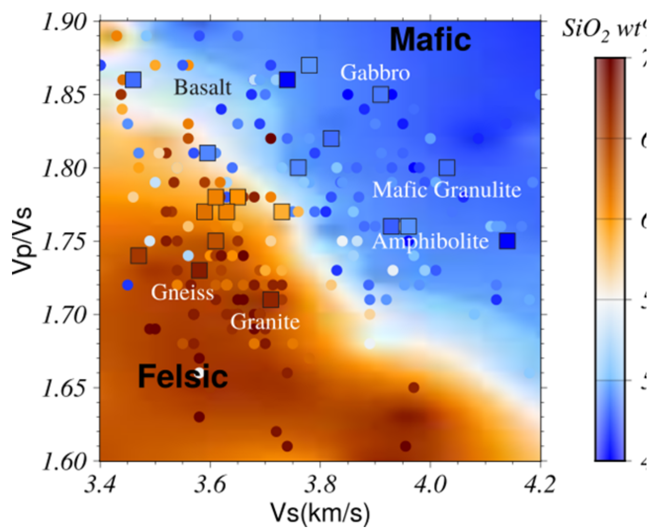

Figure 1. *SiO_2 wt% for a variety of crustal rocks (Christensen, 1996, squares; Hacker et al., 2015, dots), and their lab-measured seismic quantities. A general trend can be found that a more mafic rock (low SiO_2 wt%) has a higher Vs and Vp/Vs, while a more felsic rock has a lower Vs and lower Vp/Vs.*

The goal of this funded project is to take advantage of the trend shown in Fig.1, and apply it to locally measured Vs and Vp/Vs across the S. California region to infer the crustal chemical composition. Particularly, three major tasks are carried out to meet the main objective: 1) constructing a high-resolution Vp/Vs map of the S. California region based on densely deployed seismic arrays (Fig. 2). 2); 2) Combining the newly Vp/Vs map with the community seismic model (CVM, Shaw et al., 2015; Small et al., 2017) to quantify the SiO2 wt% and construct a 3-D compositional model with uncertainties. 3) Benchmarking the result with the SiO2 wt% derived from the community geological framework, and performing a preliminary analysis to its rheological implications. In this report, we present the results for the 3 tasks by showing the data and processing in Section 2 (Data and methods); and we present the major result, a 3-D compositional model of S. California in Section 3. The geological implications and an outlook for future working directions are presented in Section 4 (Discussions and Summary). Finally, we list all the publications and presentations supported by this award.

2. Seismic Data Processing and Results

The seismic stations used in this study is shown in Fig. 2. In total, 628 stations from CI, US-TA, USGS, and other arrays are used. These stations span an area that extends from the mid- Central Valley in the north to the southern Salton Trough in the south. Southwestern basin and range in S. Nevada is also included in the study area (dashed line in Fig. 2).

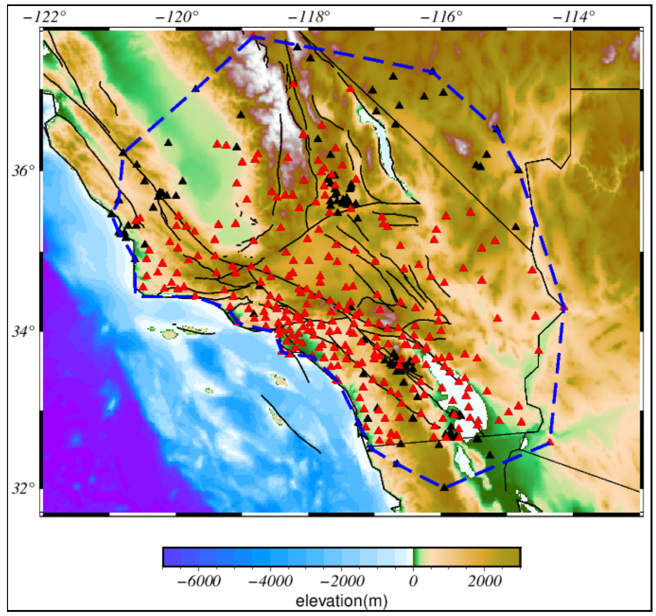

Figure 2. *Study region and seismic stations involved in this study. Red triangles represent 460 stations (265 broadband, 195 strong motion) from CI array. Black triangles represent 148 broadband stations from other seismic arrays. The solid lines are the major faults in Southern California (USGS, 2019). The blue dashed contour shows the study region, defined by the extent of the station distribution. Etopo1.0 elevation is plotted in the background (Amante and Eakins, 2009).*

In order to obtain the crust Vp/Vs ratio, we use the waveforms of large earthquakes (Magnitude>5.5) recorded in the past 10 years (2010-2020). These data are downloaded and used to calculate the receiver functions using a time derivative deconvolution method (Ammon et al., 1991). After rigorous quality controls on the individual receiver function waveform, a sequential H-κ receiver function stacking method is applied to estimate the crust Vp/Vs (Yeck et al. 2013). In this method, we obtain Vp/Vs ratio and thickness separately for the sediment and crystalline crust for 279 stations in the study area. Compared with the traditional H-k stacking method (Zhu & Kanamori 2000;), the reverberation of body waves in the sedimentary layer is separately stacked, and thus is not affecting the stacking of later phases from Moho. Shown in Fig. 3, the new Moho depth derived from this method is consistent with the latest CVM-H model (Lee et al., 2014ab, Shaw et al. 2015) and that of Zhu & Kanamori 2000 respectively. However, the Vp/Vs for the crystalline crust in this study shows more small-scale variations, after the influence from the sedimentary layer is considered and eliminated. After Vp/Vs measurements at station locations are obtained, they are further interpolated to generate a smooth map at grid points spaced 0.25 degree. This high-resolution map of the crystalline crust Vp/Vs, which will lead to a compositional model with high resolution, represents a major progress of this project.

In order to compare these seismic quantities (Vs and Vp/Vs) with lab-measured relationships, we correct them to room temperature and 600 MPa using empirical temperature and pressure derivatives. Attenuation is also corrected so all the seismic quantities are at infinite frequency band. Examples of corrected Vs and Vp/Vs for a grid point near the station LUC2 are shown in

Fig. 4a and b, respectively. The uncertainties in crustal Vs are assumed to be 2%, according to Shen and Ritzwoller 2016, and the uncertainties of Vp/Vs are measured during the sequential H-k stacking.

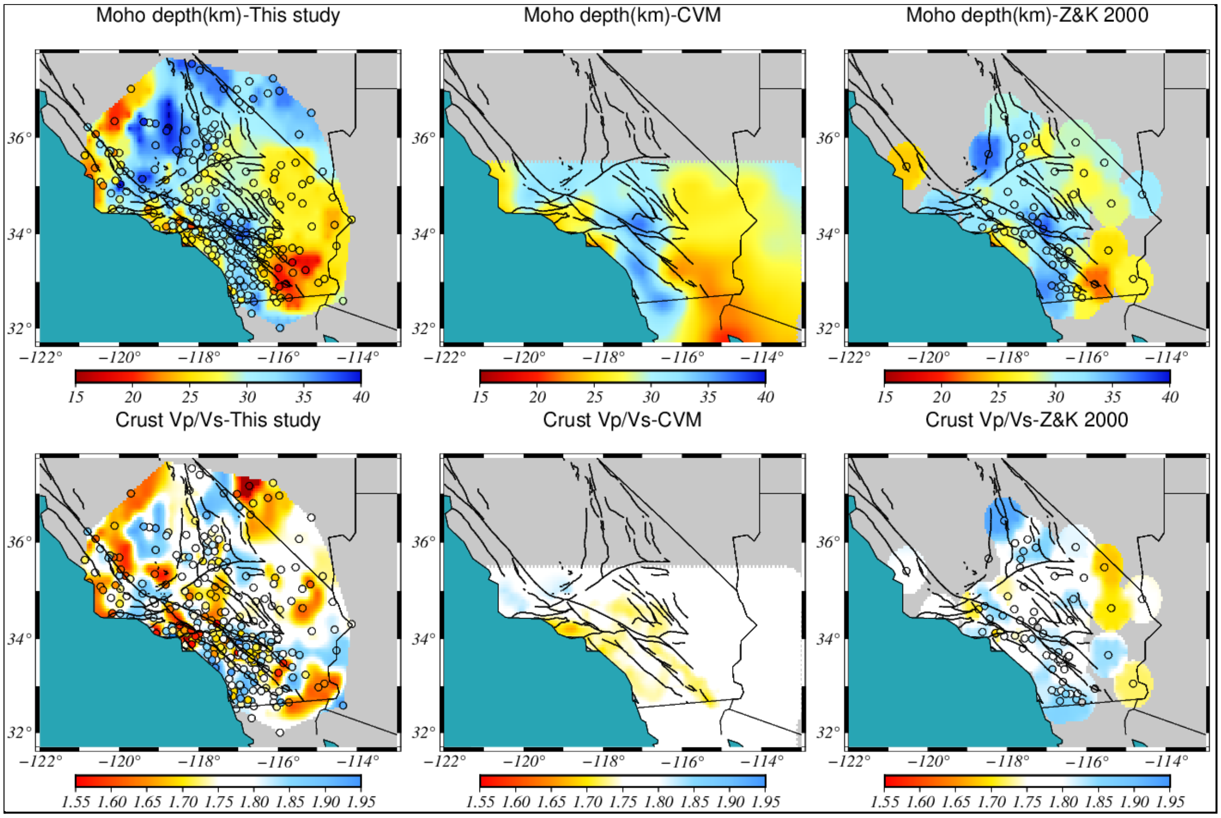

Figure 3. *Moho depth and crust Vp/Vs from this study, CVM-H and Zhu & Kanamori 2000 (Z&K 2000). The open circles represent the stations, with their colors showing the Moho depth or crust Vp/Vs of local estimations.*

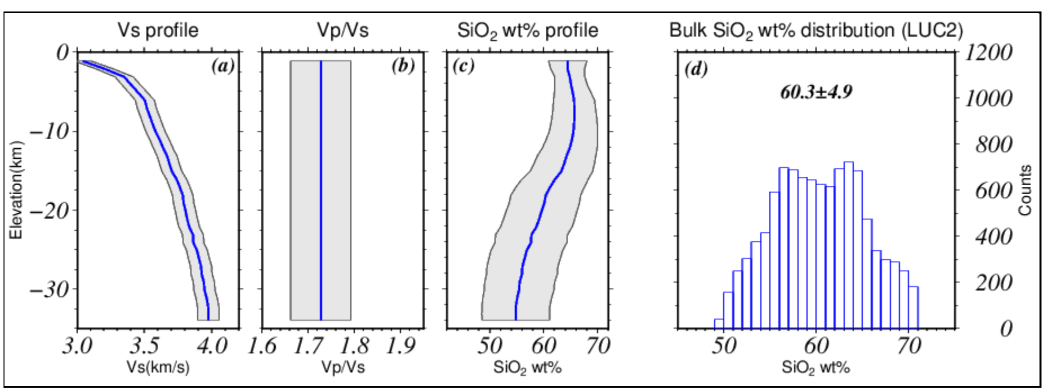

Figure 4. *An example of quantifying the depth-dependent SiO2 wt% with uncertainty at a grid near the station LUC2. a-c) Vs, Vp/Vs and SiO2 wt% and uncertainty. The blue lines represent the values with 1-sigma uncertainty in gray shadow polygons. d)The distribution of bulk SiO2 wt% at a grid near the station LUC2 in the Mojave Desert.*

3. A 3-D Crustal Compositional Model for S. California

Once temperature- and pressure- corrected Vs and Vp/Vs profiles are constructed for each grid point, a Monte Carlo sampling with 10,000 realizations is carried out for each grid point. Particularly, for each grid point, we randomly sample the Vp/Vs and Vs profiles following Gaussian distributions whose widths are determined based on their uncertainties. For each random pair of Vs and Vp/Vs profiles, a SiO_2 wt% profile is determined from the relationship discussed in 2.1 (Fig. 1). 10,000 realizations of SiO_2 wt% profiles are collected accordingly. This ensemble of 1-D SiO_2 wt% profiles (shown in Fig. 4c) also allows us to calculate a distribution of bulk SiO_2 wt% values by integrating through the depth. As shown in Fig. 4d, the average SiO2 wt% for the crystalline crust near the station LUC2 is ~ 60%, exhibiting an overall intermediate chemical composition beneath this point. A total of more than 500 individual average silica profiles are calculated, allowing us to construct a 3-D model of crustal composition for the S. California.

The bulk average SiO_2 wt% of Southern California crust is shown in Fig 5a. The average value of the bulk SiO_2 wt% at these 279 stations is ~59.0% +/- 4.65%, which is more felsic than the estimation of the average of the continental US (~55%, Sui et al., submitted). This value also shows that most parts of Southern California have an intermediate crust on average. Strong lateral variations occur across different tectonic regions. Great Valley, Western Transverse Ranges and Peninsular ranges have more mafic crust, while Santa Maria Basin, Los Angeles Basin and Salton Trough have more felsic crust.

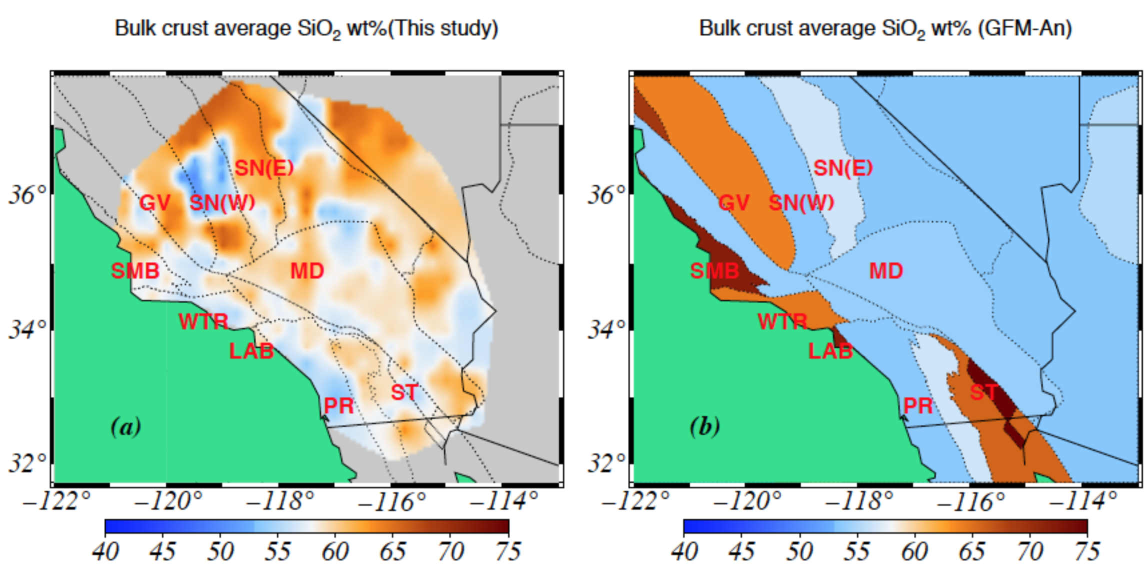

__Figure 5.__ Bulk crust average SiO2 wt% in Southern California. a)Bulk crust SiO2 wt% from this study. GV (Great Valley); SN (Sierra-Nevada); MD (Mojave Desert); SMB (Santa Maria Basin); WTR(Western Transverse Ranges) LAB (Los Angeles Basin); PR (Peninsular Ranges); ST (Salton Trough). b): Bulk crust SiO2 wt% calculated based on the Geological Framework Model (GFM) of the CRM. We assume that all feldspar is anorthite endmember, which leads to a more mafic composition for areas like Mojave Desert.

4. Discussion and Conclusions

In order to compare the resulting 3-D model with a known geological record, the community Geological Framework Model (GFM) that contributes to the Community Rheology Model (CRM, Hearn et al., 2020) serves as a good benchmark. Fig. 4b shows the bulk crustal SiO_2 wt% for each tectonic block from the GFM rock chemical composition. Since we are not able to collect the complete compositional information in the mineral composition used in GFM, assumptions used in CRM are used (e.g., feldspar is modeled by its anorthite endmember). As a result, it only shows a mafic realization of the geologically constrained model. But the similarities in variations revealed in the model are striking. For instance, both models exhibit a more mafic Peninsula Range and a more felsic Salton Trough. Compositional variations between the Great Valley (GV) and western Sierra Nevada are also seen in both models, exhibiting a felsic-to-mafic boundary in that area. These similarities show that the seismologically-derived composition is in consistency with what has been perceived to be geologically. We also noticed that regions such as the Mojave Desert show a more felsic composition than the GFM. This is perhaps due to the assumption in which the anorthite endmember is used to calculate the SiO2 of GFM. But overall the new model shows a more contrast between the regions with known mafic lower crust (e.g., Peninsula Ranges, Barak et al., 2015) and the regions with a more felsic composition (e.g., Mojave Desert, Oskin et al., 2017)

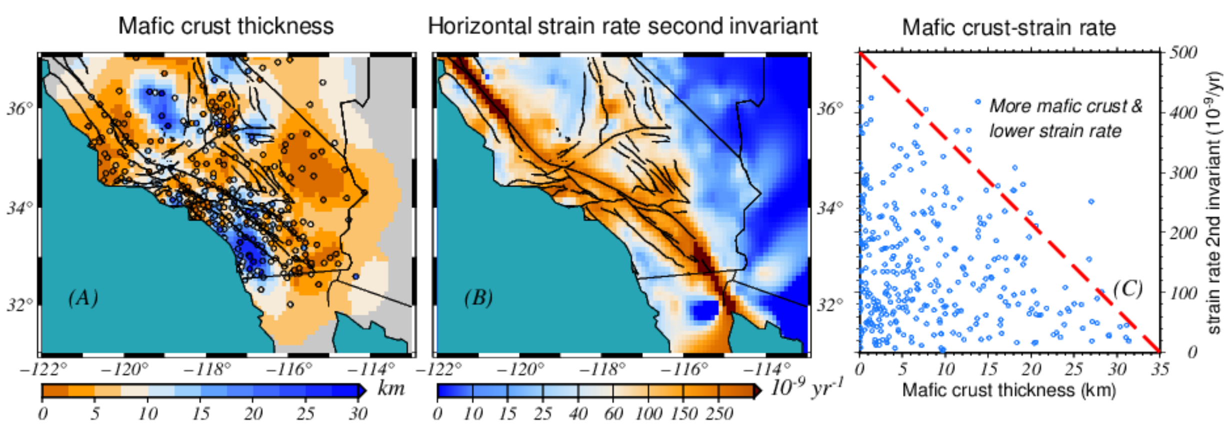

Figure 6. *Mafic lower crustal thickness and strain rate. A) Small circles and their colors represent the location and mafic crust thickness of individual stations. B) Horizontal strain rate second invariant calculated from the GPS observations. C) The horizontal strain rate second invariants at seismic stations are interpolated from panel B and plotted against the mafic crust thickness. The red line marks a possible boundary of the scatter plot.*

Moreover, we also compare features in the resulting compositional model with surface strain rate. Mafic crust usually bears higher strength as mafic rocks are rheologically stronger than felsic rocks at the same physical conditions. Fig. 6a shows the thickness of the mafic lower crust (defined as the layer that has SiO_2 wt% < 53). Regions such as the western Sierra Nevada and Peninsula Ranges have some of the thickest mafic lower crust. Surface strain rate derived from the continuous GPS records, meanwhile, also shows a relatively lower strain rate in these areas (Fig. 6b, Kim et al., 2021). As a result, when individual stations are plotted against the mafic crust thickness and strain rate, a pattern shows up that the crust with thicker mafic crust also disproportionately bears a lower strain rate (defined as the 2nd invariant of horizontal strain tensor, Fig. 6c): most of S. California crust tends to reside at the “thin mafic lower crust” and “low strain rate” side, and for the crust with > 20 km of mafic lower crust, its strain rate bears go above 150 $*10^{-9}$/year. This first order observation indicates how crustal compositional structure is related to (maybe responsible for) the deformation patterns in the S. California. To further investigate the casualty of the two quantities, a full 3-D geodynamic model that incorporates the new compositional model needs to be performed.

In summary, we have collected a decadal seismic data from multiple arrays deployed in the S. California area, and employed a systematic survey to the crustal architecture (thickness of sedimentary layer and crystalline crust; Poisson’s ratio for the crystalline crust). These new seismic quantities are then combined to extract the compositional information of the crust, constructing a 3-D SiO_2 wt% model that is comparable to the community-built Geological Framework Model, and providing new insights into the strength and deformation of the seismically active area. A list of publications (both published and in-prep) as well as conference abstracts are listed at the end of this report.

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Sui, S. & Shen, W., Revealing the sub-ice geology: crustal composition determined by seismic networks in Antarctica, Abstract [C032-09] presented at 2020 Fall Meeting Online, AGU, 10 Dec.

Sui, S. & Shen, W., A high-resolution 3-dimensional compositional model of S. California and its implications on crustal strength, Abstract [S070-02] presented at 2020 Fall Meeting Online, AGU, 17 Dec.

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Kim, J., Bahadori, A., & Holt, W.E. (2021). Crustal strain patterns associated with normal, drought, and heavy precipitation years in California. Journal of Geophysical Research: Solid Earth, 126, e2020JB019560. https://doi. org/10.1029/2020JB019560

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Sui S., Shen, W., and Holt., B., A crustal compositional model of S. California and its geodynamic implications, in prep for EPSL.

Meeting abstracts:

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