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Coseismic offsets recorded by borehole strainmeters from the 2014, Mw 6.0 South Napa, California earthquake: Reconciling tidal calibrations with earthquake source models.

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ABSTRACT: The 24 August 2014 Mw 6.0 South Napa, California earthquake produced significant offsets on 12 borehole strainmeters in the San Francisco Bay area. These strainmeters are located between 24 and 80 km from the source and the observed offsets ranged up to 400 parts-per-billion (ppb), which exceeds their nominal precision by a factor of 100. However, the observed offsets in tidally-calibrated strains have RMS deviation of 130 ppb from strains predicted by previously published moment tensor derived from seismic data. Here, I show that the large misfit can be reduced by a combination of better tidal calibration and better modeling of the strain field from the earthquake. Borehole strainmeters require in-situ calibration, which historically has been accomplished by comparing their measurements of Earth tides with the strain-tides predicted by a model. Although borehole strainmeters accurately measure the deformation within the borehole, the long-wavelength strain signals from tides or other tectonic processes recorded in the borehole are modified by the presence of the borehole and the elastic properties of the grout and the instrument. Previous analyses of surface-mounted, strainmeter data and their relationship with the predicted tides suggest that tidal models could be in error by 30%. The poor fit of the borehole strainmeter data from this earthquake can be improved by simultaneously varying the components of the model tides up to 30% and making small adjustments to the point-source model of the earthquake, which reduces the RMS misfit from 130 to 18 ppb. This suggests that calibrations derived solely from tidal models limits the accuracy of borehole strainmeters. On the other hand, the revised calibration derived here becomes testable on strain measurements from future, large Bay area events.

Background and Previous Work

Tides and Calibration: Borehole strainmeters require in-situ calibration to convert raw gauge measurements to units of strain. The presence of the borehole distorts the applied strain (ie, tectonic and/or tidal strains).

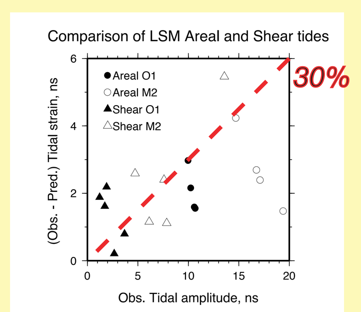
Borehole strainmeters precisely measure tidal strains; M2 @ 12.4 hr and O1 @25.8 hr.

The measured tide can be compared with the modeled tide that incorporates ocean loading and localized loading from nearby bodies of water. In fact, comparing the modeled and the observed tides has typically been used to calibrate these strainmeters.

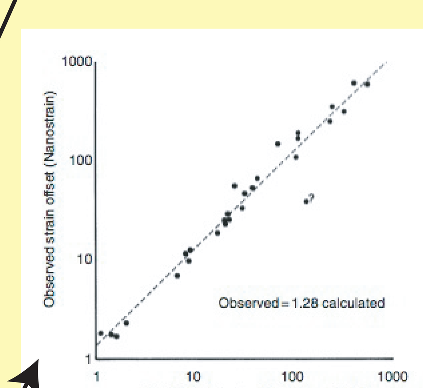
Yet, comparison of the modeled tide with measurements from surface mounted, longbase strainmeters suggest an imperfect fit -- perhaps around 30% error.

Coseismic Offsets: An earlier study of coseismic offset measured by dilatometers in the 1980s and 1990s showed a close one-to-one match between the observed and predicted offsets from earthquakes.

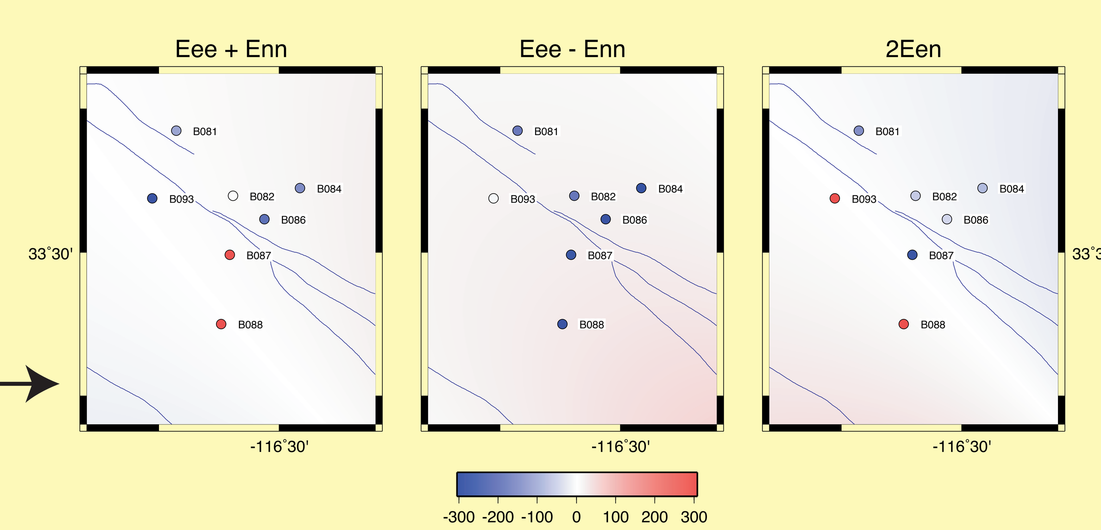
Yet, a recent study of coseismic offsets recorded at nine tensor strainmeters near Anza, Calif. from the El Mayor Cucapah (EMC) earthquake (M7.2, 2010) shows a gross miss-match between observed and predicted offsets.



Study by Langbein (2010) reconfirms earlier results of Berger and Beaumont (1975) that compared earth tides measured on surface mounted strainmeters with modeled tides. Comparing the observed tides with the difference between the observed and predicted suggests a 30% error. Although the models incorporate ocean loading and loads from nearby estuaries, the models do not account for topography nor earth structure near the strainmeter. Consequently, if tides are used for insitu calibration of borehole strainmeters, it could contribute a 30% error in any estimate of strain change. The error budget for any observed strain change comes from both the repeatability of the data and the calibration error; for offsets, the calibration error could dominate.

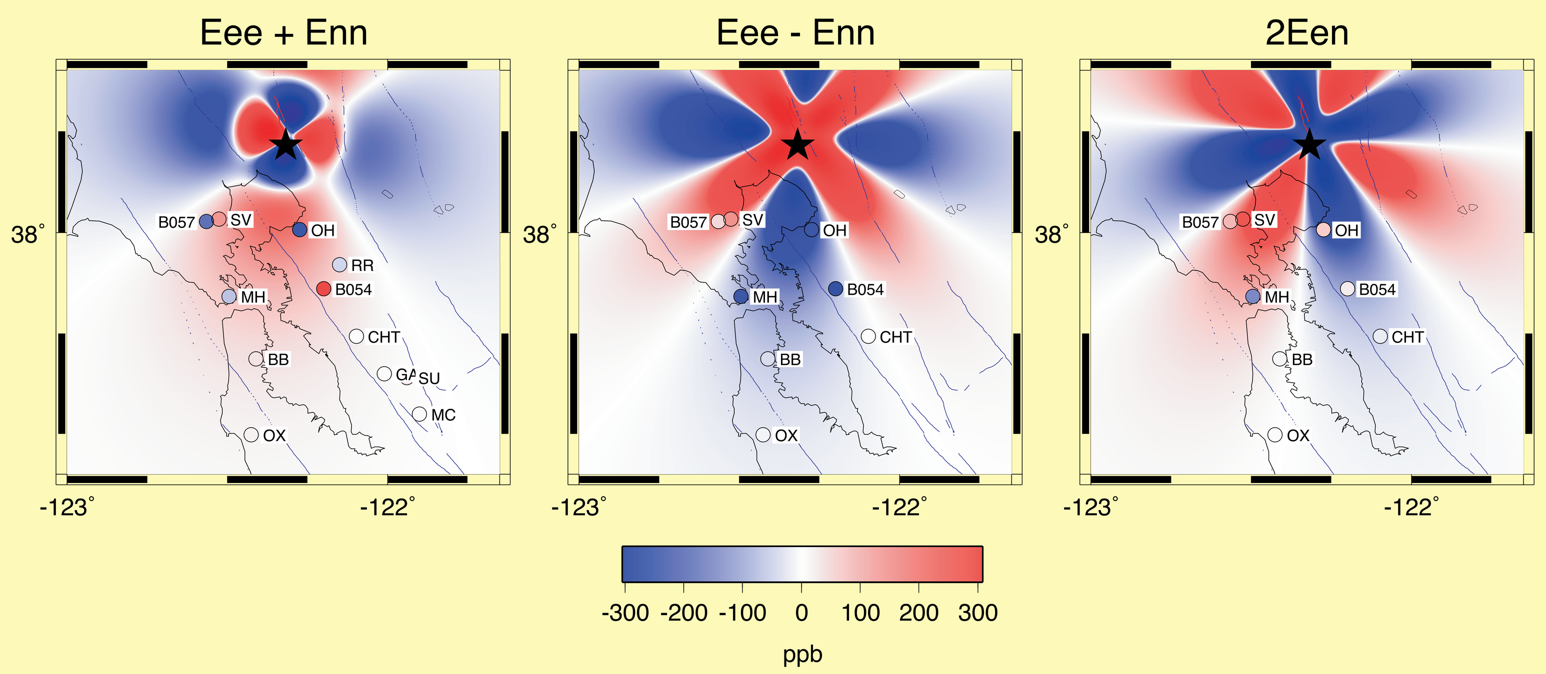


Compilation coseismc offsets by Johnston and Linde (2002) recorded at dilatometers from 19 earthquakes (1979-1994) located in central and southern Calif. Not compiled are data from tensor strainmeters, Loma Prieta, and the 2004 Parkfield earthquakes.



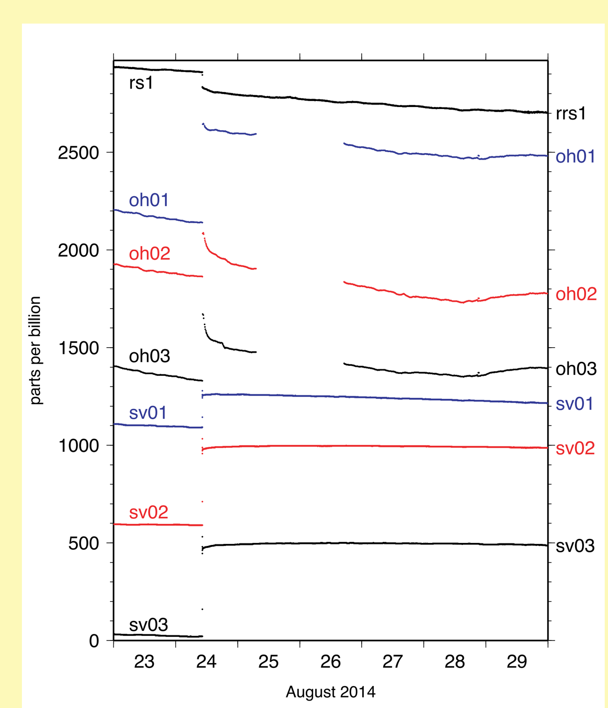
Response of borehole strainmeters to El Mayor Cucapah earthquake, M7.2. Barbour et al. (2015) studied the response of the Gladwin Tensor Strainmeters (GTSM) installed by UNAVCO (for PBO) near Anza Calif. This earthquake is located ~200KM distant from this network and models for this event suggest that the coseismic offsets should be of the order of a few 10s parts per billion (ppb). This strain field, resolved into areal dilatation and two components of shear are shown draped over a map showing the distribution of the strainmeters and the major faults (San Jacinto). Examination of the measured coseismic offsets yield strain changes in the 100s of ppb. These are shown on the map as colored circles at the location of each strainmeter. In addition, for many of the strainmeters, the sign of the offset is opposite that of the prediction. The large discrepancy is not a result of a bad model of the earthquake nor miss calibration of the strainmeter.

Borehole strainmeter response to South Napa earthquake: Earthquake strains are roughly consistent with expectations – but more investigation is need.



Map showing the locations of the 12 strainmeters in the SF Bay Area that recorded offsets from the SN earthquake. The location of each meter is color coded to the value of tensor strain derived from the observed offset and a calibration that uses the value of the predicted Earth tide at that location. In A), the dilatation is shown for all 12 sites. In B) and C), the shear components Eee - Enn and 2Een are shown for the 8 multi-component strainmeters. Superimposed on the map is the strain field from a point-source model of the earthquake which best fits these data.The star shows the location of the earthquake from Brocher et al. (2015). Blue lines show the major, active faults.

Strain changes from the recent Mw 6.0 South Napa (SN) earthquake of 24 August 2014 were recorded at 12 borehole strainmeters located within the San Francisco Bay Area. All 12 sites recorded offsets; these exceeded 100 ppb at four sites. Unlike the strainmeters that recorded the EMC earthquake, which are all of the same design, the instrumentation in the SF Bay Area is diverse, spanning the existing technology. As a first cut, offsets from the strainmeters were estimated using pre-determined calibrations derived from predicted Earth tides and those offsets were compared with predictions using a point-source representation of the earthquake derived from broadband, seismic data (Brocher et al., 2015). Although the magnitudes and signs of the observed strains are roughly consistent with predictions, they are different enough to warrant more investigation.



Time series of observed strain changes at three sites for a one-week interval spanning the SN earthquake. Both the Earth tide signals and the affect of atmospheric pressure have been removed. For both RR and SV, the time-series were derived from the 100 or 200~sps observations and decimated to 1-minute samples (Agnew and Hodgkinson 2007). For these time-series, there are a few points located within the "offset" and their exact value could be corrupted from aliasing. The suffixes 01, 02, and 03 for SV and OH correspond to their three components.

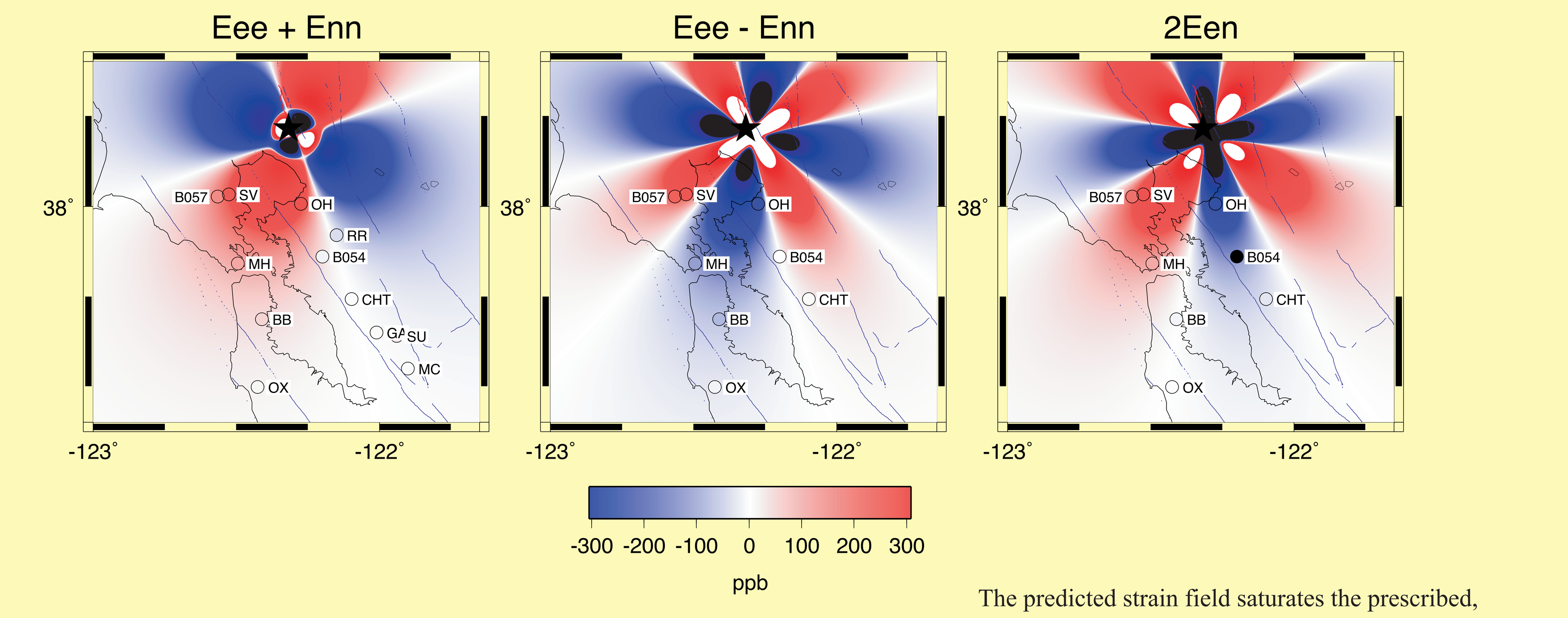
Types of borehole strainmeters: The borehole instruments discussed here come in three varieties:

The Sacks-Evertson dilatometer (Sacks et al., 1971), of which there are five installed in the SF Bay Area, consists of a 3-meter-long hydraulic sensor cylinder, where a change in the cylinder's volume is amplified through a hydraulically coupled bellows, whose displacement is converted to a voltage using a linear voltage displacement transformer (LVDT). As such, these instruments measure only changes in areal strain.

The SES-3 three component strainmeter (Sakata and Sato 1986), of which there are five installed in the SF Bay Area, is a variant of the dilatometer. In horizontal cross section, its cylinder is divided into three 120 degree sectors, and each has a hydraulic amplifier and LVDT. With three sensing elements, the instrument is capable of measuring changes of three components of horizontal strain tensor.

The other multi-component strainmeter is the GTSM (Gladwin, 1984 and Gladwin and Hart, 1985), of which there are three installed in the SF Bay Area. This instrument consists of a vertical stack of four extensometers with each extensometer enclosed in a 9 cm diameter by 37 cm long cylinder. Three of the extensometers are oriented 60 degrees from each other and the fourth is oriented 90 degrees from one of the three. The sensing element consists of a capacitance bridge measured using a ratio transformer. The USGS installed one of these in the SF Bay area in the early 1990s, while UNAVCO has installed approximately 75 throughout the western US, including two in the SF Bay Area in 2005. These instruments also recorded the deformation from the EMC earthquake.

After recalibration; Simultaneous fitting of a point-source representation of the SN earthquake and dithering the modeled tides by up to 30%; **Good agreement achieved**.



A mixed grid-search and Monte-Carlo method provides an improved agreement between the strainmeter observations and the predicted strains for the SN earthquake.

These results are obtained by simultaneously varying the model parameters for the point-source representation of the earthquake and making random variations to the predicted tides, up to 30%, about those computed using SPOTL and NLOADF (Agnew, 1996, 1997). The parameters of the point source are optimized by a simple grid search limited in location, dip, strike, rake, and slip. Complimenting the search for a fault model, a series of randomized tidal components is generated, and then observed data from each component or gauge of the strainmeter are used to simultaneously fit the new tides and the earthquake strains. That way, for each earthquake model, a new set of calibration values is determined that provides an optimal fit to the observed tides and earthquake offsets.

The predicted strain field saturates the prescribed, 300 ppb strain field yielding regions of black and white close to the source, the star. The strain field shown here is from a point source model located at 5 km depth rather than 10 km for the model used to construct the previous map.

Note that there are two PBO strainmeters, B054 and B057. Although the results for B054 are shown, that instrument is not completely functional as it never went into the expected compression after its installation and only two of the four gauges record tides. Hence, it shows a poor match to the predicted strains, especially 2Een. On the other hand, both B057, which is near SV, and the older GTSM, CHT provide satisfactory results.

Source parameters for the SN earthquake obtained from the strainmeter data compared with those obtained from a combination of continuous GNSS and InSAR data (Barnhart et al. 2015 and Brocher et al. 2015).

Similar fault planes

Strain and geodetic data suggest shallower, 5 km, depth than that obtained from seismic data (9.4 km).

The major difference between the models is that the geodetic analysis places the center of mass of slip approximately 5 km north-northwest of the earthquake epicenter, while the strainmeter data suggest that the slip was concentrated above the hypocenter.

But, sensitivity analysis for the source model derived from the strain data only suggests that the center of mass of slip can not extend south of the earthquake epicenter.

The moment estimated from the borehole strain data, 1×10^{25} dyne-cm is 40% to 80% less than the moments obtained from geodesy. But, strain data is not particularly sensitive to the moment; Mo up to the tested 1.4×10^{25} dyne-cm are consistent with the strainmeter data.

Conclusions

Standard models of earth tides are not adequate to calibrate borehole strainmeters.

Although the use of simultaneously using earthquake offsets and dithering tides provide a means to calibrate these instruments, this is not a satisfying result – one should be able use independently calibrated instruments to measure a physical process such as an earthquake.

Contrary to the poor response of the Anza strainmeters to the EMC earthquake, the Bay Area strainmeters provided excellent data from the SN earthquake.

For more information

Langbein, J. (2015) Borehole strainmeter measurements spanning the 2014 M6.0 South Napa earthquake, Calif., The effect from instrument calibration, J. Geophys Res doi:10.1002/3015JB012278

References (partial list):

Barbour, A.J., D.C. Agnew, and F.K. Wyatt (2015), Coseismic strains on Plate Boundary Observatory borehole strainmeters in Southern California, Bull. Seismol. Soc. Amer., 105(1), 431-444, doi:10.1785/0120140199

Brocher, T.M, A.S. Baltay, J.L. Hardebeck, F.F. Pollitz, J.R. Murray, A.L. Llenos, D.P. Schwartz, J.L. Blair, D.J. Ponti, J.J. Leinkaemper, V.E. Langenheim, T.E. Dawson, K.W. Hudnut, D.R. Shelly, D.S. Dreger, J. Boatright, B.T. Aagaard, D.J. Wald, R.M. Allen, W.D. Barnhart, K.L. Knudsen, B.A. Brooks, and K.M. Scharer, (2015), The Mw 6.0 24 August 2014 South Napa Earthquake, Seismol. Res. Lett. 86 2A doi:10.1785/0220150004.

Hodgkinson, K, J. Langbein, B. Henderson, D. Mencin, and A. Borsa (2013), Tidal calibration of plate boundary observatory borehole strainmeters, J. Geophys. Res., 118, DOI: 10.1029/2012JB009651.

Johnston and Linde (2002), Implications of crustal strain during conventional, slow, and silent earthquakes, In: W.H.K Lee (Ed.) International Handbook of Earthquake and Engineering Seismology, Vol. 81A, Academic Press, San Diego, 589-605.

Langbein, J. (2010), Effect of error in theoretical Earth tide on calibration of borehole strainmeters, Geophys. Res. Lett., 37, L21303, doi:10.1029/2010GL044454.