Tectonic regionalization of the Southern California crust from tomographic cluster analysis

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Abstract

We map crustal regions in Southern California that have similar depth variations in seismic velocities by applying cluster analysis to 1.5 million P and S velocity profiles from the three dimensional tomographic model CVM-S4.26. We use a k-means algorithm to partition the profiles into K sets that minimize the inter-cluster variance. The results for K ≤ 7 are insensitive to initialization and trimming of the model periphery; nearly identical results are obtained if the P and S velocity profiles are treated separately or jointly. The regions for K = 7 can be associated with major physiographic provinces and geologic areas with recognized tectonic affinities, including the Continental Borderland, Great Valley, Salton Trough, and Mojave Desert. The regionalization splits the Sierra Nevada and Peninsular Range batholiths into the western and eastern zones consistent with geological, geochemical, and potential-field mapping. Three of the regions define a geographic domain comprising almost all of the upper crust derived from continental lithosphere. Well-resolved regional boundaries coincide with major faults, topographic fronts, and/or geochemical transitions mapped at the surface. The consistent alignment of these surface features with deeper transitions in the crustal velocity profiles indicates that regional boundaries are typically narrow, high-angle structures separating regions with characteristic crustal columns that reflect different compositions and tectonic histories.

Introduction

- We regionalize crustal structure in Southern California based on the 3D community velocity model CVM-S4.26 (Lee et al., 2014)
- The set of 1.5 million P-wave (α) and S-wave (β) velocity profiles ($0 < z < 50$ km) is parsed into K regions ($3 \le K \le 10$) following the approach of Lékic & Romanowicz (2011)
  - Model covers Southern California and peripheral portions of Arizona, Nevada, and Baja California
  - 992 x 1536 x 100 nodes at 500 m spacing (380,928 km^2)
- Model comprises a diverse set of physiographic and geologic provinces, including the Great Valley, the Salton Trough, the deep sedimentary basins of Los Angeles, Santa Maria, and Ventura, the Peninsular Range and Sierra Nevada batholiths, the Mojave block, Proterozoic terranes, and portions of the Basin & Range

Methods

- At the n^{th} geographic point, CVM-S4.26 specifies *P*-wave and *S*-wave velocity profiles as 100-component vectors:

$$\boldsymbol{\alpha}_n = [\alpha(\mathbf{x}_n, z)], \qquad \boldsymbol{\beta}_n = [\beta(\mathbf{x}_n, z)], \qquad z = 0.0\,, 0.5, 1.0, \ldots, 49.5\ \text{km}$$

- The concatenation of these two vectors is a 200-component vector:

$$\boldsymbol{\gamma}_n = \begin{bmatrix} \boldsymbol{\alpha}_n/\sqrt{3} \\ \boldsymbol{\beta}_n \end{bmatrix}$$

- The k-means++ algorithm (*Arthur & Vassilvitskii, 2007*) is used to calculate the mean profiles of the k^{th} cluster, the cluster centroids, as:

$$\bar{\boldsymbol{\alpha}}^{(k)} = \frac{1}{N_k}\sum_{\mathbf{x}_n \in \mathbf{X}_k} \boldsymbol{\alpha}_n\,, \qquad \bar{\boldsymbol{\beta}}^{(k)} = \frac{1}{N_k}\sum_{\mathbf{x}_n \in \mathbf{X}_k} \boldsymbol{\beta}_n\,, \qquad \bar{\boldsymbol{\gamma}}^{(k)} = \begin{bmatrix} \bar{\boldsymbol{\alpha}}^{(k)}/\sqrt{3} \\ \bar{\boldsymbol{\beta}}^{(k)} \end{bmatrix}$$

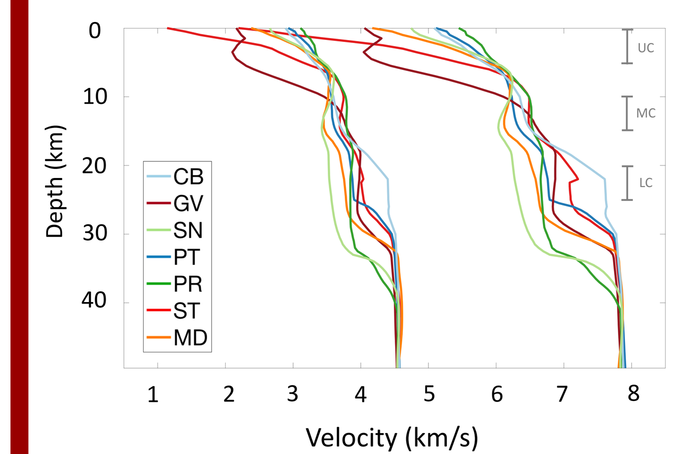
- Regionalizations are identified as $\mathbf{RK}_\alpha$, $\mathbf{RK}_\beta$, **and** $\mathbf{RK}_\gamma$
- MATLAB® k-means function is used to calculate Euclidean distance:

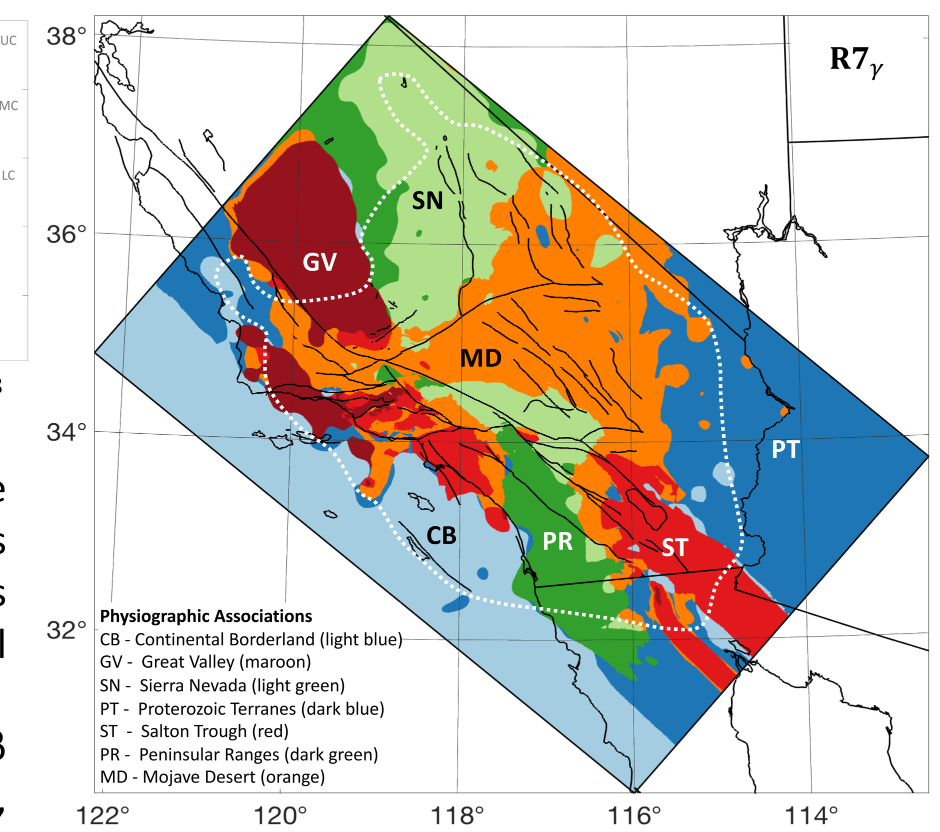
$$\left\|\Delta\boldsymbol{\gamma}_n^{(k)}\right\| = \left(\sum_z [\gamma(\mathbf{x}_n, z) - \bar{\gamma}^{(k)}(\mathbf{x}_n, z)]^2\right)^{1/2}$$

then assign location $\mathbf{x}_n$ to cluster $\mathbf{X}_k$ if k minimizes $\left\|\Delta\boldsymbol{\gamma}_n^{(k)}\right\|$, i.e.:

$$k_n^{(\gamma)} = \arg\min_{1 \le k' \le K} \left\|\Delta\boldsymbol{\gamma}_n^{(k')}\right\|$$

Results

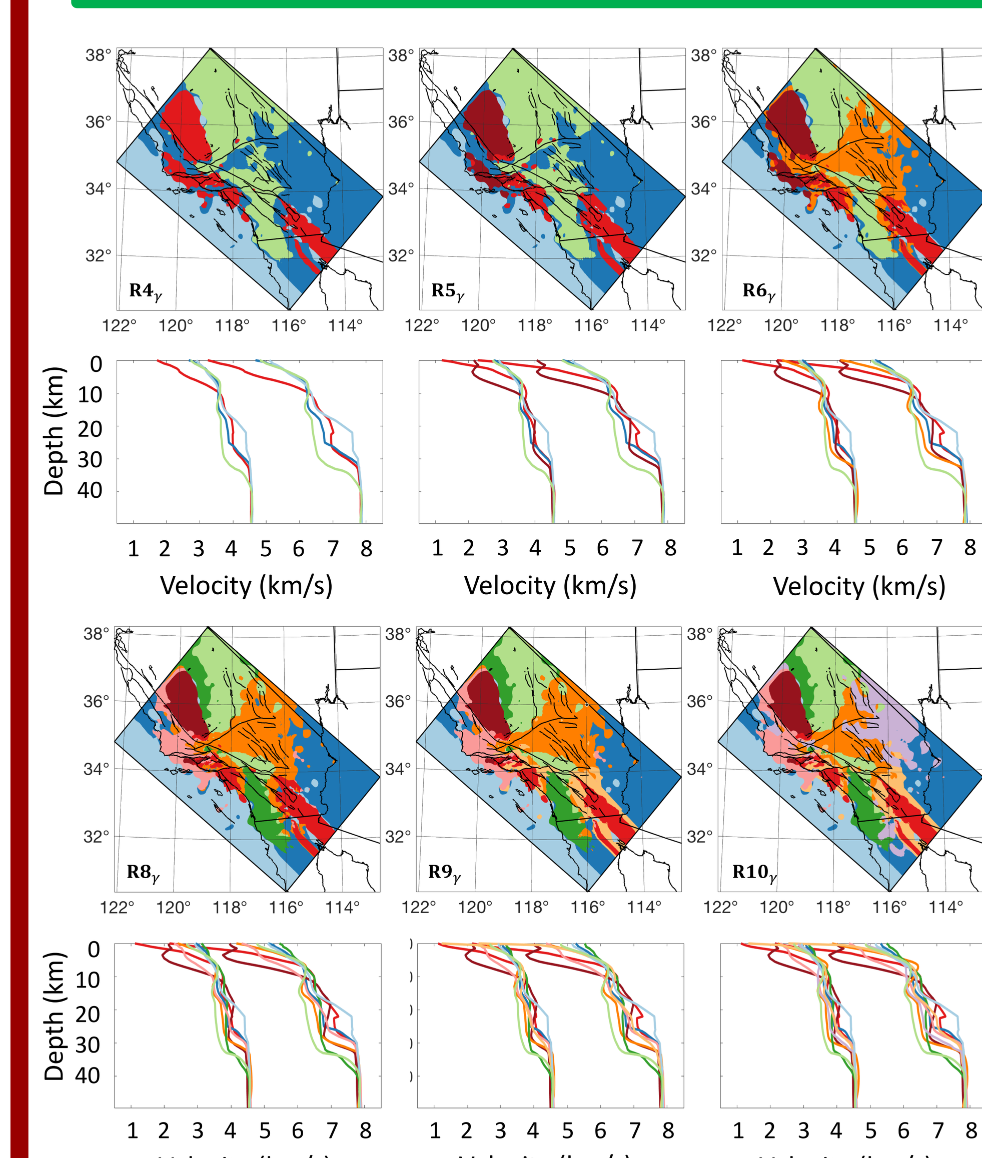




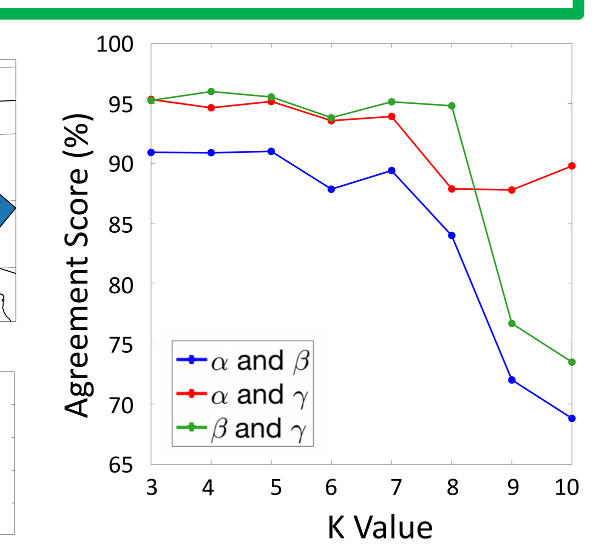
Right: K = 7 regionalization of the concatenated α and β profiles (R7γ). White dotted line encloses area of higher mid-crustal resolution for CVM-S4.26.
Top: Corresponding α and β profiles, with locations of upper, middle, and lower crust.

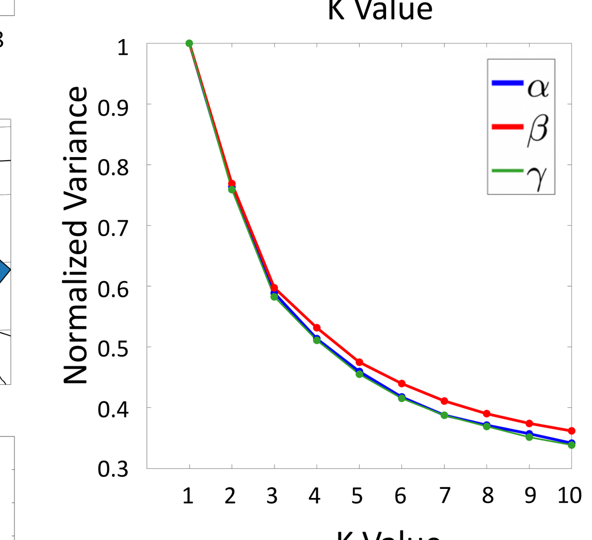
Robustness Properties of Clustering

1.) Results are insensitive to cluster initiation
2.) Unsupervised clustering maps from a trimmed model domain show similar features as full-domain maps
3.) Agreements between RK_α and RK_β are consistently good for K ≤ 7
4.) Regions are geographically coherent and comprise multiple provinces with similar physiography and geology
5.) Region boundaries often conform to major faults, topographic fronts, and geochemical transitions
6.) Progression of regionalizations for increasing K yields a coherent set of structural refinements; new regions typically form as partitions of larger regions or within transition zones between two regions



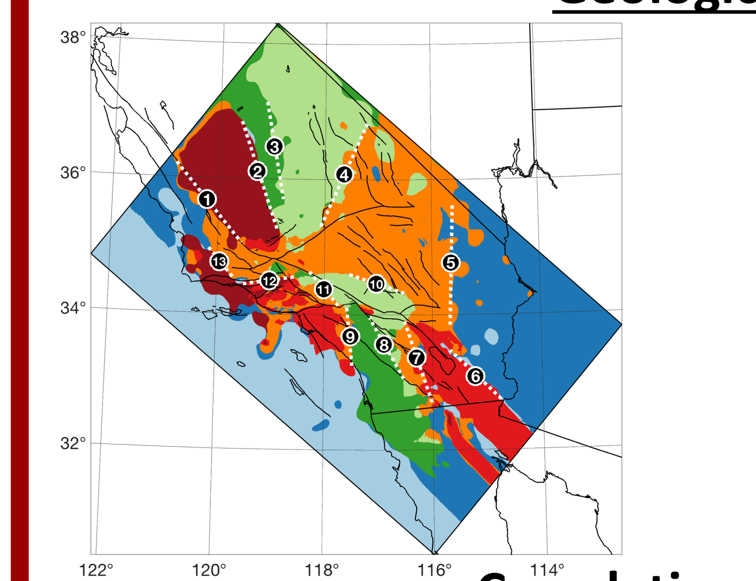
Left Panel: Development of RK_γ from K = 4 to 6 (top) and K = 8 to 10 (bottom) indicated in bottom left corner. R7$_\gamma$ shown enlarged above. Each new output represents a coherent, geologically describable region and is shown in the new color.





Top: Agreement score between $\mathbf{RK}_\alpha$, $\mathbf{RK}_\beta$, and $\mathbf{RK}_\gamma$ from K = 3 to 10. Note the high agreement for K ≤ 7. **Bottom:** Total residual variance value normalized to value at K = 1 (unclustered model) for $\mathbf{RK}_\alpha$, $\mathbf{RK}_\beta$, and $\mathbf{RK}_\gamma$.

Geologic Boundaries

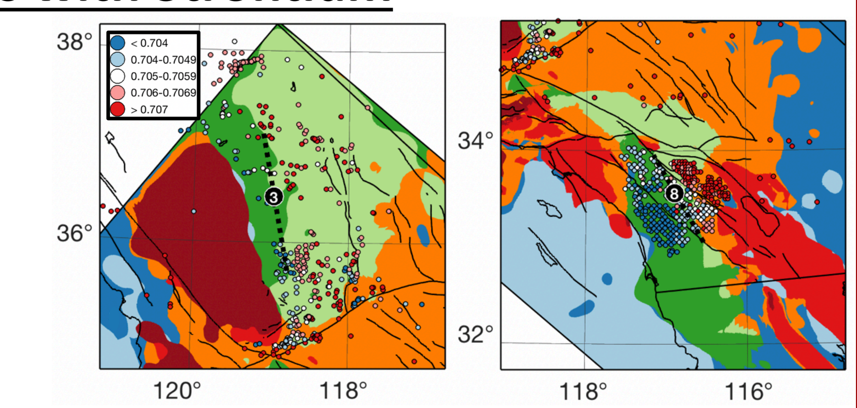


Line	Geologic Description	Regions
1	San Andreas Fault	GV & MD
2	Western boundary of the Great Valley Ophiolite	GV & PR
3	Eastern-Western Zone Batholith Boundary	PR & SN
4	Topographic Front/Gravity Anomaly	SN & MD
5	Lithospheric Transition	MD & PT
6	Algadones-Altar Fault Zone/San Andreas Fault	ST & PT
7	Western Salton Detachment Fault	ST & MD
8	Eastern-Western Zone Batholith Boundary	PR & SN
9	Cristianitos Fault	PR & MD
10	North Frontal Thrust of San Bernadino Mountains	SN & MD
11	Vincent Fault	SN & MD
12	San Cayetano-Ventura-Pitas Point Fault System	MD, ST, & GV
13	Nacimiento Fault	GV & MD

Regional boundaries (Lines 1-13) separate clusters based on geological and tectonic features described in Table.

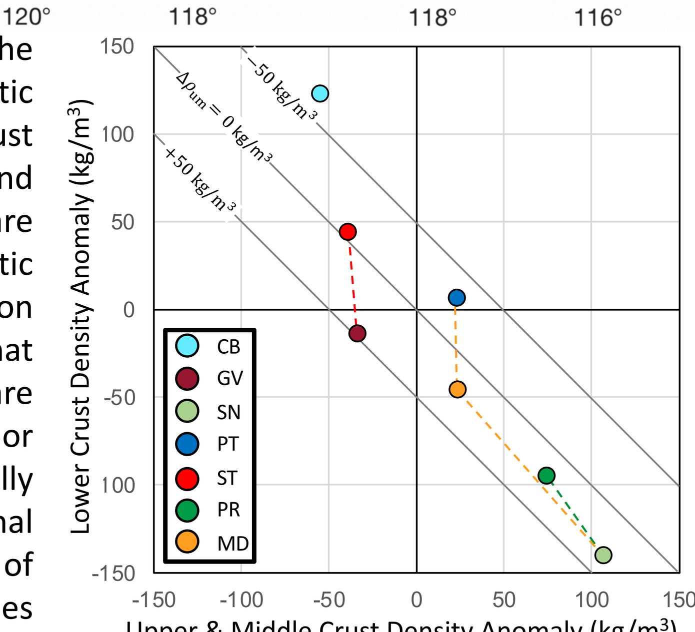
Correlations with Strontium

Initial strontium ratios $^{87}Sr/^{86}Sr$ compiled by Chapman (2012) and Kistler et al. (2003) show transition between SN and PR in Sierra Nevada (**left**) and Peninsular Range (**right**). Blue and white circles indicate $^{87}Sr/^{86}Sr < 0.706$, while pink and red indicate $^{87}Sr/^{86}Sr \geq 0.706$.



Crustal Isostasy

We constructed an isostatic model and found that the regionalized crustal columns are in approximate isostatic balance. Mass anomalies of the upper/middle crust correlate negatively with lower-crustal mass anomalies, and mantle density anomalies required for exact balance are within range inferred from petrologic data for eclogitic enrichment and depletion of the mantle lid. The dispersion of regions along the anti-diagonal (**right**) demonstrates that the diagnostic differences among CVM-S4.26 profiles are not simply distinctive features confined to upper crust or lower crust, but rather region-wide properties vertically correlated across the entire crustal column. These regional signatures are characterized by correlated variations of seismic velocities in crustal layers with typical thicknesses on the order of 10 km – a vertical scale that is easily resolved by the CVM-S4.26 inversions in areas of good wavepath coverage (Lee et al., 2014). This resolving power helps to explain the robustness of regionalization results.



Isostatic balance equation:

$$-\Delta\rho_{\text{um}}^{(k)} = \left[\frac{\Delta M_{\text{uc}}^{(k)} + \Delta M_{\text{mc}}^{(k)}}{\Delta z_{\text{um}}}\right] + \frac{\Delta M_{\text{lc}}^{(k)}}{\Delta z_{\text{um}}}$$

Mantle density anomaly; Upper & mid-crust density anomaly; Lower-crust density anomaly

Conclusions

- K-means clustering produces regionalizations that generally conform to large-scale physiographic provinces of Southern California
- Objective machine learning approach recognizes major tectonic features supported by geology, geochemistry, and tomography
- Geophysical regionalization is consistent with continent-ocean dichotomy expressed in geochemistry of Southern California
- Regional boundaries match major geologic features
- Regional signatures are characterized by correlated variations of velocities in crustal layers with typical thickness on the order of 10 km

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