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# Analysis of Earthquake Data from the Greater Los Angeles Basin and Adjacent Offshore Area, Southern California

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Element I & III

**Key words:** Geophysics, seismology, seismotectonics

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## ABSTRACT

We synthesize and interpret local earthquake data recorded by the Caltech/USGS Southern California Seismographic Network (SCSN/CISN) in southern California. The goal is to use the existing regional seismic network data to: (1) refine the regional tectonic framework; (2) investigate the nature and configuration of active surficial and concealed faults; (3) determine spatial and temporal characteristics of regional seismicity; (4) determine the 3D seismic properties of the crust; and (5) delineate potential seismic source zones. Because of the large volume of data and tectonic and geologic complexity of the area, this project is a multi-year effort and has been divided into several tasks.

## RESULTS

### Earthquake Monitoring in Southern California for Seventy-Seven Years (1932–2008)

The Southern California Seismic Network (SCSN) has produced the SCSN earthquake catalog from 1932 to the present, a period of more than 77 years. This catalog consists of phase picks, hypocenters, and magnitudes. We present the history of the SCSN and the evolution of the catalog, to facilitate user understanding of its limitations and strengths. Hypocenters and magnitudes have improved in quality with time, as the number of stations has increased gradually from 7 to ~370 and the data acquisition and measuring procedures have become more sophisticated. The magnitude of completeness ($M_c$) of the network has improved from $M_c$ ~3.25 in the early years to $M_c$ ~1.8 at present, or better in the most densely instrumented areas (Figure 1). Mainshock–aftershock and swarm sequences and scattered individual background earthquakes characterize the seismicity of more than 470,000 events. The earthquake frequency-size distribution has an average b-value of ~1.0, with M ≥6.0 events occurring approximately every 3 years. The three largest earthquakes recorded were 1952 $M_w$ 7.5 Kern County, 1992 $M_w$ 7.3 Landers, and 1999 $M_w$ 7.1 Hector Mine sequences, and the three most damaging earthquakes were the 1933 $M_w$ 6.4 Long Beach, 1971 $M_w$ 6.7 San Fernando, and 1994 $M_w$ 6.7 Northridge earthquakes. All of these events ruptured slow-slipping faults, located away from the main plate boundary fault, the San Andreas fault. Their aftershock sequences constitute about a third of the events in the catalog. The fast slipping southern San Andreas fault is relatively quiet at the microseismic level and has not had an M >6 earthquake since 1932. In contrast, the slower San Jacinto fault has the highest level of seismicity, including several M >6 events. Thus, the spatial and temporal seismicity patterns exhibit a complex relationship with the plate tectonic crustal deformation (for more details, see *Hutton et al*., 2010).

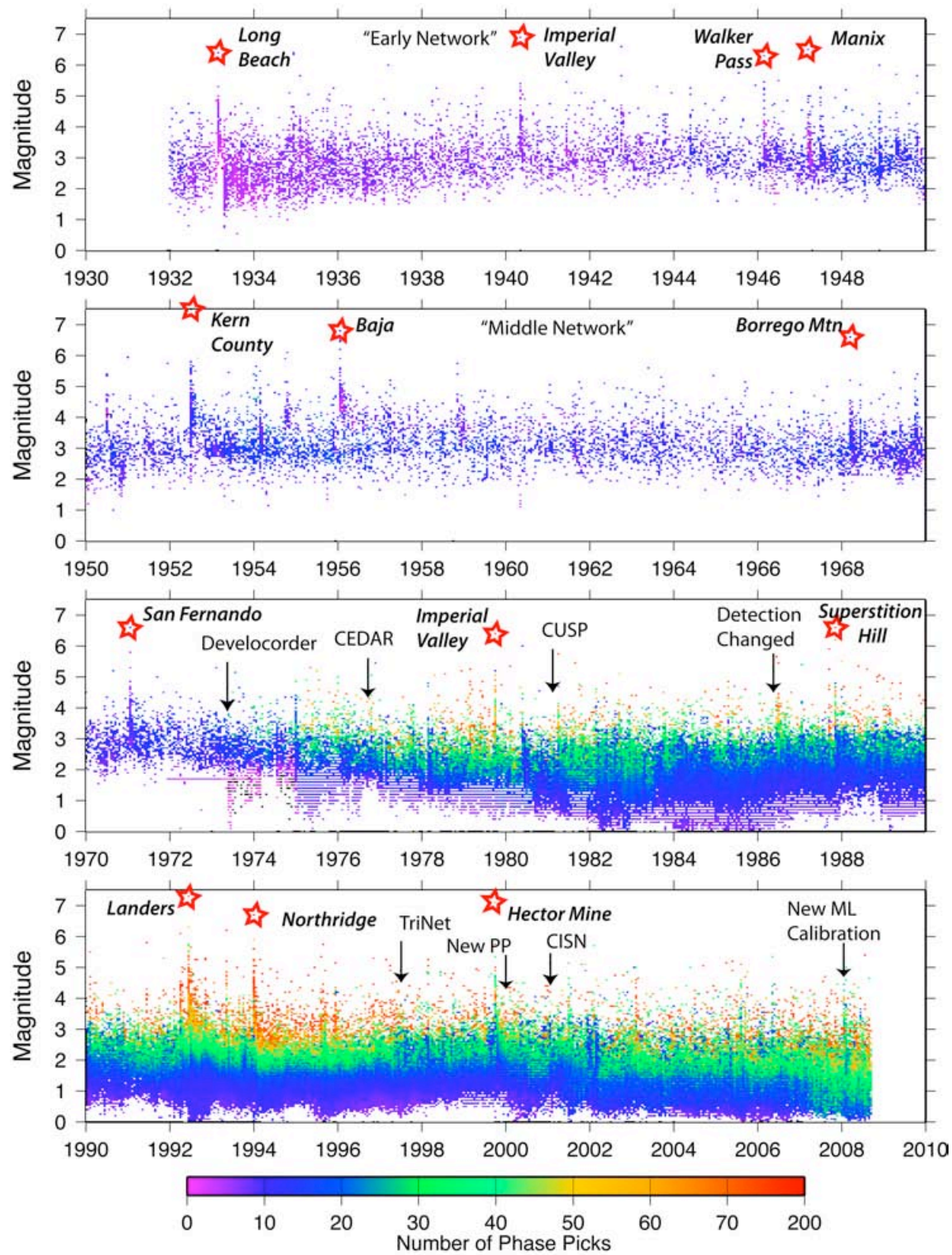


*Figure 1. The preferred magnitudes of more than 470,000 earthquakes are shown as a function of time, revealing possible changes in both operational procedures and in seismicity rate through SCSN history. The color, which is adjusted to cover similar areas in the plot, shows the number of phase picks as a function of time. The dates of major earthquakes and network changes are annotated.*

## Topography, Heat Flow, Crustal Thickness, and Depth of Earthquakes

The depth of earthquakes in the southern California crust varies across the region, ranging from depths of ~1 km to ~30 km, with the bulk of the focal depths in the range of 2 to 12 km. The thickness of this seismogenic zone is affected by both static and dynamic crustal parameters. The static parameters include topography, heat flow, crustal thickness, and lithology. The dynamic parameters are represented by some measures of tectonic loading such as the dilatational crustal strain field or the geographical distribution of late Quaternary faults, as a proxy for the tectonic shear strain rate. These static and dynamic crustal parameters vary across southern California as well as the thickness of the seismogenic zone. In general, areas of low topography, high heat flow, high Vp/Vs, and thin crust have a narrow seismogenic zone. Also, somewhat surprisingly, areas of high topography, low heat flow, low Vp/Vs, and thick crust also have a thin seismogenic zone. In contrast, areas of intermediate topography, average heat flow, average Vp/Vs and crustal strains coincide with seismogenic zones of average thickness. We determine an empirical relationship between heat flow and crustal thickness to show how the ~400°C temperature isotherm gradually deepens with crustal thickness and forms the base of the seismogenic zone for crustal thickness from 22 to 37 km. For crustal thickness ranging from 37 to 43 km, the ~250°C isotherms forms the base of the seismogenic zone, suggesting that seismic faulting is confined to the top of the upper crust, and thus does not accommodate plate motion. Below, we summarize some preliminary findings, which are part of a manuscript in preparation, (Hauksson et al., 2010).

*Topography*. The topography where earthquakes occur varies from 0 to ~3500 m above sea level in southern California (Figure 1a). The depth distribution of earthquakes versus topographic elevation shows that earthquakes are common at sea level and in the elevation range of 600 m to 1600 m, with a decrease in both focal depths and the number of events at higher elevations (> 1600 m), including beneath the Sierra Nevada (Figure 1b). Similarly, the normalized earthquake density is high from 600 m to 1600 m, and still higher from 1600 m to 2800 m (Figure 1c). Thus earthquake density is highest at high elevations, in part because very small part of southern California has high topography. These observations imply that earthquakes do not predominantly occur at any unexpected elevation range.

*Heat Flow*. The heat flow and spatial density of earthquakes varies across southern California (Figure 2a). The depth distribution of the heat flow and seismicity suggest that most of the earthquakes occurs in three heat flow regimes (Figure 2b). The relative density of seismicity and heat flow values are similar across southern California, with 90% of the seismicity occurring at average heat flow values, between heat flow of 50 to 100 mW/m2 (Figure 2c). At very low heat flow values of 20 to 50 mW/m2, below the high Sierras and parts of the Peninsular Ranges, there are small clusters of hypocenters scattered at shallow depth. There is also a prominent decrease in the depth of earthquakes with increasing heat flow, in the heat flow range of 90 to 220 mW/m2. This complex pattern suggests that other factors than just heat flow by itself affect the thickness of the seismogenic zone.

*Crustal thickness*. The Moho-depth varies beneath southern California from ~22 to ~43 km depth (Yan and Clayton, 2007). They used receiver functions to determine crustal thickness (Figure 3a). The shallow Moho is found beneath the Continental Borderland and the Salton Trough. The deep Moho is found beneath a corridor that extends from the San Bernardino Mountains to the south, across the Peninsular Ranges. The deep Moho also exists beneath the high Sierra Nevada as well as the deepest part of the Ventura Basin. The bulk of the seismicity is in the Moho depth range of 22 to 37 km, with some scattered shallow earthquakes in the Moho depth range of 37 to 43 km (Figure 3b).

The depth of earthquakes varies from ~13 to ~20 km as the Moho-depth changes from 22 to 37 km. For deeper Moho, from 37 to 43 km the focal depths become shallower, with depths from ~1 to ~12 km. If the crust is very thick, the seismicity appears to be mostly confined to the shallow part of the upper crust, like beneath the high Sierra Nevada. The histograms in Figure 3c show the relative density of seismicity and Moho-depth values. The central peak of seismicity is formed by the 1992 Landers aftershocks sequence. The far-right peak at 22 km Moho-depth is associated with in part, induced seismicity caused by geothermal activity, near the south end of the Salton Sea. The relative density of quakes per unit of Moho-depth shows several smaller peaks where quake density is high. Similarly, there are relatively few earthquakes in areas with crustal thickness that exceeds 37 km.

*Crustal Temperature*. We apply the 1D heat flow equation to calculate the temperature as a function of depth within the crust (Bonner et al., 2003). The Fourier law for one dimensional vertical steady-state heat flow can be expressed as:

$$kd^2T/dz^2 = -A(z) \qquad (1)$$

where $k$ is the thermal conductivity, $T$ is the temperature, and $A$ is the heat production (Tanaka and Ishikawa, 2002).

Radioactive heat generation that contributes to the temperature of the continental crust decays exponentially with depth (Lachenbruch, 1970). For the heat flow, (Tanaka and Ishikawa, 2002) showed that the temperature ($T$) as a function of depth ($z$) is given by,

$$T = T_0 + ((q_0 - Az_1)/k)z + (Az_1^2/k)(1 - \exp(-z/z_1)) \qquad (2)$$

where $q_0$ is heat flow, the thermal conductivity within the California crust ($k$) is 2.5 $Wm^{-1}K^{-1}$ and the average heat generation ($A$) is 1.7 $\mu Wm^{-3}$ (Bonner et al., 2003). The constant values are from (Tanaka and Ishikawa, 2002); $z_1$ = 10 km, $T_0$ = 13.4 °C. In a previous study, Bonner et al. (2003) applied the equation above to determine the temperature isotherms for the California crust.

Using our data set of heat flow versus Moho-depth we derive the following empirical relationship between heat flow and Moho-depth (MD) in km:

$$q_0 = B - C * MD \qquad (3)$$

where $B$ is the average heat flow at the surface and $C$ is the heat flow depth gradient. A linear fit provides $B$ = 110.2 (mW/m$^2$) and $C$ = 1.4 (mW/m$^2$/km). We insert equation (3) into equation (2) and determine the temperature isotherms in the two dimensional space of focal-depth and Moho-depth (Figure 4). These temperature isotherms deepen with increasing crustal thickness. The clear increase in depth of seismicity with thicker crust from 22 km to 37 km, is bracketed at depth by the ~400°C isotherm. The coherent relationship between the focal-depths and the Moho-depth suggest that other parameters than temperature such as lithology play a minor role in influencing earthquake depths.

The deepening of the isotherms and the abrupt shallowing in focal depths at 37 km could be caused by the increased crustal thickness and corresponding increase in normal force being too high to allow rupture of the whole depth range of the brittle ductile transition zone. Thus the earthquakes in the shallow part of very thick crust may signify other processes that plate tectonic boundary motion.

The apparent streaks of deep events, below ~400°C, could be the effects of larger sequences that temporarily extend into the ductile lower crust. Alternatively, they could be caused by special geological conditions such as crustal delamination processes in the Ventura Basin and Banning Pass. It is unlikely that they could also be artifacts of the interpolation of the Moho-depth data or poorly determined focal depths.

The line with slope of 1.0 in Figure 4 represents the Moho boundary that separates crust and mantle. This line demonstrates that the thickness of the lower crust changes twice as fast as the thickness of the upper crust. A few earthquakes that apparently seem to locate within the Mantle may have poorly determined focal depths.

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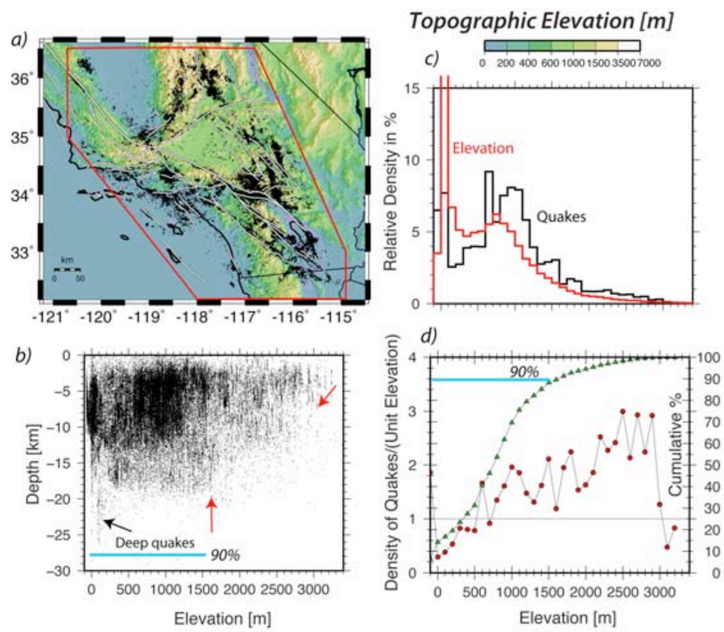


*Figure 1. Topography and seismicity. (a) Earthquakes of M≥1.8 are plotted on top of the topography of southern California. (b) Each hypocenter is plotted at the respective focal depth and corresponding elevation read from the topographic map. (c) Relative density of quakes and 'elevation values' for each 100 m of elevation. (d) Density of quakes per 100 m step in elevation, and cumulative number of quakes. The blue bar indicates the range of elevation where the 90% of the seismicity occurs.*

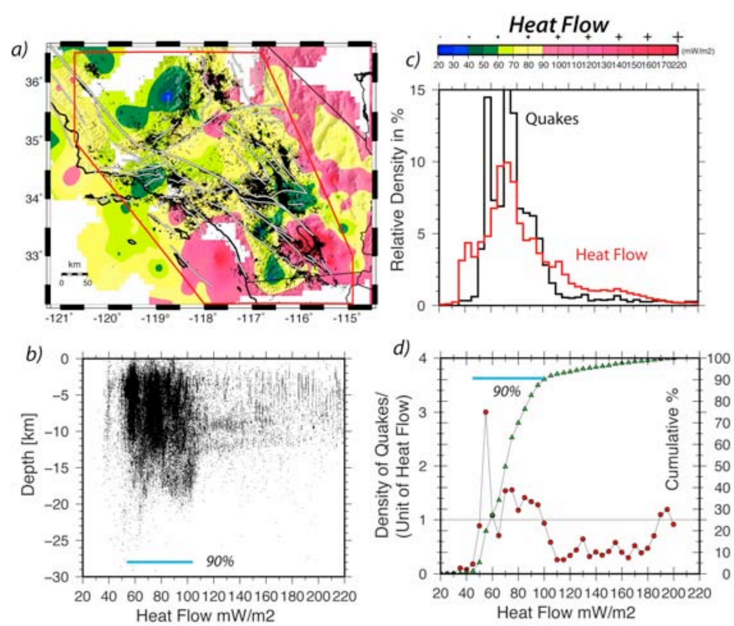


*Figure 2. Heat flow and seismicity. (a) Earthquakes of M≥1.8 are plotted on top of the heat flow for southern California. (b) Each hypocenter is plotted at the respective focal depth and heat flow value read from the map. (c) Relative density of quakes and 'heat flow values' for each 10 mW/m2 of heat flow. (d) Density of quakes per 10 mW/m2 step in heat flow, and cumulative number of quakes. The blue bar indicates the range of heat flow where the 90% of the seismicity occurs.*

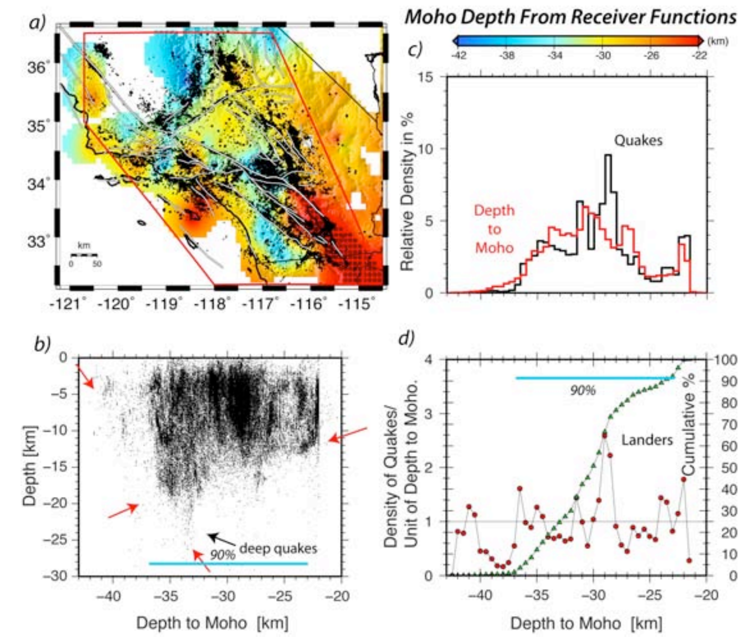


*Figure 3. Moho-depth and seismicity. (a) Earthquakes of M≥1.8 are plotted on top of the Moho-depth map for southern California. (b) Each hypocenter is plotted at the respective focal depth and Moho-depth read from the map. (c) Relative density of quakes and 'Moho-depth values' for each 100 m step of Moho-depth. (d) Density of quakes per unit Moh-depth, and cumulative number of quakes. The blue bar indicates where the 90% of the seismicity occurs.*

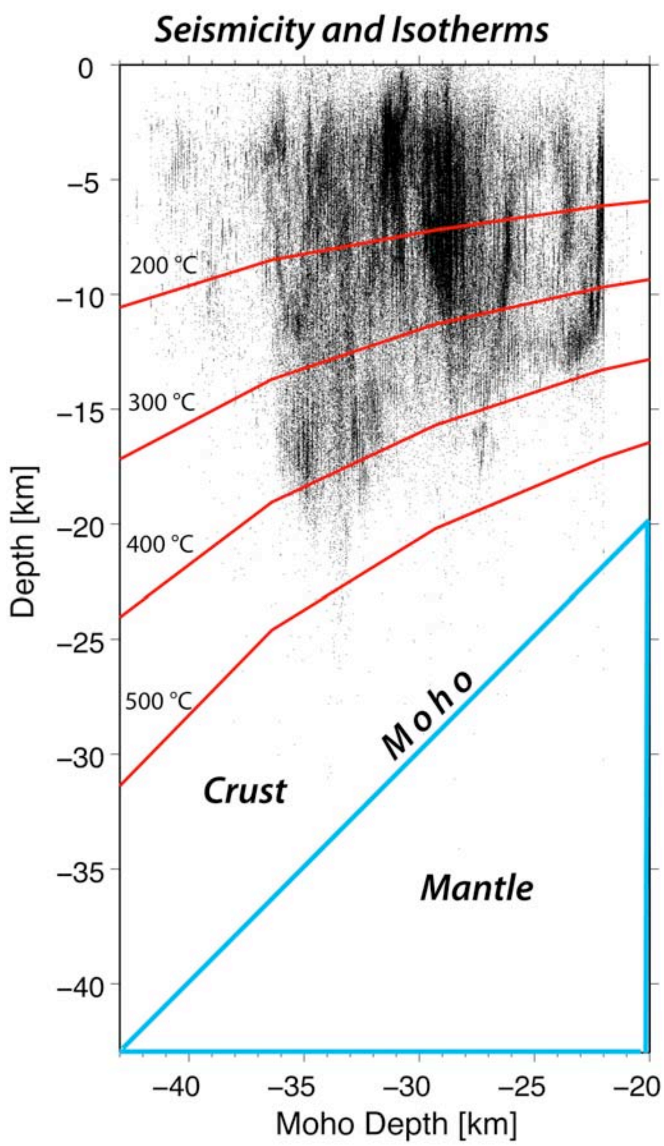


*Figure 4. Focal depth versus Moho-depth, including temperature isotherms, and the Moho boundary. The line with slope 1.0 represents Moho in this plot.*

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