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

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Summary

Focal Mechanism Catalog: 1981 to 2010

Using the HASH method (Hardebeck and Shearer, 2002, 2003), we calculate focal mechanisms for earthquakes that occurred in the southern California region from 1981 to 2010. When available, we use hypocenters refined with differential travel-times from waveform cross-correlation. We apply grid search to determine the best-fitting double-couple focal mechanism solution. The data consist of both the P-wave first motion polarities and the S/P amplitude ratios computed from three-component seismograms. We process data from more than 480,000 earthquakes, and analyze the statistical features of the whole data set. As more S/P amplitude ratios become available after 2000, the average nodal plane uncertainty decreases significantly compared with solutions that include only P-wave polarities. We filter a preliminary data set with criteria associated with mean nodal plane uncertainty and azimuthal gap, and obtain a high quality catalog with approximately 179,000 focal mechanisms. In general the parameters of the focal mechanisms have been stable during the three decades. The dominant style of faulting is high angle strike-slip faulting with the most likely P axis centered at N5°E. For earthquakes of $M < 2.5$, there are more normal faulting events than reverse faulting events while the opposite holds for $M > 2.5$ events. A comparison of 23,000 common earthquakes shows our results generally agree with the focal mechanism catalog obtained by Hardebeck and Shearer (2003). Using 210 moment tensor solutions in Tape et al (2010) as benchmarks, we compare the focal plane rotation angles of common events in the catalog. 70% of common earthquakes in both catalogs match well, with rotation angles less than the typical nodal plane uncertainty in the total first motion and S/P ratio mechanisms. The common events with relatively large rotation angles are either located around the edge of the SCSN network or poorly recorded.

The 2010 Mw7.2 El Mayor-Cucapah Sequence

The M_w7.2 El Mayor-Cucapah mainshock that occurred on the 4th of April 2010 exhibited complex faulting, possibly starting with a ~M6 normal faulting event, followed ~15 sec later by the main event, which included simultaneous normal and right-lateral strike-slip faulting. The aftershock zone extends for 120 km from the south end of the Elsinore fault zone north of the US-Mexico border almost to the northern tip of the Gulf of California. We have analyzed the whole sequence as described in Hauksson et al. (2010).

3-D Crustal Models and Seismicity

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

This project analyzes data recorded by the Southern California Seismic Network (SCSN/CISN) to associate earthquakes with faults, estimate fault-scale seismicity parameters, determine the state of stress in the crust, and evaluate 3D-fault configurations in southern California. Further, we interpret the geophysical parameters in the context of geology and the spatial and temporal evolution of seismicity. Several aspects of this work are being done collaboratively with Dr. P. Shearer at UCSD and other investigators.

First motion focal mechanisms have been used to address important tectonic problems, such as determining the state of stress in the vicinity of the San Andreas fault, but different investigators disagree on the results (e.g. Hardebeck and Hauksson, 2001). In a catalog comparison study, Kagan (2002) questioned the quality of these mechanisms by pointing out that the SCSN first motion focal mechanisms were only a factor of two within random rotations of a double-couple source. To make further progress in interpreting these data sets, we have focused our research to produce an improved catalog of focal mechanisms and to improve our understanding of the error sources that contribute to the scatter in the focal mechanisms.

The occurrence of the April 4th 2010 El Mayor Cucapah Mw7.2 earthquake triggered many aftershocks in southern California and provided ample data for seismotectonic studies in southernmost California and northern Baja California. Around 16,000 aftershocks had been recorded by the SCSN as of October 2011. In comparison, the southern California background seismicity rate consists of ~1200 earthquakes per month. We have studied the aftershocks that occurred along the mainshock rupture zone in Baja (Borrego and other faults), as well as increased seismicity along neighboring parallel faults zones to the north, such as the San Jacinto faults zone and the Elsinore faults zone.

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 was inversely related to heat flow, and that epicentral distributions tend to parallel thermal transitions. 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). This study has improved our understanding of the depth distribution of the southern California seismicity.

Focal Mechanism Catalog: 1981 to 2010

We have applied the HASH method of Hardebeck and Shearer (2002) to determine a catalog of first motion mechanisms (Figure 1). We have relaxed most quality constraints and determine a 'complete' catalog of ~137,000 first motion mechanisms. To analyze the error distribution, we plot the average fault plane error for each mechanism versus standard quality parameters. The data in these plots illustrate that the quality of focal mechanisms is mostly dependent on first motion data rather than commonly used quality parameters. The distributions of rake versus dip or dip-direction values shows three clusters corresponding to right-lateral strike-slip, normal faulting, and dip-slip faulting. These distributions are overlapping and indicate a continuous distribution of the style of faulting. Using the standard quality parameters to filter the catalog shows that poorly constrained events do not add biases to the catalog. Time-series (1981 – present) of the rake and dip show minimal variations with time, with a consistent average rake of ~ -170° and dip of ~70°. Similarly, the three measures of quality, average number of first motions per event, the station distribution ratio (STDR), and the average plane errors only exhibit minor fluctuations with time. Thus neither the occurrence of major events such as the 1992 Mw7.3 Landers earthquake nor changes in the configuration of the seismic network seem to have affected significantly the average properties of the mechanisms or their quality.

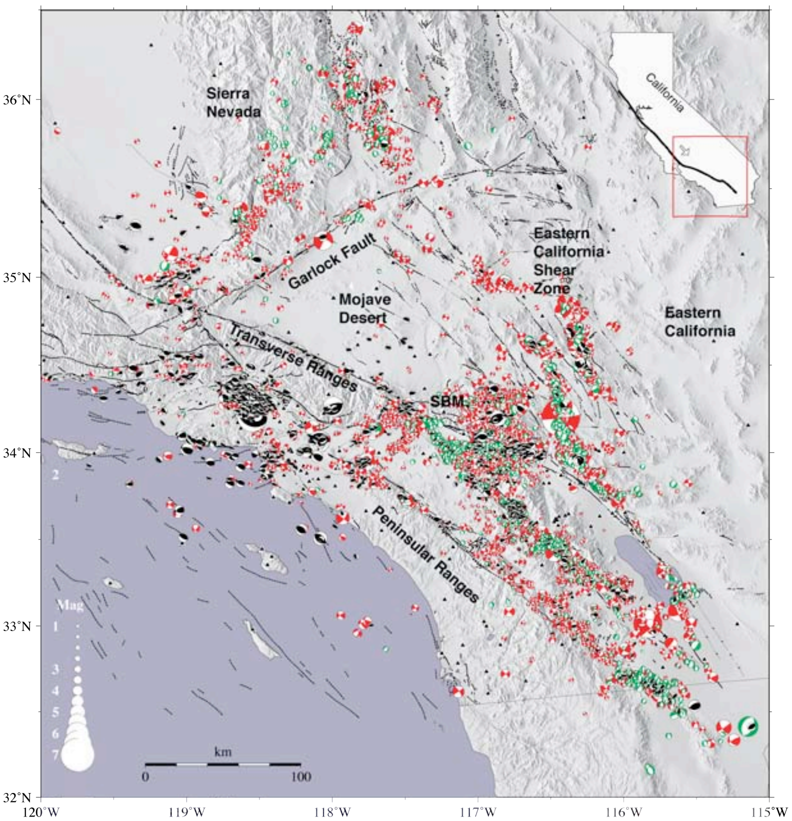

Figure 1. Map view of quality A focal mechanisms with around 13,000 earthquakes from the refined P wave first motion polarities and S/P amplitude ratios focal mechanism catalog (1981 - 2010). Focal mechanisms are plotted in the order of strike-slip (red), normal (green) and reverse (black). To each style of faulting, events are overlapped temporally. The sizes of beach balls are scaled with magnitudes with legend at the bottom left corner. Seismic stations are in blue triangles. Faults are in black curves. SBM, San Bernardino Mountain. The insert panel at the top right corner shows the relative location of the map area (red box) in the state of California. The San Andreas Fault in bold black curve separates the Pacific Plate and the North America Plate with arrows indicating relative motions.

To analyze the style of faulting, we classified earthquakes with focal mechanisms as normal, reverse, and strike-slip faulting based on rake angle with a simple 90° separation rule: events with rake angles in [-45° - -135°] exhibit normal faulting, in [45° - 135°] exhibit reverse faulting, and the remaining events exhibits strike-slip faulting with any rake angles. The average style of faulting is summarized by magnitude bins. In all magnitude bins, the strike-slip faulting events constitute more than 2/3 of all mechanisms. With magnitude bins ranging from 0.0 to 5.0, the fraction of reverse faulting increases from 11% to 21%, and the fraction of normal faulting drops from 22% to 2%. Such a change in style of faulting with increasing magnitudes matches with the fact that large earthquakes, which occurred in the southern California region, are either strike-slip or reverse faulting (*Yang et al.,* 2012).

The 2010 El Mayor-Cucapah Earthquake Sequence

Spatial and Temporal Patterns. The 2010 M_w7.2 El Mayor-Cucapah earthquake sequence occurred within the Mexican Pacific margin in northern Baja California (BC), a region of high seismicity straddling the complex Pacific - North America plate boundary. The seismically active parts of the northeast Baja California region follow the Pacific North America plate boundary from the northern

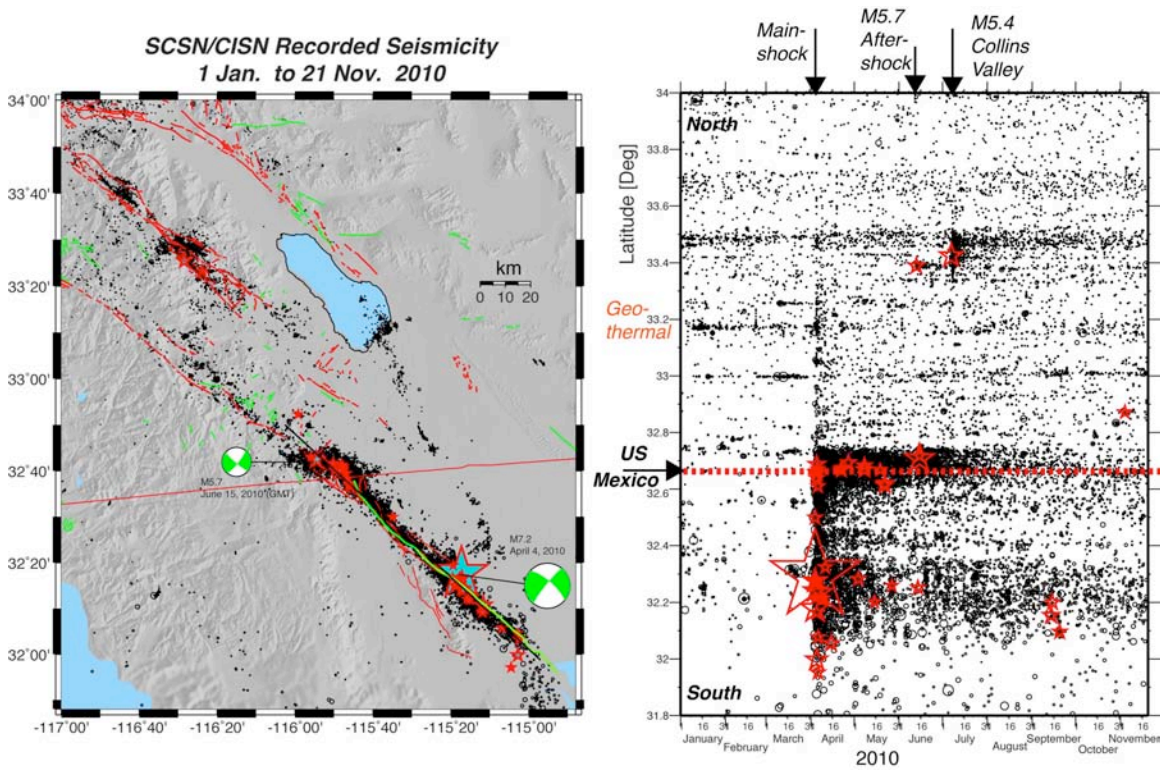

Figure 2 (Left) Map of El Mayor sequence and the background seismicity from 1 Jan. to 21 Nov. 2010. (Right) Time-space plot of latitude versus time of El Mayor aftershocks triggered earthquakes to the north along the San Jacinto and Elsinore fault zones.

shores of the Gulf of California, crossing major sedimentary basins and connecting up to the faults of the plate boundary zone in southern California, including the Elsinore and San Jacinto faults, and the southernmost San Andreas fault in the Salton Sea to the north. Within hours following the El Mayor-Cucapah mainshock, triggered earthquakes occurred farther north along the Elsinore and San Jacinto faults (Figure 2). Both faults are capable of a major earthquake, which would significantly affect the large metropolitan areas of southern California.

The triggered seismicity along the Elsinore fault extended about 60 km to the north. Many of the aftershocks near Ocotillo occurred on northwest-striking faults that trend subparallel to the Elsinore fault in this region. The Elsinore fault is more than 170 km long, and extends into the Los Angeles area as the Whittier fault.

The triggered seismicity along the San Jacinto fault extended 80 km to the north (Figure 2). As of mid-March 2011, the largest triggered earthquake on the San Jacinto fault was M_w5.4 on July 7[th] 2010. During the 20th century the San Jacinto fault has been the most active fault in southern California with more than a dozen earthquakes of M>6 (Sanders and Kanamori, 1984). In particular, the southern San Jacinto fault has accommodated major earthquakes in the past (Gurrola and Rockwell, 1996).

No triggered seismicity was associated with the southern San Andreas fault although the fault is close to reaching the end of its interseismic loading phase (Fialko, 2006). However, surficial triggered slip was documented along the fault (Sandwell et al. 2010; Treiman et al. 2010).

There are only a few previously documented cases of aftershock migration, and subsequent triggering of a major earthquake. In one case, Hauksson et al. (1993) reported that the 1992 M6.1 Joshua Tree aftershocks migrated over a time period of two months for a distance of ~10 km to the north-northwest, towards the future epicenter of the 1992 M_w7.3 Landers earthquake. However, Helmstetter et al. (2003)

who used data from 20 California earthquake sequences argued that aftershock diffusion is very limited and in most cases does not occur. Thus, when future earthquakes happen along the Elsinore and San Jacinto faults their causative relation to the El Mayor-Cucapah earthquake will probably be stated in terms of triggered seismicity.

Seismotectonics. The El Mayor-Cucapah earthquake sequence differed from past sequences in southern California with its more complex style of faulting than observed before. The El Mayor-Cucapah, Landers, and Hector Mine earthquakes all ruptured multiple fault strands with varying degrees of overlap. Both the Landers and Hector Mine mainshocks ruptured successively four major fault segments each, which previously were thought to be unlikely to rupture in one earthquake. Similarly, the El Mayor-Cucapah earthquake ruptured at least four segments, with two different styles of faulting, accommodating complementary seismotectonic processes. Prior to the occurrence of the earthquake, Fletcher and Spelz (2009) had mapped these two styles of faulting in the field but it was unclear if they happened simultaneously. Further, the El Mayor-Cucapah mainshock did not rupture along seismicity trends that had developed over the last decade. Rather, it ruptured along the length of the Sierra Cucapah causing partial down-dropping of the eastern side of the mountain range. Thus, the mainshock contributed also to the westward widening of the Mexicali Valley through the extensional part of its focal mechanism. Such extension that contributes to east-west widening of basins in the northern Gulf extensional province has not been documented in detail previously in the Baja California region (*Hauksson et al*., 2010).

3-D Crustal Models and Seismicity

The geographical distribution of the (1981 to 2005) seismicity in southern California forms a ±150 km broad zone adjacent to the Pacific-North America plate boundary, 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 distribution of the seismicity that includes both mainshock-aftershock sequences and background events is affected by both static and kinematic geophysical parameters of the crust. The static parameters include heat flow, topography, crustal density, Vp/Vs ratio, hypocentral fault-distance, and crustal thickness from receiver functions. The tectonic loading is represented by kinematic parameters such as the crustal shear strain rate field, and the dilatational strain rate field. In our analysis, we normalize the seismicity relative to the areal density of the range of values of each of the parameters. Most of the seismicity occurs in areas of average heat flow, low to intermediate topography, average Vp/Vs, and high late Quaternary fault density, and forms seismogenic zones that extend through the brittle crust. The location of late Quaternary faults, often described as zones of weakness, influences the geographical distribution of seismicity more than any other parameter (Figure 3). Although above or below average crustal properties such as high heat flow, thin crust, or very low Vp/Vs values exist, these properties only influence the spatial distribution of seismicity in a minor way. As an example, the Salton Trough area of low topography, high heat flow, high Vp/Vs, high shear strain rate, and thin crust has distributed seismicity within a thin seismogenic zone. Also, somewhat surprisingly, areas of high topography, low heat flow, low Vp/Vs, low shear strain rate, and thick crust have low seismicity rates but a thin seismogenic zone. 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 thicknesses from 22 to 37 km. For crustal thickness ranging from 37 to 43 km, the ~250°C isotherm forms the base of the seismogenic zone, suggesting that seismic faulting in these regions is confined to the top of the upper crust (12 to 14 km), and thus does not accommodate plate motion (*Hauksson*, 2011).

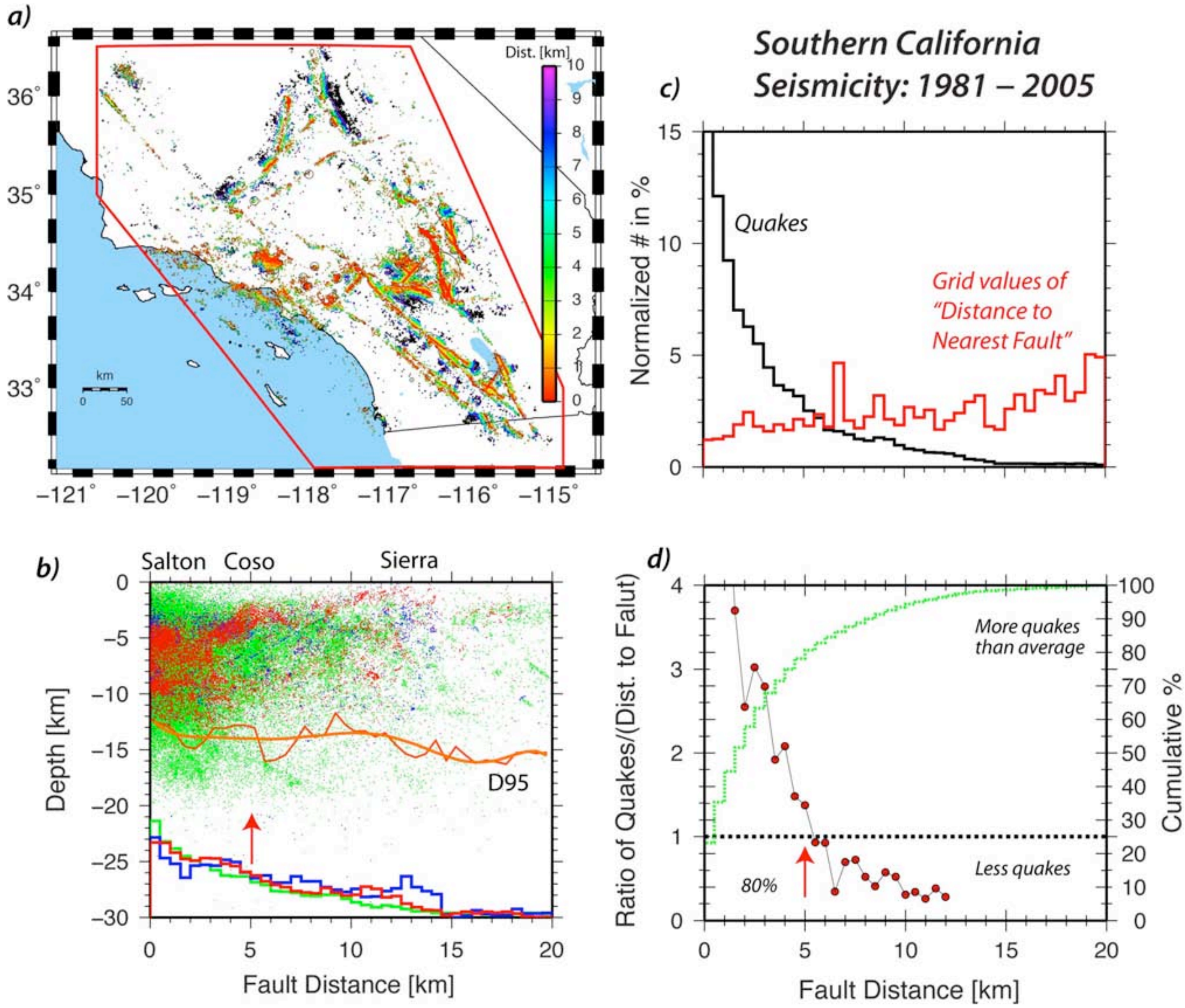

Figure 3. Fault-distance and seismicity. (a) Fault-distances for earthquakes of M≥1.8 are plotted in color; the study area outlined by the red polygon. The late Quaternary mapped fault traces are not included. (b) Each hypocenter is plotted at the respective distance from the nearest principal slip-surface of a late Quaternary fault. Detailed and smooth versions of the 95% maximum seismicity depth contour are plotted in orange color. (Bottom) histograms separating the three ranges of heat flow values, 0-55 (blue), 55-110 (green), and 110-3000 (red) mWm^2, with y=log10(1.0+frequency percent) with full scale of 5.0. (c) Normalized histograms 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) Ratio of the two histograms in c) per 1 km step in fault-distance (curve with red dots), and cumulative number of quakes (green curve). The arrows indicate the range of fault-distances where the percent (value shown in plot) of the seismicity occurs.

Outreach Activities

The outreach activities consisted of publishing the results of the research in peer-reviewed journals. Also, the focal mechanism catalog is being distributed to researchers via the Southern California Earthquake Data Center (SCEDC).

References

Bonner, J. L., Blackwell, D.D. & Herrin, E.T., 2003. Thermal Constraints on Earthquake Depths in California, *Bull. Seism. Soc. Am.*, **93**, No. 6, pp. 2333–2354.

Fialko, Y. (2006), Interseismic strain accumulation and the earthquake potential on the southern San Andreas fault system, Nature, v. 441|22 June 2006|; doi: 10.1038/nature04797.

Fletcher, J. M., and Spelz, R. M. (2009), Pattterns of Quaternary deformation and rupture propagation associated with an active low-angle normal fault, Laguna Salada, Mexico: Evidence of a rolling hinge, *Geosphere*, vol. 5, no. 4, 385-407; doi: 10.1130/GES00206.1.

Gurrola, L. D., and Rockwell T. K. (1996), Timing and slip for prehistoric earthquakes on the Superstition Mountain Fault, Imperial Valley, southern California, *J. Geophys. Res.,* v 101, no B3, 5977-5985.

Hardebeck, J.L. and E. Hauksson, Crustal stress field in southern California and its implications for fault mechanics, *J. Geophys. Res., 106,* 21,859-21,882, 2001.

Hardebeck, J.L. and P.M. Shearer, A new method for determining first-motion focal mechanisms, *Bull. Seismol. Soc. Am*, **92**, 2264-2276, 2002.

Hardebeck, J.L. and P.M. Shearer, Using S/P amplitude ratios to constrain the focal mechanisms of small earthquakes, *Bull. Seismol. Soc. Am.*, **93**, 2434-2444, 2003.

Hauksson, E., Jones, L. M., Hutton, K., and Eberhart-Phillips, D. (1993), The 1992 Landers Earthquake Sequence: Seismological Observations, *J. Geophys. Res., 98,* 19,835-19,858.

Hauksson, E., J. Stock, K. Hutton, W. Yang, A. Vidal, and H. Kanamori, The 2010 Mw7.2 El Mayor-Cucapah Earthquake Sequence, Baja California, Mexico and Southernmost California, USA: Active Seismotectonics Along the Mexican Pacific Margin, *Pure Appl. Geophys, Topical Issue: Geodynamics of the Mexican Pacific Margin*, DOI 10.1007/s00024-010-0209-7, 2010.

Hauksson, E., Crustal geophysics and seismicity in southern California. *Geophysical Journal International,* 186: 82–98. DOI: 10.1111/j.1365-246X.2011.05042.x, 2011.

Helmstetter, A., Quillon, G., and Sornette, D. (2003), Are aftershocks of large Californian earthquakes diffusing?, *J. Geophys. Res.*, v 108, no B10, doi: 10.1029/2003JB002503.

Kagan, Y., Y., Modern California earthquake catalogs and their comparison, *Seismol, Res., Letters*, 73, 921-929, 2002.

Lin, G., P. M. Shearer and E. Hauksson, Applying a 3D velocity model, waveform cross-correlation, and cluster analysis to locate southern California seismicity from 1981 to 2005, *J. Geophys. Res.*, **112**, B12309, doi: 10.1029/2007JB004986, 2007.

Lundgren, P., Hetland, E. A., Liu, Z., and Fielding, E. J. (2009), Southern San Andreas- San Jacinto fault system slip rates estimated from earthquake cycle models constrained by GPS and interferometric synthetic aperture radar observations, *J. Geophys. Res.*, v. 114, B02403, doi: 10.1029/2008JB005996.

Sanders, C. O., and Kanamori, H. (1984), A seismotectonic analysis of the Anza Seismic Gap, San Jacinto Fault Zone, southern California, *J. Geophys. Res.*, v 89, 5873-5890.

Sandwell, D. T., Wei, M., Gonzales, J., Gonzales, A., Lipovski, B., Funning, G., Fialko, Y., Mellors, R., Agnew, D., and Peterson, R. (2010), InSAR and GPS measurements of crustal deformation from the El Mayor earthquake: Liquefaction and Triggered Slip, Cordilleran Section, *Abstract LB1-8*, Anaheim, California

Tape, C., Q. Liu, A. Maggi and J. Tromp, Adjoint tomography of the southern California crust, *Science*, **325**, 988–992, doi: 10.1126/science.1175928, 2009.

Treiman, J.A., Rymer, M.J., Kendrick, K.J., Lienkamper, J.J., Weldon, R.J. II, Hernanadez, J.L., Irvine, P.J., Knepprath, N., Olson, B.P.E., and Sickler, R.R. (2010), Triggered slip in southern California as a result of the April 5, 2010 El Mayor-Cucapah earthquake, Geological Society of America, Cordilleran Section, *Abstract LB2-5*, Anaheim, California.

Wei, S., Sladen, A., Leprince, S., Avouac, J.-P., Fielding, E. J., Chu, R., Simons, M., Helmberger, D., Hauksson, E., and Lohman, R. (2010), Joint inversion of geodetic and seismic slip models for the April 04, 2010 El Mayor-Cucapah earthquake, Geological Society of America, Cordilleran Section, *Abstract LB1-4*, Anaheim, California.

Yang, W., E. Hauksson, and P. Shearer, Computing a large refined catalog of focal mechanisms for southern California (1981 – 2010): Temporal Stability of the Style of Faulting, *Bull. Seismol. Soc. Am.*, (*accepted*), January 2012.

Publications Supported by SCEC3

Hauksson E., K. Felzer, D. Given, M. Giveon, S. Hough, K. Hutton, H. Kanamori, V. Sevilgen, S. Wei, and A. Yong, Preliminary Report on the 29 July 2008 Mw5.4 Chino Hills, Eastern Los Angeles Basin, California, Earthquake Sequence, *Seismo. Res. Letters*, vol. 79, p. 855- 868, 2008

Hauksson, E., Spatial Separation of Large Earthquakes, Aftershocks, and Background Seismicity: Analysis of Interseismic and Coseismic Seismicity Patterns in Southern California, *Special Frank Evison Issue of Pure Appl. Geophys.*, DOI 10.1007/s00024-010-0083-3, 2010.

Hauksson, E., J. Stock, K. Hutton, W. Yang, A. Vidal, and H. Kanamori, The 2010 Mw7.2 El Mayor-Cucapah Earthquake Sequence, Baja California, Mexico and Southernmost California, USA: Active Seismotectonics Along the Mexican Pacific Margin, *Pure Appl. Geophys, Topical Issue: Geodynamics of the Mexican Pacific Margin*, DOI 10.1007/s00024-010-0209-7, 2010.

Hauksson, E., Crustal geophysics and seismicity in southern California. *Geophysical Journal International,* 186: 82–98. DOI: 10.1111/j.1365-246X.2011.05042.x, 2011.

Hauksson, E. and W. Yang, and P. M. Shearer, Waveform Relocated Earthquake Catalog for Southern California (1981 to June 2011); Submitted to: *Bull. Seismol. Soc. Am.,* January 2012.

Holzer T. L., A. S. Jayko, E. Hauksson, J. P. B. Fletcher, T. E. Noce, M. J. Bennett, C. M. Dietel, and K. W. Hudnut, Liquefaction caused by the 2009 Olancha, California (USA), M5.2 earthquake, *Engineering Geology*, doi: 10.1016/j.physletb.2003.10.071

Hutton, L. K., J. Woessner, and E. Hauksson, Seventy-Seven Years (1932 – 2009) of Earthquake Monitoring in Southern California, *Bull. Seismol. Soc. Am*, v. 100; no. 2; p. 423-446; DOI: 10.1785/0120090130, 2010.

Lin, G., P. Shearer, and E. Hauksson, A Search for Temporal Variations in Station Terms in Southern California from 1984 to 2002, *Bull. Seismol. Soc. Am.,* 98: 2118 – 2132, 2008.

Lin, G., C. H. Thurber, H. Zhang, E. Hauksson, P. M. Shearer, F. Waldhauser, T. M. Brocher and J. Hardebeck, A California statewide three-dimensional seismic velocity model from both absolute and differential times, *Bull. Seismol. Soc. Am.*, **100**, 225-240, doi: 10.1785/0120090028, 2010.

Lin, G., C. H. Thurber, H. Zhang, E. Hauksson, P. M. Shearer, F. Waldhauser, T. M. Brocher, and J. Hardebeck, A California Statewide Three-Dimensional Seismic Velocity Model from Both Absolute and Differential Times, *Bull. Seismol. Soc. Am.*, 100, 1, 225–240, doi: 10.1785/0120090028, 2010.

Luo Y., Y. Tan, S.Wei, D. Helmberger, Z. Zhan, S. Ni, E. Hauksson, and Y. Chen,Source Mechanism and Rupture Directivity of the May 18, 2009 Mw4.6 Inglewood, California Earthquake, *Bull. Seismol. Soc. Am.*, December, 2010; v. 100; no. 6; p. 3269-3277; DOI: 10.1785/0120100087.

Tormann,T., S. Wiemer, and E. Hauksson, Changes of Reporting Rates in the Southern Californian Earthquake Catalog, Introduced by a New Definition of M_L, *Bull. Seismol. Soc. Am*, August 2010; v. 100; no. 4; p. 1733-1742; DOI: 10.1785/0120090124.

Uhrhammer, R. A., M. Hellweg, K. Hutton, P. Lombard, A. W. Walters, E. Hauksson and D. Oppenheimer, California Integrated Seismic Network (CISN) Local Magnitude Determination in California and Vicinity, *Bull. Seismol. Soc. Am., v. 101, no. 1, p. 427-432; DOI: 10.1785/0120100136*, 2011.

Unruh, J. and E. Hauksson, Seismotectonics of an Evolving Intracontinental Plate Boundary, Southeastern California *Geological Society of America Special Papers 2009, 447, p. 351-372, doi: 10.1130/2009.2447(16),* 2009.

Wei, S., E. Fielding, S. Leprince, A. Sladen, J.-P. Avouac, D. Helmberger, E. Hauksson, R. Chu, M. Simons, K. Hudnut, T. Herring, and R. Briggs, Superficial simplicity of the 2010 El Mayor-Cucapah earthquake of Baja California in Mexico, *Nature Geoscience* **4**, 615–618 (2011) doi: 10.1038/ngeo1213, 2011.

Yang, W. and E. Hauksson, Evidence for Vertical Partitioning of Strike-Slip and Compressional Tectonics From Seismicity, Focal Mechanisms, and Stress Drops in the East Los Angeles Basin Area, California, *Bull. Seismol. Soc. Am.*, v. 10, no. 3, p. 964-974; DOI: 10.1785/0120100216, 2011.

Yang, W., E. Hauksson, and P. Shearer, Computing a large refined catalog of focal mechanisms for southern California (1981 – 2010): Temporal Stability of the Style of Faulting, *Bull. Seismol. Soc. Am.*, (*accepted*), January 2012.