A Decade of Regional Moment Tensor Analysis at UC Berkeley

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Abstract

The California Integrated Seismic Network (CISN) is moving forward with the development of a statewide earthquake monitoring system. This collaborative effort among Berkeley, Caltech, the USGS Pasadena and Menlo Park, and the California Geological Survey, involves the testing and calibration of software and the development of common standards for earthquake processing. As part of this project, a CISN working group is addressing issues related to the determination and reporting of magnitude. In addition to efforts to examine attenuation relationships and station adjustments for local magnitude on a statewide basis, this working group has also been addressing the question of magnitude reporting hierarchies, particularly the issue of when moment magnitude (Mw) should be preferred over local magnitude (ML).

Scientists at the UC Berkeley Seismological Lab (BSL) have been making routine determinations of the seismic moment tensor and moment magnitude for over 10 years. These determinations are made automatically for events with local magnitude of 3.5 and higher in northern California and typically reviewed for events of M4.0 and higher. The BSL moment tensor catalog includes nearly 400 events in northern and central California, southern Oregon, and eastern Nevada, as well as events of interest in Washington, Idaho, Utah, and Arizona. In this study, we examine estimates of Mw obtained from the moment tensor inversions. Two methods have been routinely employed at the BSL - the complete waveform modeling technique (CW) of *Dreger and Romanowicz* (1994) and the surface wave inversion method (SW) of *Romanowicz et al.* (1993).

We discuss the robustness of the automated estimates of ML and Mw. Comparisons of regional estimates of Mw with local magnitude are good, although some areas of Northern California show systematic differences. In the Cape Mendocino area, for example, estimates of Mw are consistently 0.5-1.0 magnitude units higher than ML for offshore events in the transform. We have also observed a small systematic difference between estimates of ML between northern and southern California.

We also compare the regional estimates of Mw with other regional methods as well as global solutions from the Harvard CMT Project. The regional estimates of Mw agree extremely well with the global estimates, with the exception of an intriguing systematic shift of ~0.08 magnitude units.

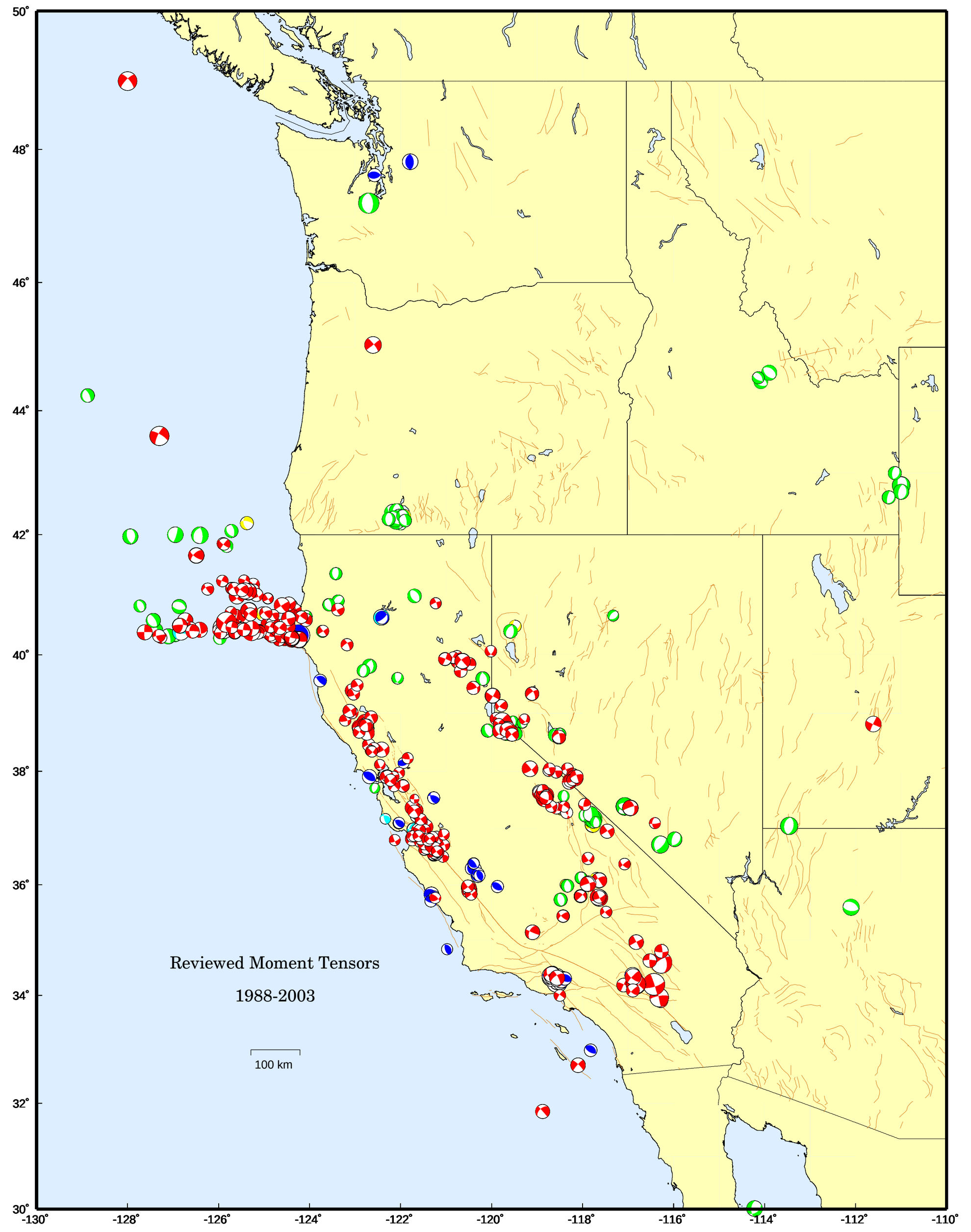


Figure 1: This map illustrates the catalog of ~400 regional moment tensor solutions from UC Berkeley. Solutions based from both the complete waveform inversion and surface wave inversion are included. The mechanisms are color coded by faulting type (strike-slip - red; normal - green; thrust - blue; mixed - yellow).

Reporting Mw in Real Time

Several different magnitudes are currently computed and reported in real-time as part of the Northern California Seismic System of the CISN (Figure 2). Md or duration magnitude is computed for all earthquakes. ML is computed for events with Md greater than 3, and Mw is computed for events of ML 3.5 and higher. In order to avoid problems with noisy stations or the influence of teleseisms on local events, the Northern California Seismic System requires that a variance reduction of 40% or higher in the moment tensor solution before Mw is reported automatically. Automatic reporting of Mw was implemented in 2002 in northern California.

Figures 3 and 4 compare real-time magnitude estimates with those obtained after human review for ML and Mw, based on events from 6/1/2002-11/21/2003 and selected older events, using the results from the complete waveform moment tensor method. In general, the automatic estimates of ML and Mw agree well with the reviewed solutions, particularly for well-located events (RMS <0.2 sec). Automatic moment tensor solutions with variance reduction of 40% or higher show excellent agreement with reviewed estimates of Mw.

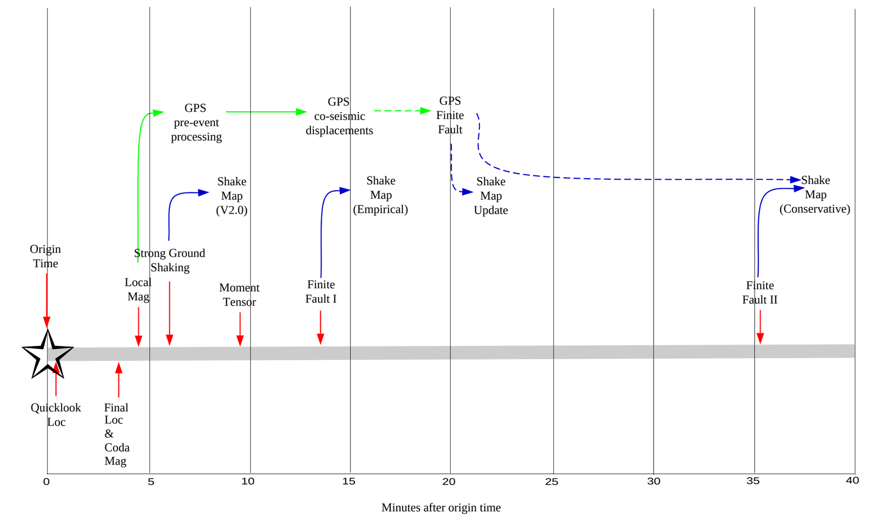


Figure 2: Schematic diagram illustrating the current real-time processing flow in northern California, showing the computation of seismic moment tensors, GPS data processing, and finite-fault inversions.

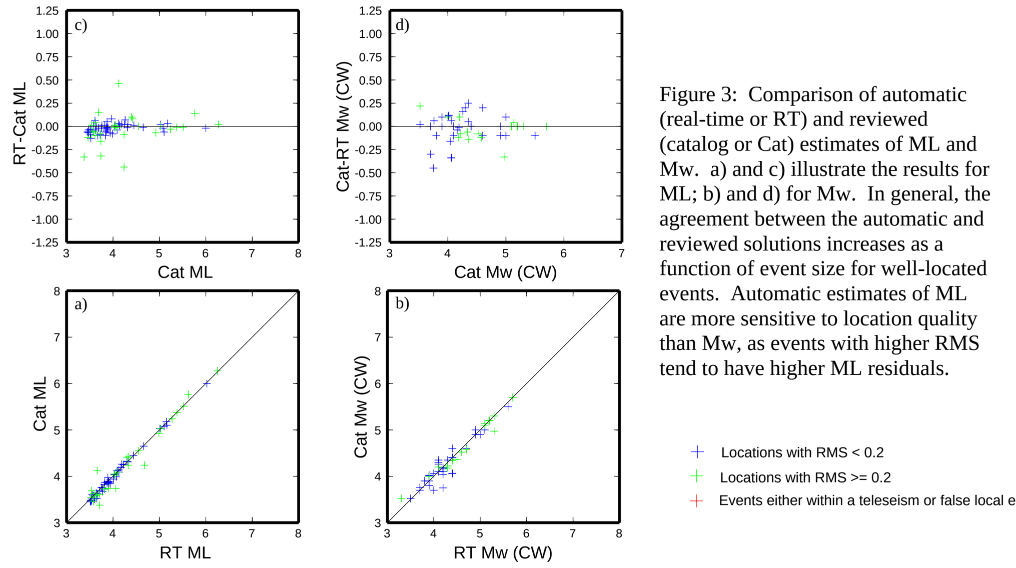


Figure 3: Comparison of automatic (real-time or RT) and reviewed (catalog or Cat) estimates of ML and Mw. a) and c) illustrate the results for ML; b) and d) for Mw. In general, the agreement between the automatic and reviewed solutions increases as a function of event size for well-located events. Automatic estimates of ML are more sensitive to location quality than Mw, as events with higher RMS tend to have higher ML residuals.

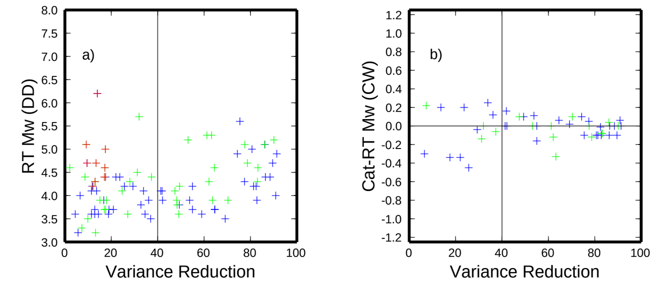


Figure 4: Comparison of automatic and reviewed (catalog) estimates of Mw as a function of the variance reduction in the automatic moment tensor solution. a) Illustrates the variance reduction obtained for all processed events. The 40% cutoff appears to screen out teleseisms that create false triggers in the network or contaminate local events (red crosses). Although many events with M <4.5 have high variance reduction, all events with M>4.5 that were not contaminated by teleseismic arrivals achieved this level of variance reduction, except for the 8/01/1999 Goldfield, NV earthquake. b) The difference in the automatic and reviewed estimates of Mw plotted as a function of the variance reduction. Over the full range of variance reduction, the mean magnitude difference is -0.03; for solutions with 40% or higher, the mean is -0.01.

Comparison of ML & Mw

One issue facing the CISN is the question of magnitude reporting hierarchies. When should Mw be preferred to ML? The automatic estimation of Mw appears to be robust for events of M4.5 and higher and for all events with a variance reduction of 40%. In the plots below, we select events in located within the northern California catalog to compare the reviewed determination of ML and Mw from the perspective of reporting magnitude in real time.

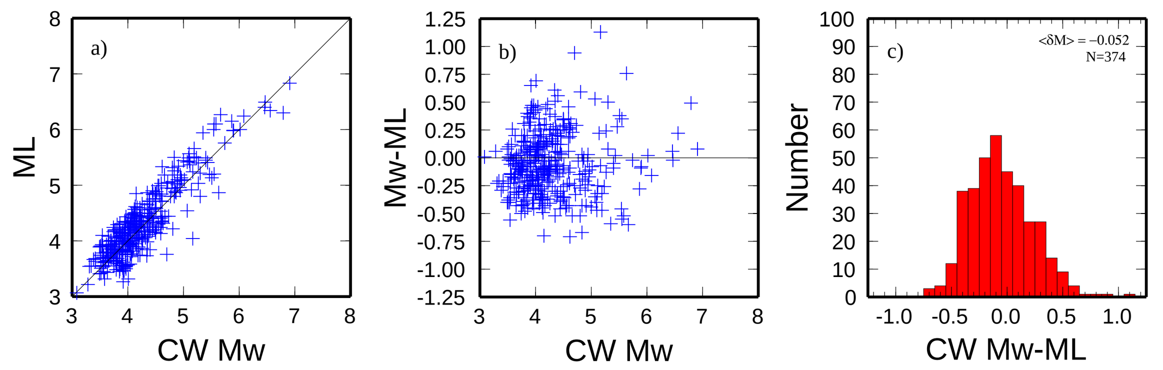


Figure 5: Comparison of Mw and ML for 374 events in the northern California catalog (1990-2003), using the CW determination of Mw. a) ML plotted against Mw; b) Mw-ML plotted as a function of Mw; and c) histogram of the magnitude residuals. These plots show good correlation between Mw and ML, but a mean difference of -0.05 and significant scatter.

Although the average Mw-ML residual is quite small (-0.05) over northern California, the distributions in Figure 5 mask the strong geographic signal in the data. In Figure 6, earthquakes with ML > Mw are drawn in red; events with Mw > ML are drawn in blue. In general, ML is consistently larger than Mw, with the exception of two regions - the North Bay/Geysers area and the Cape Mendocino/Gorda plate region. In the North Bay/Geysers area, the mean difference between Mw and ML is 0.25; in the Cape Mendocino area, it is 0.22 (although there are 9 events with differences greater than 0.5). Events in central California appear to be more evenly distributed (with ML ~ Mw), while events in eastern California/western Nevada show a distinct bias with ML > MW.

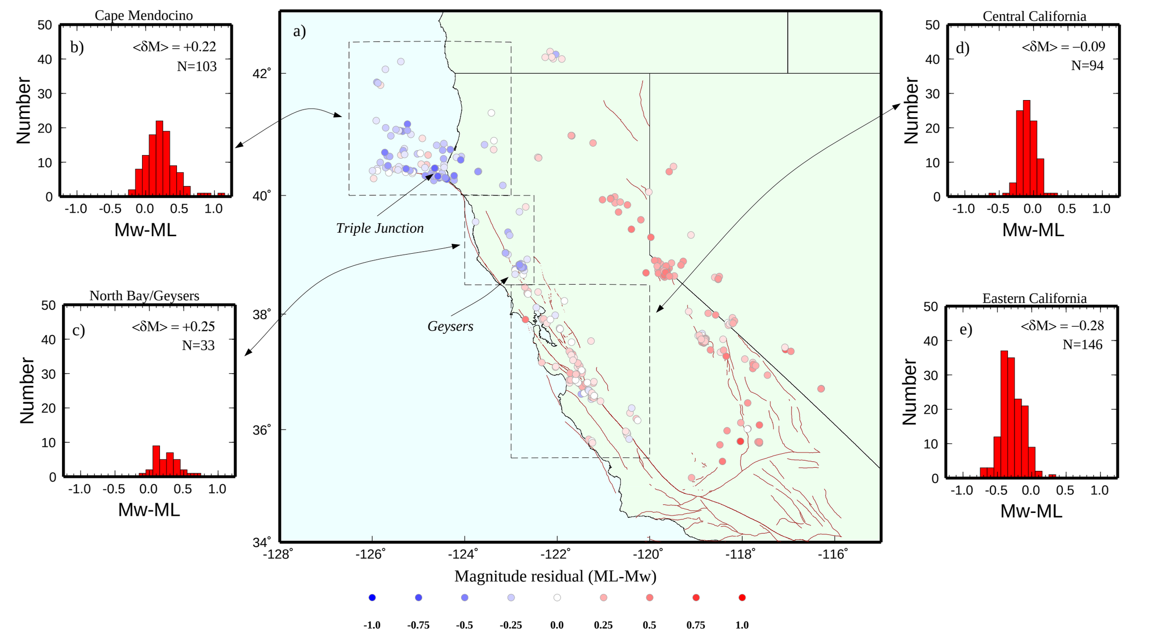
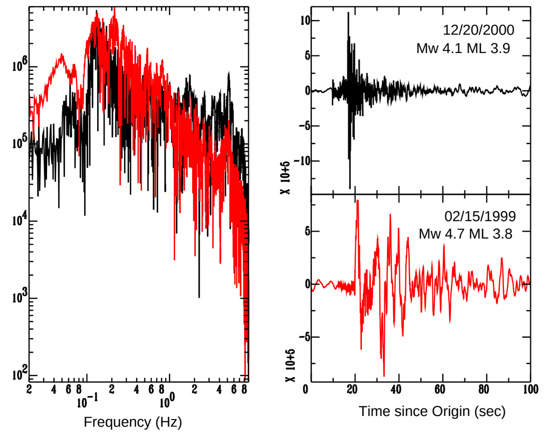


Figure 6: a) Map showing the geographical distribution of magnitude residuals (ML-Mw) in northern California. Histograms b), c), d) & e) show the magnitude residual for the boxes at Cape Mendocino, North Bay/Geysers, central California, and eastern California respectively.

In Cape Mendocino region, new studies (*Wurman et al*, 2003) have shown that events along the Mendocino transform exhibit anomalously low apparent stress drops associated with abnormal moment-rate spectra. The spectra associated with these events show a characteristic enrichment in low frequency (< 1 Hz) content and a regression of the Brune corner frequency. These spectral characteristics have been associated with slow earthquakes, particularly on oceanic transform faults.



In the North Bay, the magnitude discrepancy may be related to strong attenuation of high frequencies (e.g., *Antolik*,1996) or to source processes in the Geysers geothermal region

Figure 7: Comparison of Fourier spectra and time series for two earthquakes located in the Cape Mendocino triple junction. These broadband timeseries were recorded at the Berkeley Digital Seismic Network station ARC. These events have similar MLs (3.8 and 3.9), but very different Mws (4.7 and 4.1). The events have similar high frequency levels, but the 02/15/1999 shows an enrichment in low frequencies.

Regional & Global Comparisons of Mw

As part of the CISN investigation of magnitude reporting hierarchies, we have explored comparisons between the BSL estimates of moment and moment magnitude with other regional methodologies as well as with solutions from the Harvard Centroid Moment Tensor Project. The three panels below illustrate the comparisons between the two methods employed at the BSL (Figure 8), between the CW and other regional moment tensor solutions (Figure 9) and between the CW and the Harvard Centroid Moment Tensor solution (Figure 10). In all cases, we have used the entire BSL Moment Tensor Catalog (1989-2003) and matched events with other sources. For all three comparisons, there is significantly less scatter and much better agreement between the different estimates of Mw than between Mw and ML.

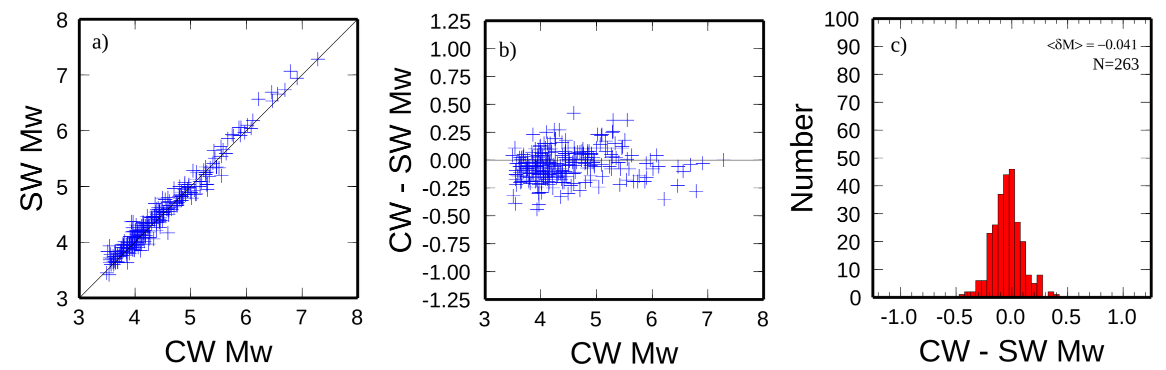


Figure 8: Comparison of estimates of Mw between the CW and SW regional moment tensor methodologies used at the BSL. a) Plot of the SW estimates of Mw against the CW estimates. b) The difference between the estimates of Mw as a function of Mw. c) Histogram of the magnitude differences. As observed in *Pasyanos et al.* (1996), the estimates of moment are in good agreement, although the SW moments are consistently larger overall. There is no apparent correlation between the differences in Mw and depth.

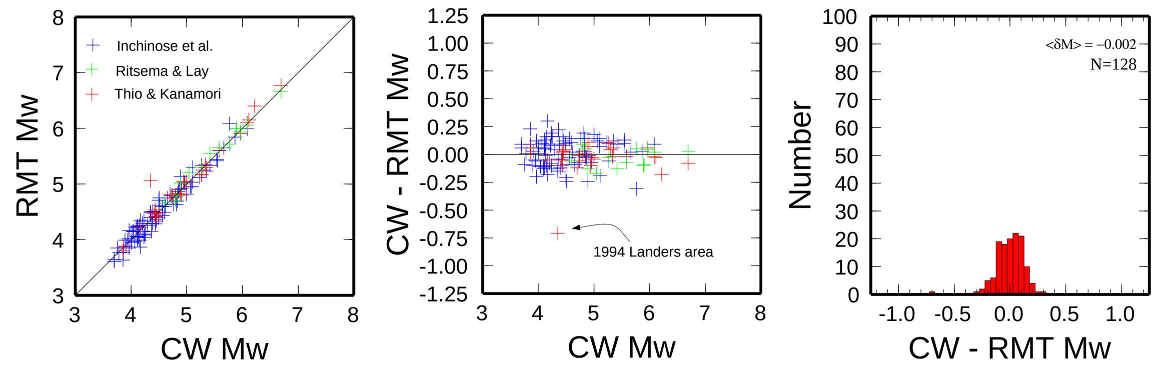


Figure 9: Comparison of estimates of Mw between the CW method at the BSL and the regional moment tensor (RMT) methods employed by *Ritsema & Lay* (1995), *Thio & Kanamori* (1995), and *Inchinose et al.*(2003). Interesting, there is less scatter between the CW methods and these solutions than between the CW and SW methods. The agreement in the estimates of Mw is excellent.

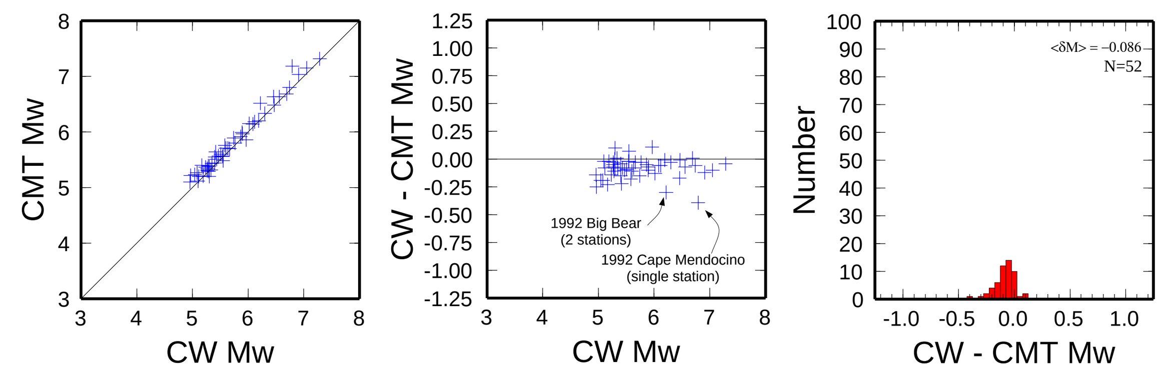


Figure 10: Comparison of estimates of Mw between the CW method and results from the Harvard Centroid Moment Tensor project (*Dziewonski & Woodhouse*, 1981). This comparison shows excellent agreement between the CW and CMT estimates of Mw and moment, but with an apparent bias: the CMT estimates of Mw are on average ~0.09 higher than the CW estimates. There is a slight suggestion that the residual is increasing at the lower end of the magnitude range. Note that the depths of the CMT solutions are generally fixed at 15 km depth for these shallow events. The two events with the largest residuals occurred in 1992 and the CW solutions were computed with a limited number of stations.

Comparison of the CW estimates of Mw with other regional methods and the CMT solutions indicate the robustness of the procedures and the continuity between the regional and global estimates. The difference between the CW and the CMT estimates of Mw shows more scatter in the results for events in the early 1990s, reflecting the limited number of the regional broadband stations at that time (Figure 11a). However a slight bias is consistent over time. We do not observe a correlation with this difference and the difference in depths (Figure 11b & c), and are currently investigating the influence of the different velocity models.

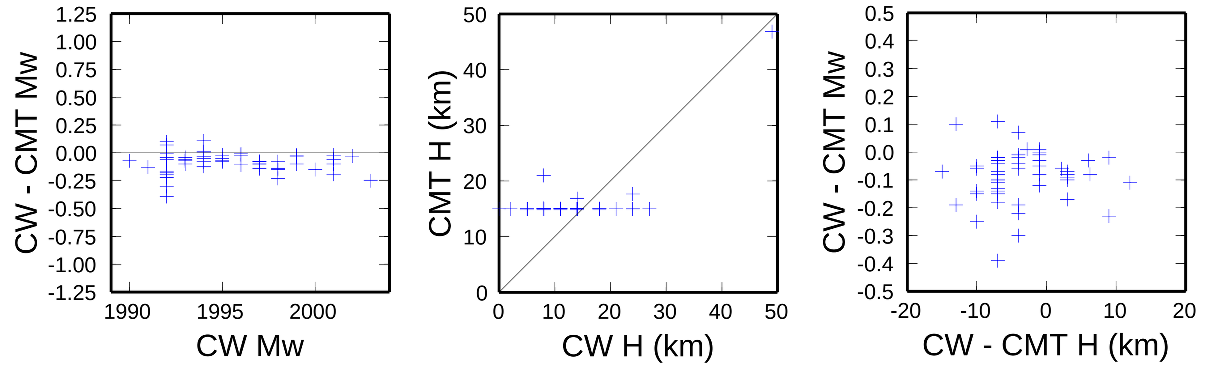


Figure 11: a) Difference between the CW and CMT estimates of Mw as a function of time. b) Comparison of the CW and CMT estimates of centroid depth. With a few exceptions, the CMT depths are usually fixed at 15 km for these small, shallow events. c) Difference in Mw estimate plotted as a function of difference in depth estimate. No correlation is apparent.

Comparison of MLs

In parallel with efforts to establish a magnitude reporting hierarchy, the CISN is working to calibrate the estimation of ML in California and is engaged in an effort determine a standardized set of station adjustments and attenuation correction for California (*Polet*, 2003). As part of our investigation of differences between ML and Mw, we have compared estimates of ML reported by Caltech (CI) and Berkeley (BK) for 480 earthquakes of M3.5 and higher from 1981-2003. Focusing on an area that spans the formal boundary between the networks, we observe a systematic bias between the estimates. Similar to the comparison between ML and Mw, the magnitude residuals show a significant geographic signal.

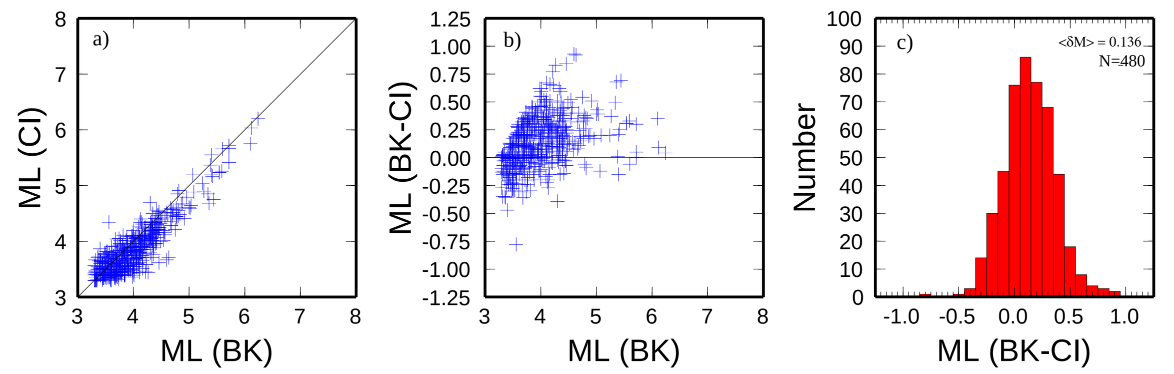
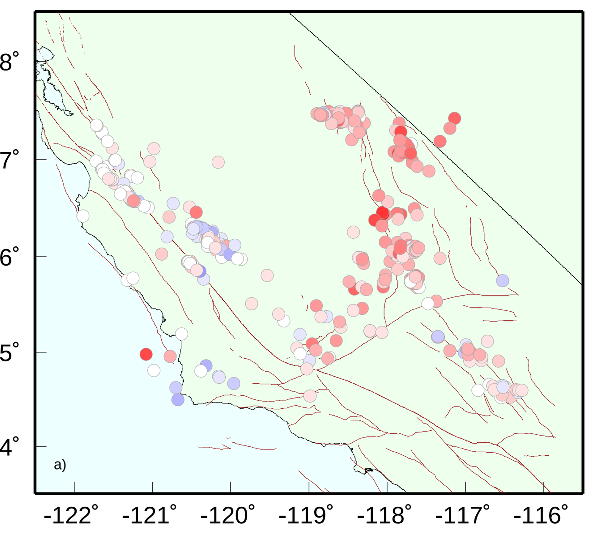
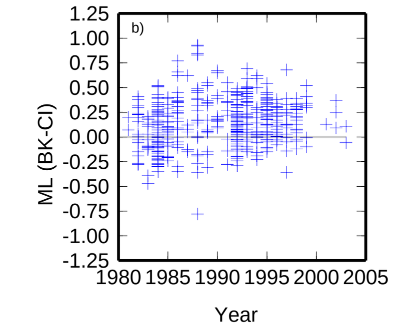


Figure 12: Comparison of ML determined by Berkeley and Caltech from 1981-2003. a) ML plotted against ML; b) δML plotted as a function of ML (BK); and c) histogram of the magnitude differences.

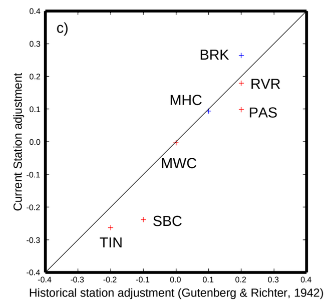
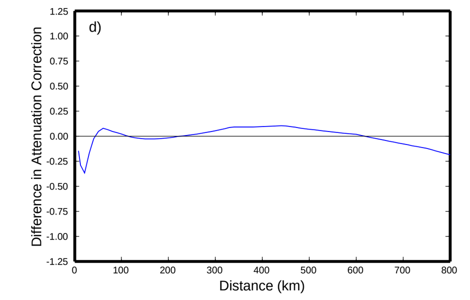


Figure 13: a) Map illustrating the geographic distribution of the ML differences. Similar to the comparison of Mw with ML, events on the eastern side of the Sierra show a strong signature, with the Berkeley estimates of ML larger than the Caltech estimates. b) Plot of the ML differences as a function of time. c) Comparison of the historical station adjustments from *Gutenberg and Richter* (1942) with the present-day adjustments for 5 Caltech (red) and 2 Berkeley stations (blue). d) Plot of the difference in the attenuation corrections used at Berkeley and Caltech.



No systematic shift in the ML differences in time is apparent from Figure 13b. Figure 13c and d suggest that at least part of the signal may be explained by drift in station adjustments and differences in the attenuation corrections in use at Berkeley and Caltech. We also are investigating path effects associated with the Sierra Nevada.

Summary & Conclusions

This effort is still a work in progress and appears to raising more questions, than providing answers, at this time. Stay tuned for more results ....

1) The real-time reporting of Mw appears to be robust in northern California. Automatic estimates of Mw agree well with reviewed estimates, particularly for events with high variance reduction.

2) Although Mw and ML correlate well, systematic regional variations are observed in northern California. Mw > ML in the Cape Mendocino and North Bay/Geysers area; Mw~ML in central California California, and ML> Mw in eastern California. A current study in the Cape Mendocino triple junction shows that events in this area are enriched in low frequencies; previous studies have shows that events in the Geysers are deficient in high frequencies.

3) The complete waveform estimates of Mw agree extremely well with other regional methodologies and with the global CMT solutions. The small, but systematic, bias between the CW and CMT estimates of Mw is currently being investigated using synthetic seismograms to quantify the influence of the different velocity models.

4) Differences between the Berkeley and Caltech estimates of ML are observed for events in the boundary region between the networks. The Berkeley estimate of ML is generally higher than the Caltech estimate, particularly for events east of the Sierras. Explanations under investigation include a drift in station corrections over time and differences in the attenuation corrections. We are also investigating the possibility that estimates of ML for events in the eastern Sierra may have significant path dependencies.