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Refining and Synthesis of 3D Crustal Models, and Seismicity Catalogs for Southern California

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Summary

We analyze the relocated background seismicity (1981-2005), and several geophysical crustal properties to improve our understanding of the brittle part of the crust in southern California, often referred to as the seismogenic zone. In particular, the thickness of the seismogenic zone depends on crustal parameters such as presence of major late Quaternary faults, lithology, density, and tectonic strain rate.

Across southern California, the thickness of the seismogenic zone is highly variable, ranging from less than 5 km in the Salton Trough and beneath the Coso Range, to greater than 25 km near the southwestern edge of the San Joaquin Valley, beneath the Ventura basin and Banning Pass, where the thick seismogenic zone extends 100 km to the south across the Peninsular Ranges. This variation in the thickness of the seismogenic zone has a complex inverse spatial correlation with nearby late Quaternary faults, which are a proxy for the regional strike-slip plate boundary strain field. In addition the thickness appears to be influenced by lithology and density as well as the regional volumetric tectonic strain field.

To understand the thickness of the seismogenic zone beneath southern California, it is particularly important to include the effects of late Quaternary faults that concentrate the high shear strain rates from plate motion in limited geographical areas. Seismicity extends to greater depths next to the major faults while other geophysical parameters have a smaller effect on the depth distribution of seismicity.

Introduction

The lower limit of the seismogenic zone is often defined as the cutout depth for microseismicity (*Sibson, 1982*). This cutout depth is usually quite sharp, below which there are very few earthquakes and shear strains may be accommodated by aseismic slip. The cutout depth of earthquakes is controlled by density, lithology, tectonic strain rate, and the local geothermal gradients (*Magistrale and Zhou, 1996; Bonner et al., 2003*).

Previously, *Nazareth and Hauksson (2004)* used relocated seismicity and finite source models for large earthquakes to determine the seismogenic thickness of the southern California crust. They found regional variations from 5 to 25 km depth in the brittle ductile transition. We extend their study and analyze the detailed properties of the seismicity near the brittle ductile transition.

The thickness of the seismogenic layer is a fundamental parameter for understanding earthquake mechanics and hazards analysis. *Bonner et al. (2003)* who used the un-relocated SCSN and NCSN catalogs, argued that the thickness of the seismogenic layer in California is inversely related to heat flow, and that epicentral distributions tend to parallel thermal transitions. They identified two distinct ranges of temperature (dependent upon location) that describe the maximum depth (D99%) of seismicity for California. These ranges are $450^{\circ}\pm 50^{\circ}\text{C}$ and $260^{\circ}\pm 50^{\circ}\text{C}$, with the lower temperature range restricted to areas with heat flow below 50 mW/m². *Bonner et al. (2003)* also showed that for

the 450°C cutout temperature the envelope for the maximum energy released by earthquakes falls below the 300°C isotherm.

To expand beyond the *Bonner et al.* (2003) study and analyze the depth distribution of seismicity in more detail, we have determined distances to the nearest fault, isostatic gravity, average crustal Vp/Vs, and volumetric strain at each epicenter in the SCSN (1981-2005) catalog relocated by *Lin et al.* (2007).

Crustal Geophysics and Seismicity

The shear stress field from the relative Pacific and North America plate motions, causes major earthquakes along the principal slip zones (PSZ) and diffuse background seismicity during the interseismic period. The crustal density, lithology, dilatational strain, and fluid content may also influence the location of seismicity. Detailed measurements of the geographical distributions of these different crustal properties are now available for southern California to resolve the effects of some of these static and dynamic properties on the seismicity patterns. We explore if some range of values of these geophysical crustal properties are more likely to accommodate earthquakes than others.

Fault-Distance

The PSZs of late Quaternary faults accommodate the major ($M > 7$) earthquakes that count for significant fraction of the North America Pacific plate motions. The PSZs are significant features that separate geological terranes and in most cases are mapped by field geologists (Plesch et al., 2007). The availability of high precision earthquake locations (Lin et al., 2007) makes it possible to precisely measure the distances between the individual hypocenters and the PSZs (Hauksson, 2010). The distribution of these measurements can be used to determine if the background seismicity is preferentially located near the PSZ.

The distance between each hypocenter and the nearest PSZ of a late Quaternary fault range from 0 to 20 km in southern California (Figure 1). The focal depth of each earthquake versus fault-distance shows that earthquakes are most common closest to the fault surface, with a rapid decrease in both focal depths and the number of events away from the fault surface (Figure 1b). Similarly, the normalized earthquake density is high closest to the fault and reaches background at 5 km distance (Figure 1c). In contrast, the distances measured from a regular grid of points across southern California show no clustering next to the PSZs. Thus earthquake density is highest near the principal slip zones, which includes both background seismicity and aftershocks. These observations imply that the spatial seismicity patterns are controlled by the geographical location and geometrical configuration of the late Quaternary faults.

Isostatic Gravity

The isostatic residual gravity anomalies represent to first order the 3-D distribution of spatial density variations at seismogenic depths within the upper crust (Langenheim and Hauksson, 2001). The positive gravity values represent the high-density mountain ranges, while the negative values represent the large basins. Large density contrasts form where basins and mountains abut in the upper crust or are caused by variations in thickness of the lower crust. The seismicity is distributed evenly through the isostatic gravity field demonstrating that there is no particular affinity between certain crustal densities and earthquake occurrence.

The relative density of seismicity and isostatic gravity values are similar across southern California, with 90% of the seismicity occurring at average isostatic gravity values of -40 to 0.0 mGals (Figure 2). The depth distribution of the isostatic gravity and seismicity shows that most of the earthquakes occurs within limited range of isostatic gravity (Figure 2b). At very low isostatic gravity values of < -40.0 mGals, below the high Sierras and parts of the Peninsular Ranges, there are small clusters of hypocenters scattered at shallow depth. There is also a small population of earthquakes with isostatic

gravity of >0.0 mGals. This complex pattern suggests that other factors than just heat flow by itself affect the thickness of the seismogenic zone.

Crustal average of Vp/Vs

The crustal average of Vp/Vs can be viewed as a proxy for lithology, and in some cases for fluid content of the crust. Yan and Clayton (2007) used receiver functions to determine Vp/Vs and crustal thickness for southern California (Figure 3). They assumed a constant Vp of 6.3 km/s. The Vp/Vs values are average crustal values with similar contributions from the upper and lower crust. The crustal average of Vp/Vs and spatial density of earthquakes exhibit an irregular distribution across southern California (Figure 3a). The low Vp/Vs values are limited to areas such as Santa Monica Mountains, south end of the Elsinore fault, northwest Mojave Desert, and parts of eastern California. In contrast, southeastern Mojave Desert, parts of the Peninsular Ranges, Los Angeles and Ventura basin are characterized by high Vp/Vs. The distribution of focal depths and assigned Vp/Vs values shows that most of the earthquakes occur in Vp/Vs range of 1.68 to 1.84, with a deep cluster at Vp/Vs~1.76 (Figure 3b). A particularly dense cluster of seismicity exists in the range from 1.73 to 1.83 and in the depth range of 2 to 12 km. Seismicity occurring within this limited range may be related to the presence of fluids in the crust. The earthquakes that occur at deeper depths may be occurring in crust with less water content. Similarly, the earthquakes that occur at low Vp/Vs values may be associated with quartz rich crust but these earthquakes are only a small fraction of the recorded seismicity.

GPS measured surface strain dilatation

To first order the crustal strain field is constant with depth. Fay et al. (2008) combined GPS based velocity solutions to estimate the dilatations rate or the rate of changes in crustal thinning or thickening. Their GPS measured surface strain dilatation and spatial density of earthquakes vary across southern California (Figure 4). Negative strain dilatation or crustal thickening occurs in the western Transverse Ranges and the western Great Valley as well as the California Coast Ranges and along the While Wolf fault system (Argus and Gordon, 2001). Crustal thinning occurs in the eastern California, including the Eastern California Shear Zone, and the Salton Trough region. The focal depth distribution of the strain dilatation suggest that most of the earthquakes occur within regions of positive strain dilatation or crustal thinning (Figures 4b and 4c). The relative density of seismicity and strain dilatation values are similar across southern California, with 90% of the seismicity occurring at average strain dilatation values, between strain values of -20 to 60 nanostrain/yr (Figures 4c and 4d). At negative strain dilatation values, below the Central Valley, southern Mojave, and the western Transverse Ranges Ventura and Los Angeles basins, there are small clusters of hypocenters scattered at shallow depth. There is also a prominent decrease in the depth of earthquakes with increasing dilatation, in the range of >40 nanostrains/yr. This complex pattern suggests that other factors than only heat flow by itself affect the thickness of the seismogenic zone.

Modeled crustal dilatation

Fay et al. (2008) predicted crustal deformation using their model with uniform upper mantle viscosity. They determined the relative horizontal dilatation rate using the strain rate tensor at 20 km depth. Negative dilatation results from crustal thickening in areas of downwelling mantle. Similarly, upwelling and divergent flow of the upper mantle causes positive dilation or crustal thinning.

The model derived crustal dilatation relative strain and spatial density of earthquakes varies across southern California (Figure 5). The depth distribution of the modeled crustal dilatation and seismicity shows that the earthquake depths increase from positive to negative dilatation (Figure 5b). The relative density of seismicity and model dilatation values are distributed evenly across southern California, with 90% of the seismicity occurring at average dilatation values, between dilatation of -0.4 to 0.4 (Figure 5c). At negative dilatational values the increasing depth trend in the focal depths terminates at relative strain rates of ~ -0.4 . The shallowest distribution of earthquakes occurs at the most positive strain rates.

This complex pattern suggests that other factors than just modeled crustal strain by itself affect the thickness of the seismogenic zone.

Discussion and Conclusions

Crustal deformation in southern California is dominated by right-lateral shear stress caused by relative motion of the Pacific and North America plates. The major late Quaternary faults are the zones of weakness that accommodate plate boundary deformation. They also control the spatial distribution of seismicity. The dilatation crustal deformation field that cause crustal thinning or thickening is superimposed on the shear deformation but does not seem to have a significant effect on the distribution of earthquakes.

Seismicity preferentially occurs near the late Quaternary faults, in crust with average geophysical properties. Density, isostatic gravity, Vp/Vs variations, and volumetric strains affect the locations of seismicity less than proximity of late Quaternary faults. About 90% of the earthquakes occur within the available range of each of the modeled geophysical variables. As an example, the heat flow of 50 to 100 mWm², isostatic gravity of -50 to 0 mGals and GPS dilatation of -60 to 40 nanostrains/yr. Similarly, they occur at elevations less than 1600 m, depth to Moho less from 37 km to 23 km, and average crustal Vp/Vs of 1.73 to 1.81.

Relatively few earthquakes are present, if the crust is too thin or too thick or the elevation is too high. Similarly, if the crust is too thin, the heat flow is very high and the deformation is spread amongst several faults covering a wider region. If the crust is too dense or there is minimal Quartz content, earthquakes are unlikely. Similarly, if the Vp/Vs, and density are low, and the elevation is high, the crust is too thick to accommodate through going faulting. The dynamic volumetric strains as well as modeling favor earthquakes in extensional regimes, with some earthquakes occurring in compressional regimes provided the strain rate is high enough.

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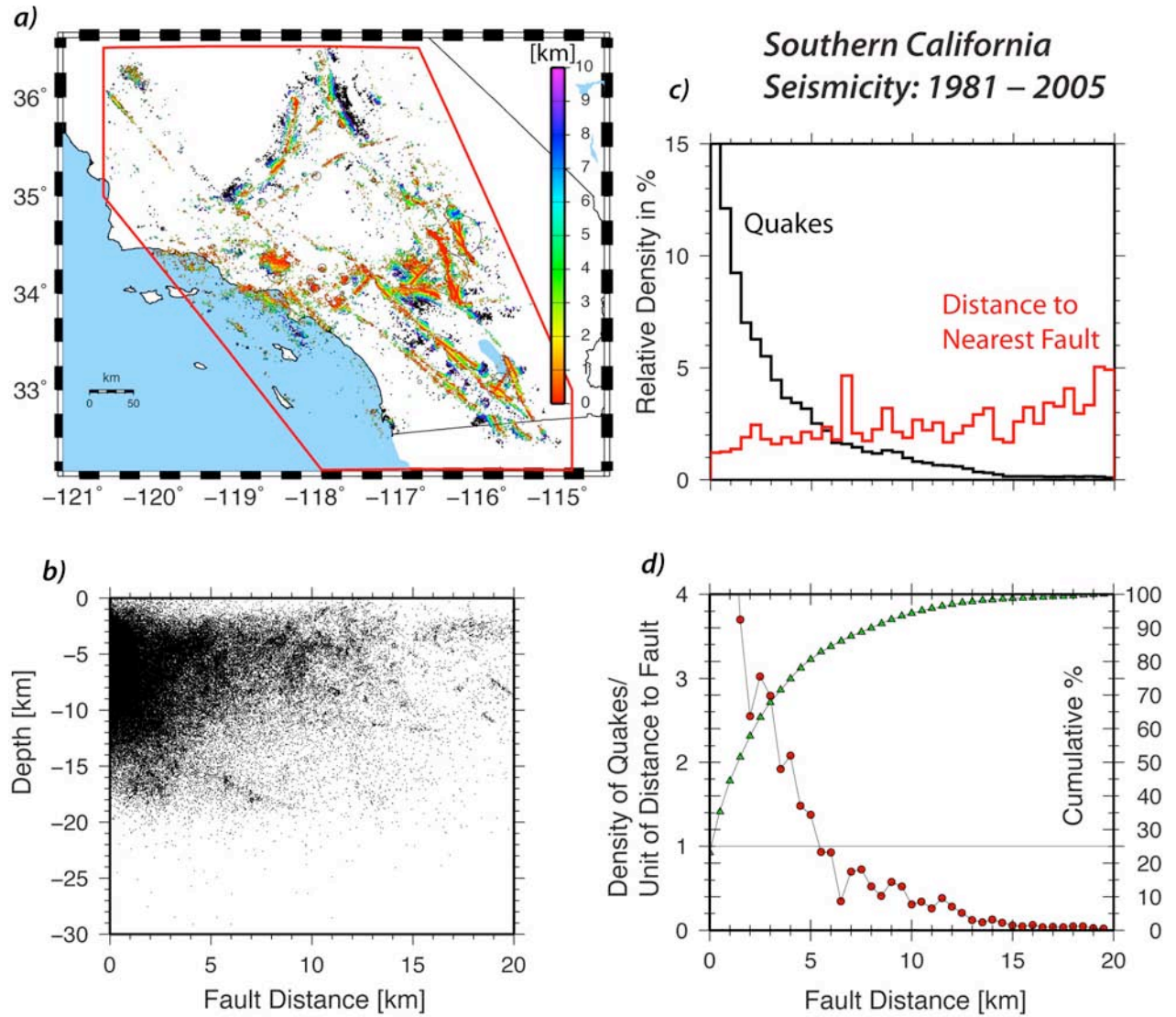


Figure 1. Fault-distance and seismicity. (a) Fault-distances for earthquakes of $M \geq 1.8$ are plotted in color. The fault traces are not included. (b) Each hypocenter is plotted at the respective distance from the nearest principal slip-surface of a late Quaternary fault. (c) Relative density of quakes and 'fault-distance' values for each 1 km of distance, and relative density of distances measured from a regular grid across southern California. (d) Normalized density of quakes per 1 km step in fault-distance, and cumulative number of quakes.

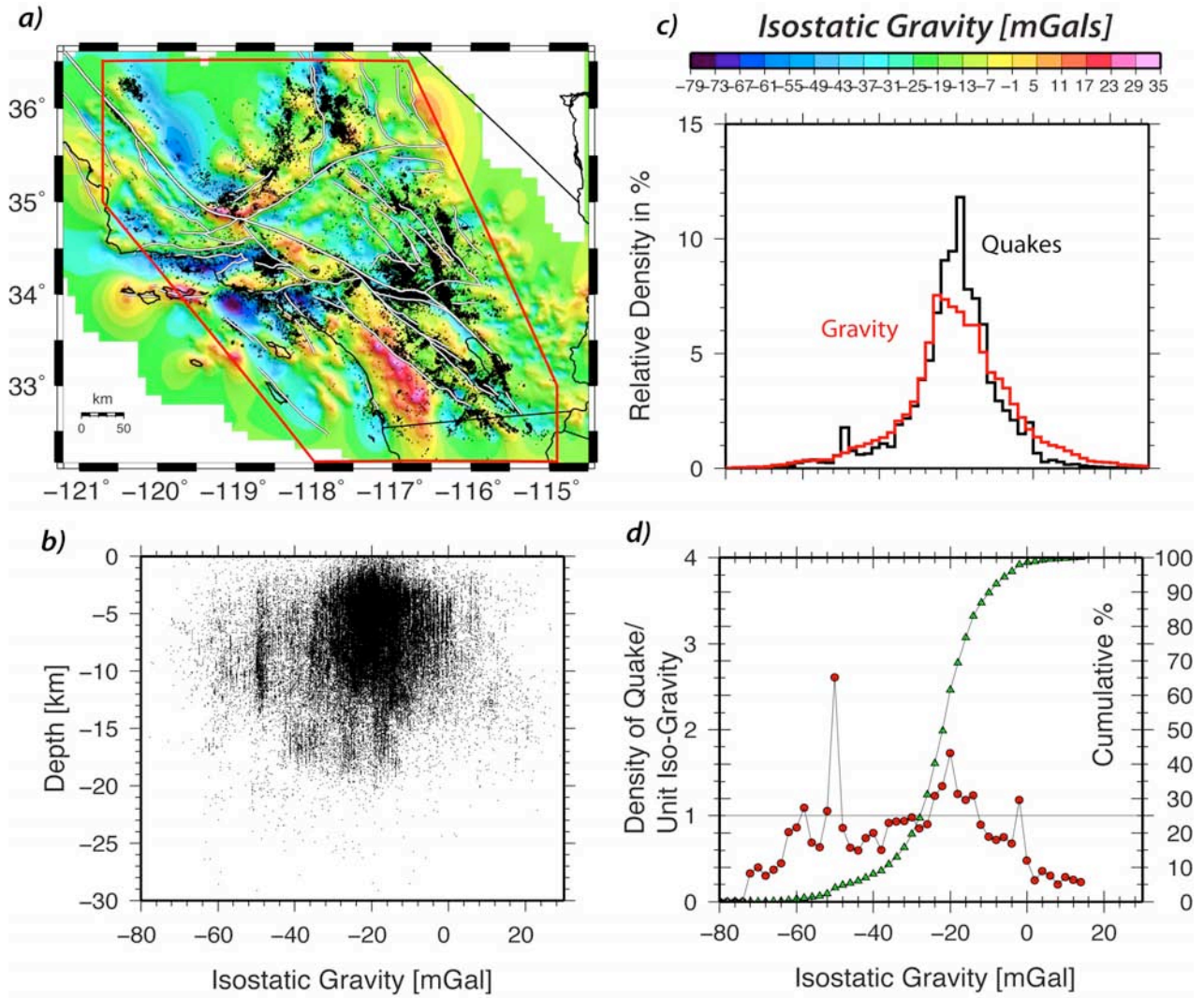


Figure 2. Isostatic Gravity and seismicity. (a) Earthquakes of $M \geq 1.8$ are plotted on top of the isostatic gravity map of southern California. (b) Each hypocenter is plotted at the respective focal depth and corresponding isostatic gravity value read from the map. (c) Relative density of quakes and 'isostatic gravity values' for each 10 mGal of isostatic gravity. (d) Normalized density of quakes per 10 mGal step in isostatic gravity, and cumulative number of quakes.

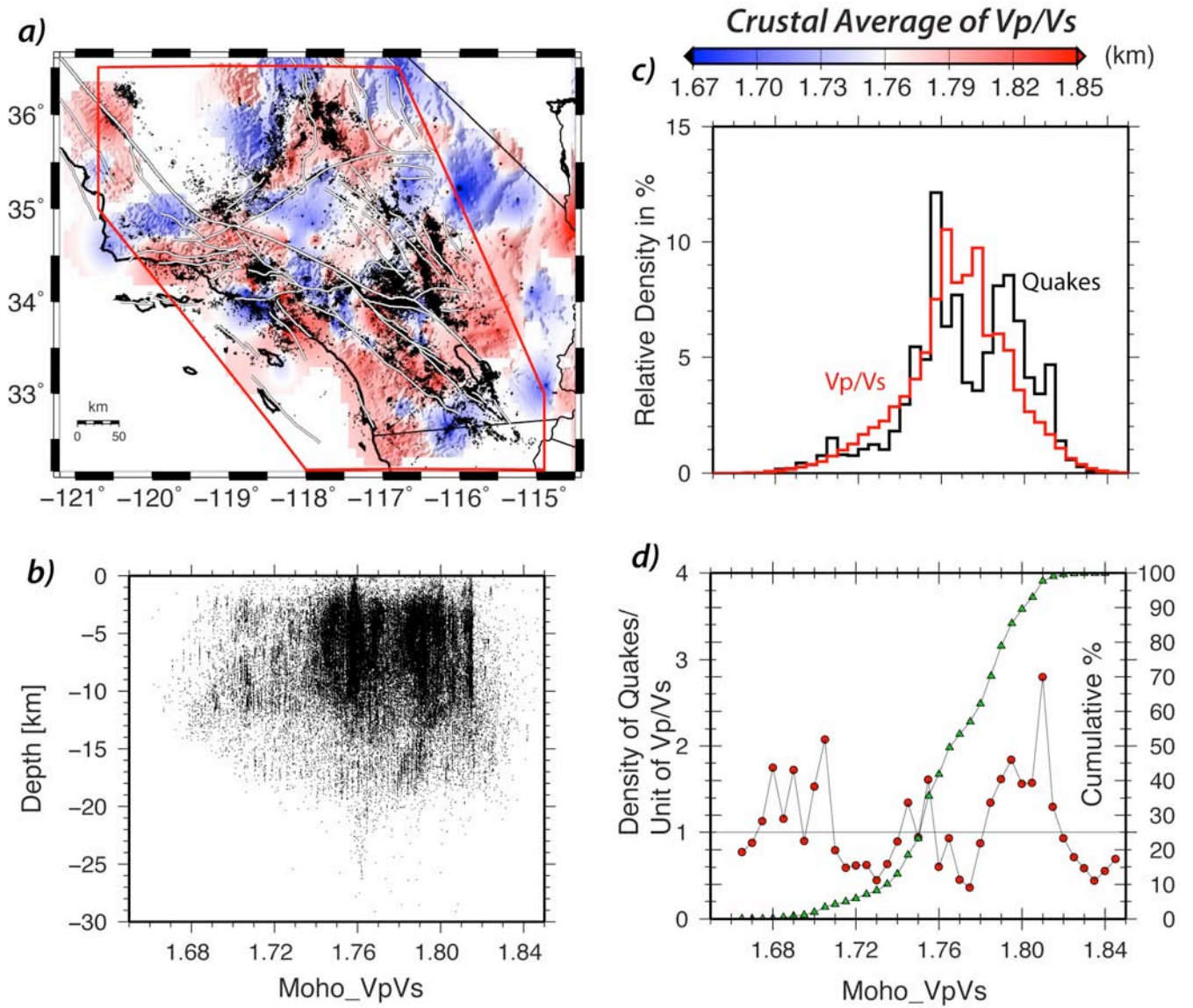


Figure 3. Crustal average of V_p/V_s and seismicity. (a) Earthquakes of $M \geq 1.8$ are plotted on top of the V_p/V_s crustal average map for southern California. (b) Each hypocenter is plotted at the respective focal depth and corresponding V_p/V_s value read from the map. (c) Relative density of quakes and ' V_p/V_s values' for each 0.01 unit of V_p/V_s . (d) Normalized density of quakes per 0.01 step in V_p/V_s , and cumulative number of quakes.

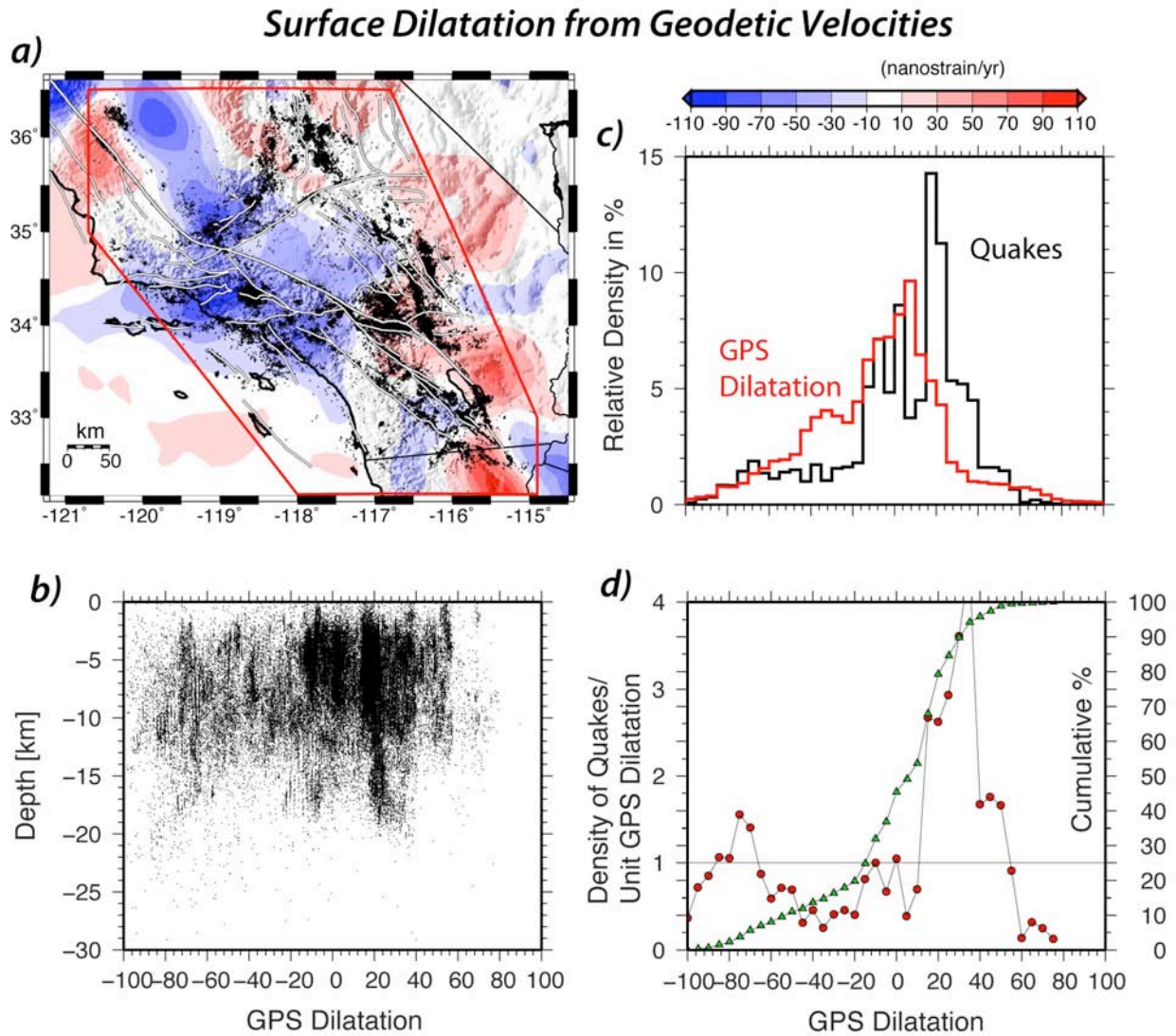


Figure 4. GPS measured surface strain dilatation and seismicity. (a) Earthquakes of $M \geq 1.8$ are plotted on top of the surface strain dilatation of southern California. (b) Each hypocenter is plotted at the respective focal depth and corresponding surface strain dilatation interpolated from the map. (c) Relative density of quakes and 'dilatation strain values' for each 5 units of dilatation strain. (d) Normalized density of quakes per 5 units step in dilatation strain, and cumulative number of quakes.

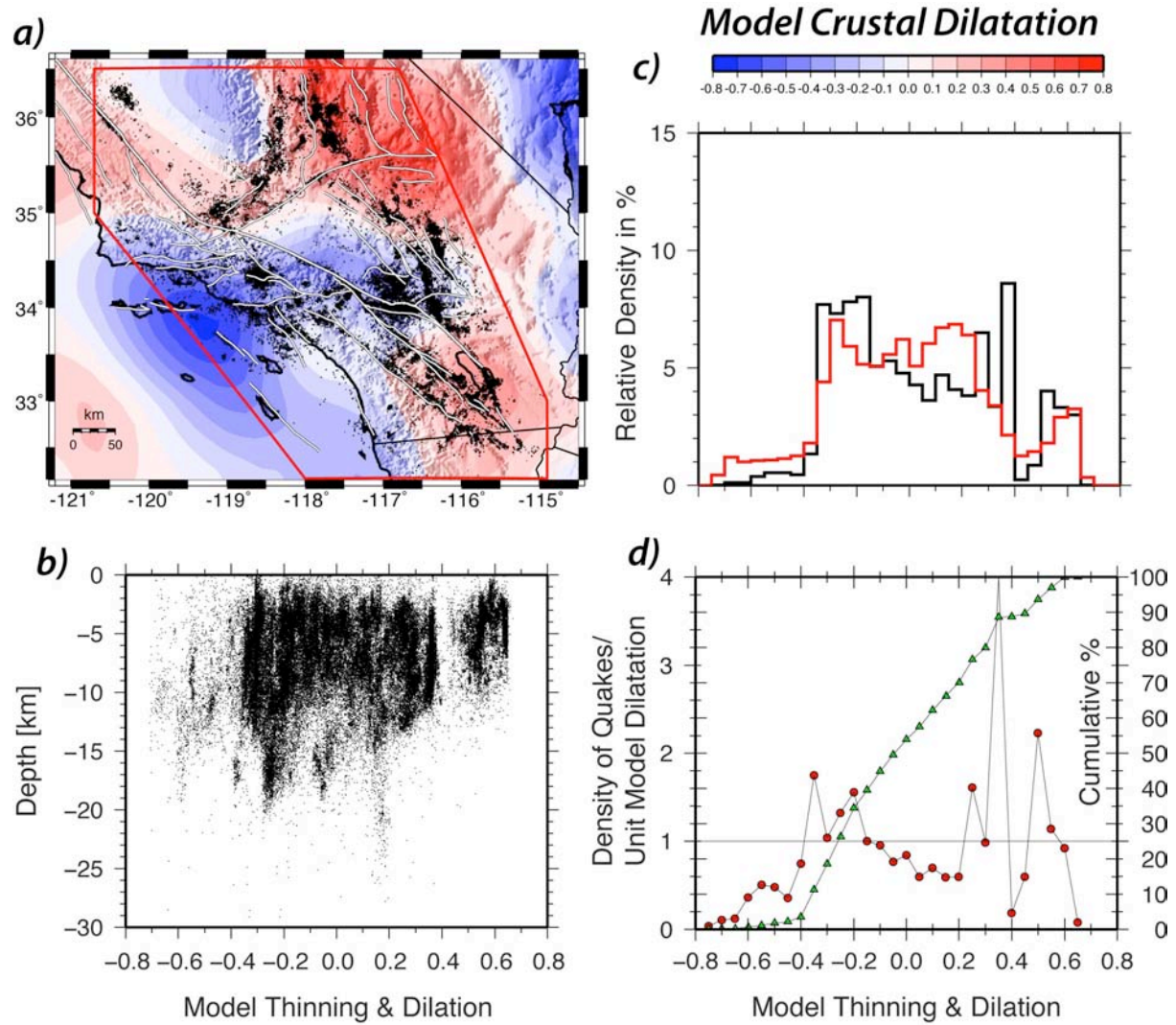


Figure 5. Modeled crustal dilatation and seismicity. (a) Earthquakes of $M \geq 1.8$ are plotted on top of the modeled dilatation of southern California. (b) Each hypocenter is plotted at the respective focal depth and corresponding modeled dilatation from the map. (c) Relative density of quakes and 'modeled dilatation values' for each 0.05 units of modeled dilatation. (d) Normalized density of quakes per 0.05 step in modeled, and cumulative number of quakes.

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