# 2013 SCEC Report

## Improvements and Applications of Earthquake Catalogs and 3-D Crustal Models to Advance Earthquake Predictability Research and SCEC Community Models

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## Summary

We apply new multi-taper spectral fitting methods to determine the long period end of S-wave spectra (sometimes called: signal moment) to calculate Mwsp magnitudes for small to moderate sized earthquakes M≤5.5. The new methods are optimized to provide a stable estimate of the value of the long period part of the spectra. Initially, we select a data set to invert for a geometrical spreading relationship for southern California and corresponding site effects for each station. We compare the Mwsp-corrections and ML-corrections with the independently determined Vs30 values available at most of the stations.

The new geometrical spreading function and station corrections will be used to determine Mwsp values for earthquakes recorded by the Southern California Seismic Network (SCSN). We focus on analyzing if the new Mwsp values are stable and have reasonable error bars compared with other magnitudes, as well as if the magnitudes are not affected by non-linear effects.

Because SCSN broadband data from multiple stations became available in 2000, we can determine a catalog with Mwsp magnitudes, extending back for 13 years. Such a catalog will be a unique SCEC Community Product because it will use the same magnitude scale extending over at least 6 units of magnitude. In the longer term, if the proposed proof-of-concept analysis is successful, we hope to make this new Mwsp algorithm part of routine SCSN operations.

The new magnitudes may potentially improve the results of studies of earthquake statistics or earthquake interactions. The new Mwsp are expected to be more stable, and thus will provide more accurate a-values and b-values in the Gutenberg-Richter relationship. In turn, the more accurate a-values will provide a more stable seismicity rate estimates. Similarly, probabilities of large aftershocks following a potentially damaging mainshock will become more accurate.

We have completed our project to invert for the state of stress in the southern California crust using a catalog of high quality earthquake focal mechanisms (1981-2010). The stress field is best resolved where seismicity rates are high and sufficient data are available to constrain the stress field across most of the region.

## Introduction

Why is there a need for improving earthquake magnitudes? A magnitude is a single number that describes the complex phenomena of source rupture corrected for both path effects and site effects. The archive of SCSN digital broadband waveforms offers a unique opportunity to determine a set of magnitudes that will potentially have much less variance than previous estimates. The SCSN magnitudes have improved with time since the late 1990s as modern instrumentation has begun to provide high-fidelity waveforms. By systematically applying new methods, we can begin to answer questions that have gone unanswered for a long time, such as: what systemic errors are in the old magnitudes, and how can these be corrected for?

The focus of this project is to use waveform spectra to determine Mwsp values for small to moderate sized earthquakes in southern California. These Mwsp values are calculated by using the available long-period bandwidth in the S-wave waveform. Such Mwsp values are not routinely available. Today, the Southern California Seismic Network (SCSN) catalog is produced with ML for M≤4.0 and Mw≥4.0 magnitude earthquakes (Clinton et al., 2006). In some cases, when insufficient number of calibrated amplitudes is available, duration magnitude (Md) is determined for small earthquakes. The Mwsp values could potentially reach from M~2 to M~<8 or over 6 orders of magnitude. Such a catalog would be unique and could complement the existing Md, ML, and Mw values. The new Mwsp-values would reach back to January 2000 covering a 13-year time period when ample broadband data became available.

Each magnitude scale has its strengths and weaknesses. The Md scale only works for small earthquakes, or up to about M~4. However, Md will not work for events that are spaced too close in time, which can occur in intense swarms of aftershock sequences. The ML scale can only be applied to small earthquakes if sufficient amplitudes are available and it begins to saturate at M~>6. The moment tensor based Mw scale extends from ~M4 to the largest earthquakes. This inhomogeneity in the preferred magnitudes can result in mismatches that may affect the earthquake statistics done by earthquake predictability modelers (e.g. Zechar and Jordan, 2010). The new Mwsp magnitudes will make it possible to explore the scaling relationships between the different magnitudes determined for southern California seismicity.

**Impact on SCEC Science, Including Earthquake Predictability**

Earthquake predictability studies and earthquake interaction studies are only as good as the earthquake catalog that is being used. In particular, there is a need for stable magnitudes to determine the a-value and the b-value in the Gutenberg-Richter relationship as well as magnitude of completeness (Mc). As an example, Zechar and Jordan (2010) had to redo an earthquake forecast for Italy, because of issues with mixing Mw and ML magnitudes in the same catalog. This could have been avoided if one magnitude type had been available for all the earthquakes in their catalog.

**Technical Discussion**

Below we discuss the results of two projects. First the in-progress Mwsp effort, and second the state-of-stress project that has been completed with a publication in Geophysical Journal International.

**Determining Mwsp: Preliminary Results**

The focus of this study is to determine new Mwsp magnitudes for small to moderate-sized earthquakes in southern California. We use the new spectral fitting methods developed by Edwards et al. (2008); Edwards and Rietbrock (2009). Most recently, Edwards et al. (2010) improved the method and adapted it specifically to the routine computation of Mwsp for earthquakes in Switzerland. The work is being carried out in collaboration with Prof. Andreas Rietbrock at Liverpool University. We follow the approach by Edwards et al. (2010):

We applied the following method to determine waveform spectra for the test data set:

1) Window waveform data into signal and noise windows.

2) Use S-pick or calculated S-arrival time to determine a signal window 5 sec before S-pick with duration from 10 s to 50 s depending on data availability.
3) Use the method of Raoof et al. (1999) to encapsulate 5-72% of the cumulative squared velocity of the record. This results in a signal window starting at the S-pick with a much shorter length than the 50 s, which is a function of the source distance. It is insensitive to picks and provides information of shaking duration.
4) A noise window prior to P-pick is selected. P-wave coda may contaminate the S-wave signal window at short epicentral distances but usually this is not a significant effect.
5) Both noise and signal windows are demeaned and tapered using multitaper algorithms (Park et al., 1987; Lees and Park, 1995).
6) Corrected to ground-velocity by deconvolution with the complex instrument response function.

The main steps in the method to determine Mwsp values using the waveform spectra involves the following steps:

1) Invert a selected set of waveforms for a geometrical spreading function and a set of corresponding station delay.
2) Using an inversion technique, the signal moments are corrected for geometrical spreading, and site effects; and seismic moments are determined.
3) The standard regression between seismic moment and spsp is used to determine the value of Mwsp for each spectra.
4) The Mwsp value for each event is the median of Mwsp values determined for all the components that provided useful spectra.

The regional attenuation of ground motion that needs to be corrected for in magnitude calculations is complex but usually is only accounted for with a 1-D attenuation relationship when calculating ML (Uhrhammer et al., 2011). In this study, we use an average own geometrical spreading function, which could cause some error because it depends on the 3D regional distribution of Q.

Another source of error could be interaction between Stress drop and Q values, which could affect the scaling relationships between ML - Mwsp (Edwards et al. 2010). Q values affect mostly the low magnitude scaling why the stress-drop affect the high magnitude scaling, where high stress drops can saturate the ML scale. We are aware of this issue and will attempt to mitigate its effects as appropriate, for instance by developing a non-linear relationship between ML and Mwsp values.

In a previous study, Shearer et al. (2006) determined stress drops for a large data set of southern California earthquakes using a complex method to average out site and path effects. As part of future work, we will look for obvious correlations between their stress-drop values and the Mwsp values determined in this study.

Unusual site effects that can be either amplification or de-amplification can also affect magnitude calculations. In the inversion for geometrical spreading and site effects, Edwards et al. (2011) require the sum of the station corrections to be equal to one.

Edwards et al. (2010) found for Switzerland that a quadratic scaling was needed between ML and Mwsp, to account deviation from a linear relationship, which occurred for the smallest and largest earthquakes. When the w-squared source spectral decay is outside of the bandwidth of the waveform data, a different possible source of error in determining Mwsp values for small earthquakes may occur. The ML may saturate for M~>6.0 earthquakes because of the limits of the Wood-Anderson filter. We will evaluate the influence of these effects when we determine our Mwsp and ML regression relationships.

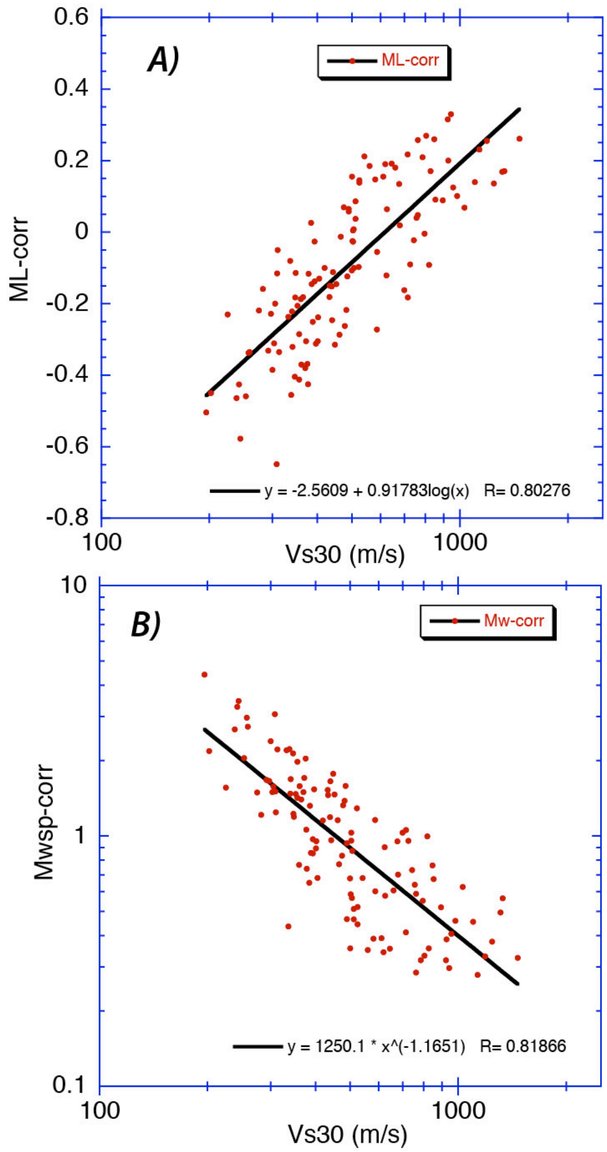


Figure 1. (A) The ML station corrections used by the SCSN and plotted versus the VS-30 measured at each station. (B) Mwsp station corrections plotted versus the VS-30 values measured at each station (Yong et al. 2012).

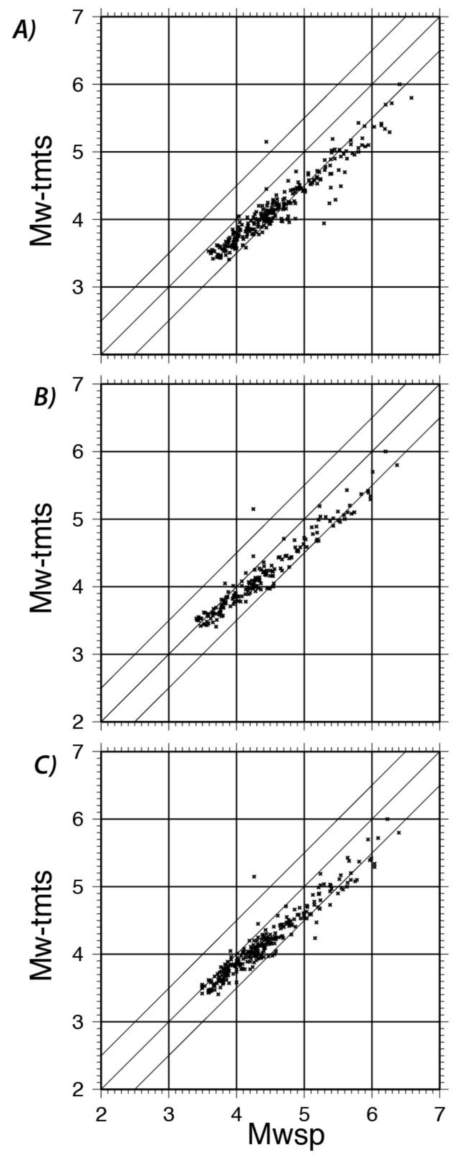


Figure 2. Mw-tmts values and Mwsp values for a selected data set. (A) An average Q of 564 and attenuation exponent of 1.0; (B) An average Q of 564 and attenuation exponent of 0.85; and (C) An average Q of 564 and attenuation exponent of 0.85; and site effects included.

Other limitations of the method as discussed by Edwards et al. (2008; 2010) are obvious assumptions that have to be made. These include assuming that every earthquake is a point source, and frequency independent Q, and no propagation of error between steps in the inversion. Nonetheless, Edwards et al. (2010) showed that the Mwsp computed from the spectral fitting method are consistent with Mw from moment tensor solution for local Swiss earthquakes in the magnitude range from 2.8 to 5.0. Thus, they demonstrated that these possible sources of error are not likely to cause bias or scatter in the calculated Mwsp values.

*Site Effects*. We use the SCSN broadband waveforms to determine Mwsp magnitudes for a selected set of earthquakes recorded since 2000. This test data set of waveforms for ~100 events of M≤5.5 consists of events that are evenly distributed across southern California and have Mw-tmts magnitudes available. The first processing step consisted of determining the geometrical spreading and corresponding station delays.

Yong et al. (2012) provided the Vs30 data, which is the estimated shear wave velocity at 30 m depth beneath a site. They used multiple surface- & body-wave methods to analyze site effect data collected at 187 seismic stations in California. Both the calculated Mwsp and ML site corrections exhibit good agreement with the Vs30 values, suggesting that the site corrections are very localized effects (Figure 1).

*Preliminary Comparison of Magnitudes*. The SCSN calculates routinely Mw-tmts magnitudes (called Mw-tmts from the name of the code used) for M≥4 earthquakes by determining a seismic moment tensor (Clinton et al. 2006). The Mw-tmts has no station corrections because these are partly taken care of by determining a complete moment tensor. We select events that have high quality Mw-tmts values and determine corresponding Mwsp values.

In Figure 2 we show preliminary Mwsp values for selected events the have available Mw-tmts values. In Figure 2A we show the results for Q value of 564, and geometrical spreading exponent of 1.0. In Figure 2B we changed the geometrical spreading to 0.85. In Figure 2C we added site effects. The decrease in the geometrical spreading exponent leads to a improved fit at lower magnitudes. Adding station corrections provides a small improvement in the fit at smaller magnitudes. The comparison of the Mw-tmts and Mwsp demonstrates as the magnitude increases the contribution of the longer periods becomes more prominent. On average the short periods radiated by southern California earthquakes appear to have higher amplitudes compared to the amplitudes of longer period waves used in the Mw-tmts determination.

**State of Stress**

From the stress field, we determine the maximum horizontal compressive stress ($S_{Hmax}$) orientations and the style of faulting across southern California (Figure 3). The trend of $S_{Hmax}$ exhibits significant regional and local spatial heterogeneities. The regional trend of $S_{Hmax}$ varies from north along the San Andreas system to NNE to the east in the Eastern California Shear Zone, as well as, to the west within the Continental Borderland and the Western Transverse Ranges. The transition zones from one state of stress to the other occur over a distance of only a few kilometers, following a trend from Yucca Valley to Imperial Valley to the east, and the western edge of the Peninsular Ranges to the west. The local scale heterogeneities in the $S_{Hmax}$ trend include NNW trends along the San Andreas Fault near Cajon

Pass, Tejon Pass, and the Cucapah Range, as well as ~NNE trends near the northern San Jacinto Fault and the Wheeler Ridge area (Yang and Hauksson, in press 2013).

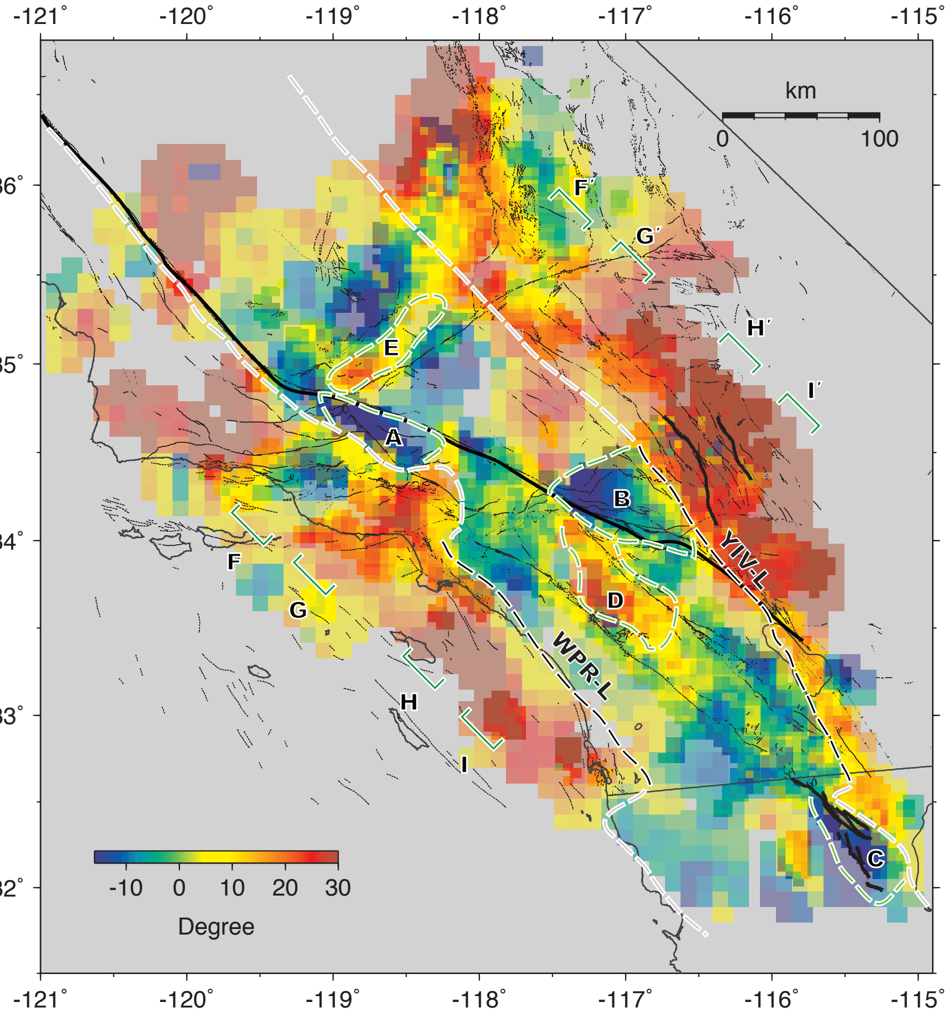


Figure 3. Composite image for $S_{Hmax}$ orientation with overlapping G05N30 above G10N15 (in light color). The San Andreas Fault, Landers, Hector Mine, and El Mayor-Cucapah surface ruptures are highlighted in bold black lines. Black dashed lines mark two $S_{Hmax}$ orientation transition lines: the Yucca-Imperial Valleys Line (YIV-L), and the Western Peninsular Ranges Line (WPR-L), respectively. "A", "B" and "C" mark the three identified wedge-shapes (green dashed polygons). "D" marks isolated NNE $S_{Hmax}$ area (green dashed polygon) along the San Jacinto Fault. "E" marks the Tehachapi Mountains stress heterogeneity. FF', GG', HH' and II' are four selected cross-sections with 0.2-degree in width and 300 km in length. The gray lines are postulated extensions of the WPR-L and the YIV-L as regional stress boundaries in southern California (Yang and Hauksson, 2013).

## 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). E. Hauksson, The Goldilocks Seismicity of Southern California,

(**talk** presented at AEG Southern California Section, Steven's Steak House in Commerce, 12 June 2012)

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Yang, W. and E. Hauksson, The 3-D Tectonic Crustal Stress Field and Style of Faulting Along the Pacific North America Plate Boundary in Southern California, *Geophys. J. Int.*, in review, March 2013.

## Abstracts for Recent Oral, Reports, or Poster Presentations

E. Hauksson, W. Yang, and P. Shearer, Elucidating Regional Tectonic and Secondary Causes of Seismicity in Southern California: Application of Waveform Relocated Seismicity and High Precision Focal Mechanisms and Other Geophysical Data Sets; Abstract; *Seismo Soc. Res. Lett.*, 83, 364, presented at the 2012 SSA Meeting, San Diego, CA, 17-19 April 2012

M. Boese, T. Heaton, E. Hanuksson, Automated real-time detection of extended fault ruptures during large earthquake, Abstract; *Seismo Soc. Res. Lett.*, 83, 360, presented at the 2012 SSA Meeting, San Diego, CA, 17-19 April 2012

X. Chen, P. M. Shearer, and E. Hauksson, Systematic analysis of foreshock sequences in southern California, Abstract; *Seismo Soc. Res. Lett.*, 83, 366, presented at the 2012 SSA Meeting, San Diego, CA, 17-19 April 2012

E. Hauksson and W. Yang, Effects of heat flow, shear strain rate, and other geophysical variables on the southern California seismicity and state of stress, (**talk** presented at USGS, Menlo Park 2012

C. Nicholson, E. Hauksson and A. Plesch, Active fault geometry and crustal deformation along the San Andreas fault system through San Gorgonio Pass, California: The view at depth in 3D from seismicity, (**talk** presented at 2012 SCEC Workshop on San Gorgonio Pass).

E. Hauksson and W. Yang, Stress at San Gorgonio, (**talk** presented at 2012 SCEC Workshop on San Gorgonio Pass).

X. Chen, P. M. Shearer, and E. Hauksson, California foreshock sequences suggest underlying aseismic process, (2012 SCEC Annual Meeting poster).

E. Hauksson, Understanding Seismicity in the Context of Complex Fault Systems and Crustal Geophysics, (2012 SCEC Annual Meeting poster).

E. Hauksson. August 2012 Brawley Earthquake Swarm in Imperial Valley, (2012 SCEC Annual Meeting invited talk).

C. Nicholson, A. Plesch, J. Shaw, and E. Hauksson, Upgrades and Improvements to the SCEC Community Fault Model: Increasing 3D fault complexity and compliance with surface and subsurface data, (2012 SCEC Annual Meeting poster).

W. Yang and E. Hauksson, Seismotectonic Crustal Stress Field and Style of Faulting Along the Pacific North America Plate Boundary in Southern California, (2012 SCEC Annual Meeting poster).

D. A. Weiser, L. M. Jones, and E. Hauksson, Aftershock Decay with Distance from a Fault, (2012 SCEC Annual Meeting poster).

E. Hauksson, and L. Jones, Understanding Earthquake Scaling in the Context of Complex Fault Systems and Crustal Geophysics; abstract for **talk** presented at ECGS workshop in Luxembourg, Oct. 2012

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E. Hauksson; Wenzheng Yang; Peter M. Shearer, Observational Constraints from Waveform Relocated Southern California Seismicity and Refined Focal Mechanisms for Synthesizing Heterogeneities in Fault Zone Properties and Signatures of Seismic Rupture, *Abstract Talk S14A-03, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*

Craig Nicholson; Egill Hauksson; Andreas Plesch*,* Active Fault Geometry and Crustal Deformation Along the San Andreas Fault System Through San Gorgonio Pass, California: The View in 3D From Seismicity, *Abstract Talk T22C-03, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*

P. M. Shearer; Robin S. Matoza; Egill Hauksson; Cecily J. Wolfe; Paul Okubo; Guoqing Lin, High-resolution earthquake catalogs for southern California and Hawaii from waveform cross-correlation *(Invited)*, *Abstract Talk* S42C-06*, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec..*

W. Yang; Egill Hauksson, The 3-D Tectonic Crustal Stress Field and Style of Faulting Along the Pacific North America Plate Boundary in Southern California, *Abstract Talk* T44A-02*, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*

*X. Chen; P. M. Shearer; Egill Hauksson.* California foreshock sequences suggest underlying aseismic process *Abstract Talk* S51F-02*, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*

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