Inverting Geodetic Time-Series With a Principal Component Analysis-Based Inversion Method (PCAIM)

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ABSTRACT

The Global Positioning System (GPS) system now makes it possible to monitor deformation of the earth's surface along plate boundaries with unprecedented accuracy. In theory, the spatio-temporal evolution of slip on the plate boundary at depth, associated with either seismic or aseismic slip, can be inferred from these measurements through some inversion procedure based on the theory of dislocations in an elastic half-space. We describe and test a Principal Component Analysis-based Inversion Method (PCAIM), an inversion strategy that relies on principal component analysis of the surface displacement time-series. We prove that the fault slip history can be recovered from the inversion of each principal component. Because PCAIM does not require externally imposed temporal filtering, it can deal with any kind of time variation of fault slip. We test the approach by applying the technique to synthetic geodetic time-series to show that a complicated slip history combining coseismic, postseismic and non-stationary interseismic slip can be retrieved from this approach. PCAIM produces slip models comparable to those obtained from standard inversion techniques with less computational complexity. We also compare an afterslip model derived from the PCAIM inversion of postseismic displacements following the 2005 8.6 Nias Earthquake, with another solution obtained from the Extended Network Inversion Filter (ENIF). We introduce several extensions of the algorithm to allow statistically rigorous integration of multiple data sources (e.g. both GPS and InSAR time-series) over multiple time scales. PCAIM can be generalized to any linear inversion scheme.

INTRODUCTION

Faults slip in a variety of ways, such as during sudden seismic events or as a result of aseismic creep. Fault slip rates can therefore vary over a wide range of time scales, from the typical 10s-100s duration of large earthquakes, to the weeks or years duration of slow earthquakes and postseismic relaxation. Monitoring how fault slip varies with time is thus key to improving our understanding of fault behavior. Fault slip at depth results in surface deformation that can be observed with geodetic techniques, paleogeodetic techniques, or remote sensing techniques. How faults slip at depth can thus be derived indirectly through modeling of surface deformation.

Theoretical surface displacements expected from some fault slip at depth is generally computed based on the theory of linear elasticity [e.g. Savage, 1983; Okada, 1985; Cohen, 1999]. This formulation is linear and easily inverted using standard algorithms. The distribution of fault slip is generally parameterized based on some discretization of the fault geometry. The cumulative fault slip needed to explain dis- placements that have occurred between two epochs for which geodetic data are available can then be obtained from some least-squares inversion. Because the number of parameters generally exceeds the number of observations, regularization constraints are generally added; for example, the roughness of the slip distribution can be penalized or a positivity con- straint can be added. One way to invert geodetic time-series for time-dependent slip distribution thus consists in inverting the displacements measured between each two successive epochs. This method is computationally very intensive when the number of epochs is large, especially when non-linear regularization criteria are used. Furthermore, this method considers each epoch individually, so measurement errors at different time steps are not properly balanced. In addition, the method also requires geodetic time-series to be sampled at each site at the same epochs, limiting the possibility of analyzing a mixed dataset which could include campaign data or InSAR data.

Instead, we use the linearity of the constiuitive laws to decompose the data into a few components which can be quickly and independently inverted, then recomposed back into a complete model of the entire time series.

GEOLOGICAL INSPIRATION

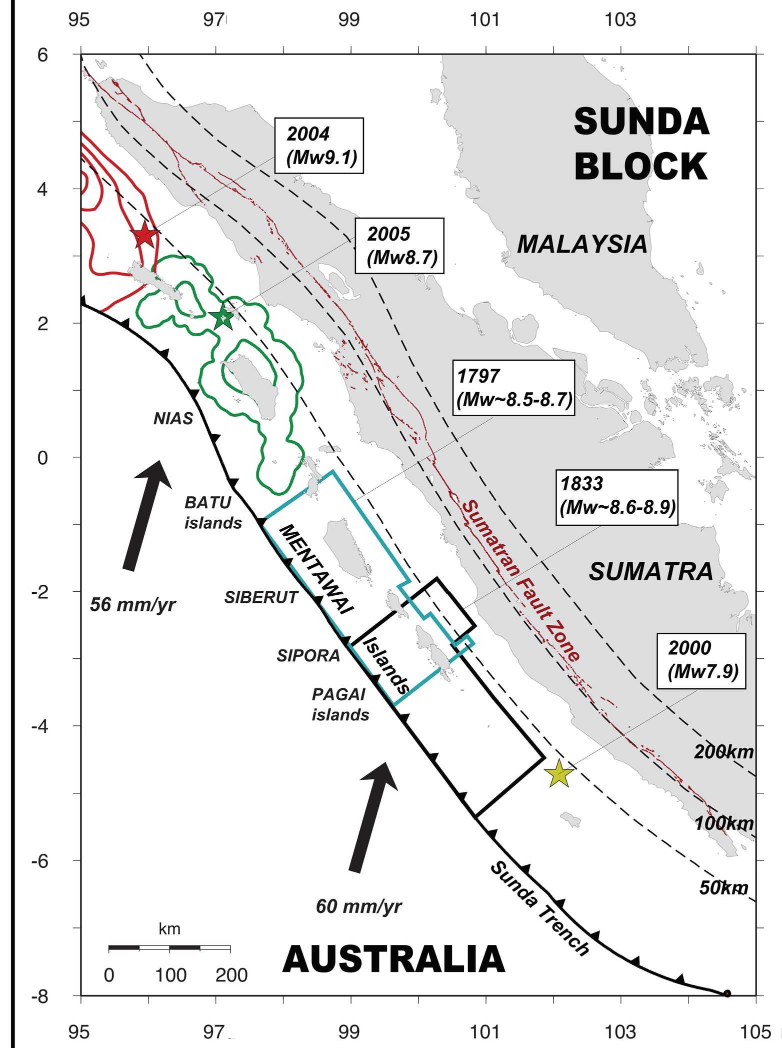

Figure 1

Located in Southeast Asia, the Sunda subduction zone lies at the interface between the Sunda block and the Australian plate. Over the last 200 years, there have been at least five giant earthquakes, including the December 26, 2004 earthquake which caused a tsunami that killed approximately 100,000 people. As such, a detailed understanding how the two plates are slipping past each other can help us understand where and when the next giant earthquake near the Sunda subduction zone is likely to occur. Modeling surface displacements as finite dislocations beneath the surface helps us uncover clues about the slip patterns.

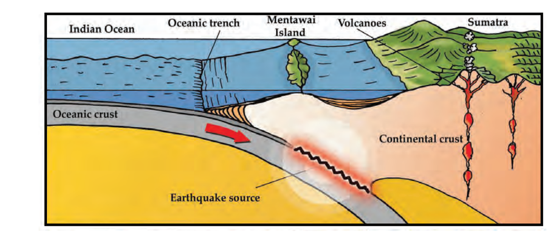

Figure 2

METHODS

Instead of directly inverting surface displacement epoch-by-epoch as in other methods, we first decompose and filter the data matrix into a small number of linear component, called principal components (top line of Figure 3). Each component consists of a surface displacement function (Figure 4, large vectors), a time function (Figure 5), and a singular value (Figure 6, white circles). Then, we invert via computed Greens functions the portion of each principal component corresponding to surface displacement for a slip distribution at depth (Figure 4, small vectors and shading). Then the product of the slip distributions by the appropriate time function and singular value gives us a slip history that explains the surface data. Symbolically, this process can be written as,

$$
\begin{aligned}
X &= USV^t \\
G \cdot L &= U \\
&\Rightarrow \\
X &= G \cdot LSV^t
\end{aligned}
$$

where X is the data matrix, U is a matrix of the spatial functions (Figure 4, long vectors), S is a diagonal matrix of the singular values (Figure 6, white circles), V is a matrix of the time functions, G is a matrix of the greens functions, and L a matrix of slip distributions at depth found via least-squares inversion.

In practice, the inversion in under-constrained, so we need to add a regularization term to make the solution unique. In both cases, we imposed a penalty on a non-zero Laplacian of the slip distributions at depth. Intuitively, this corresponds to encouraging the slip distribution to be "smooth," or more precisely, to have a small second derivative everywhere. The only two parameters to vary for the inversion are the strength of this smoothing and the number of components, both of which can be determined by cross-validation (though this has yet to be implemented).

To test this inversion method against other state-of-the-art inversion schemes, we investigate two very different scenarios, the post-seismic relaxation following the March 2005, Mw 8.6 Nias earthquake and the late 1999 slow slip event in Cascadia. We comparethe results to previous extended network inversion filter (ENIF) solutions (Hsu et. al, 2006; McGuire and Segall, 2003 respectively). The plots shown in Figures 4-6 are the intermediate steps for the Nias example to graphically show what the various parts of the components and inversion look like.

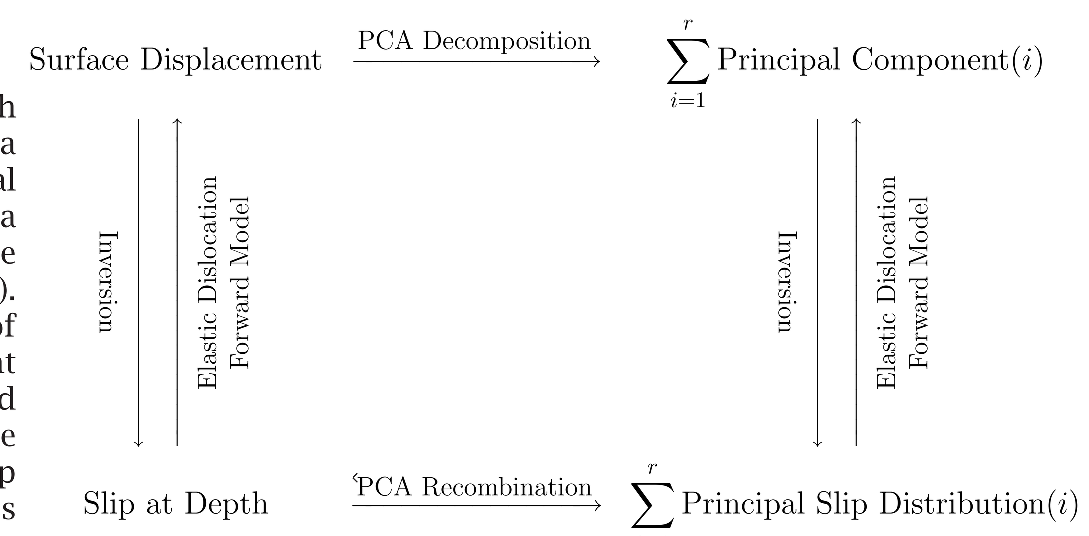

Figure 3

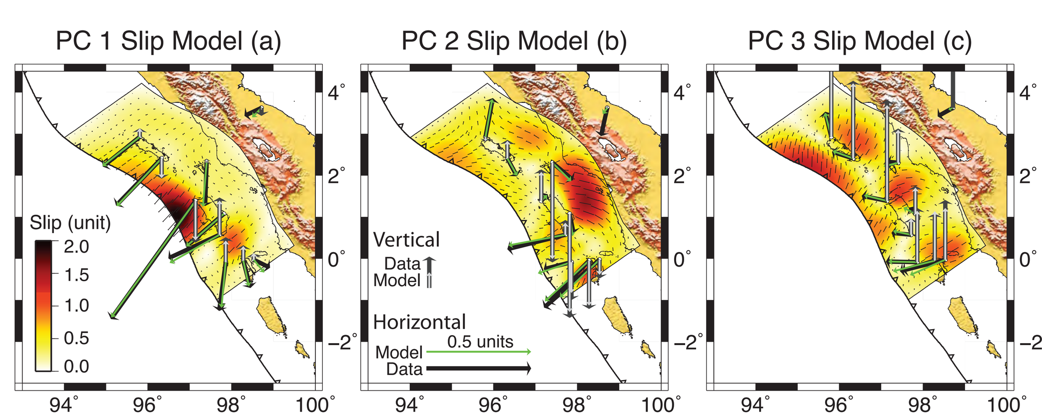

Figure 4

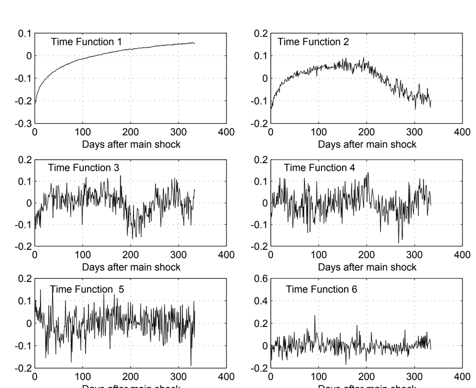

Figure 5

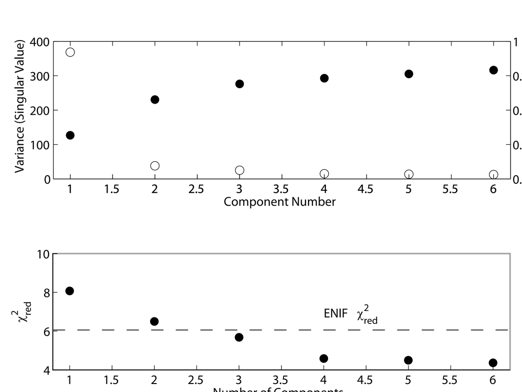

Figure 6

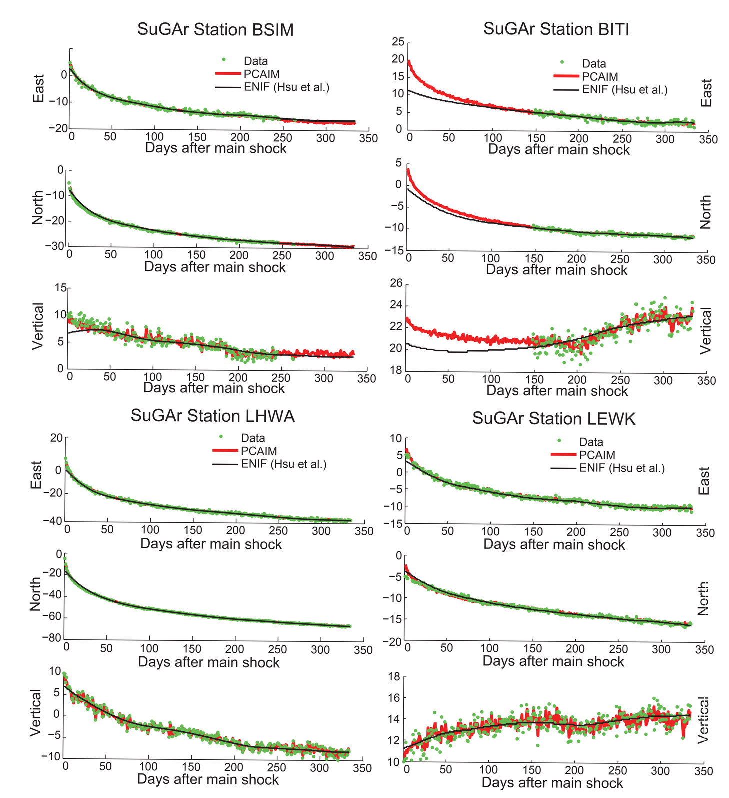

Figure 7

Nias 2005 Postseismic Relaxation

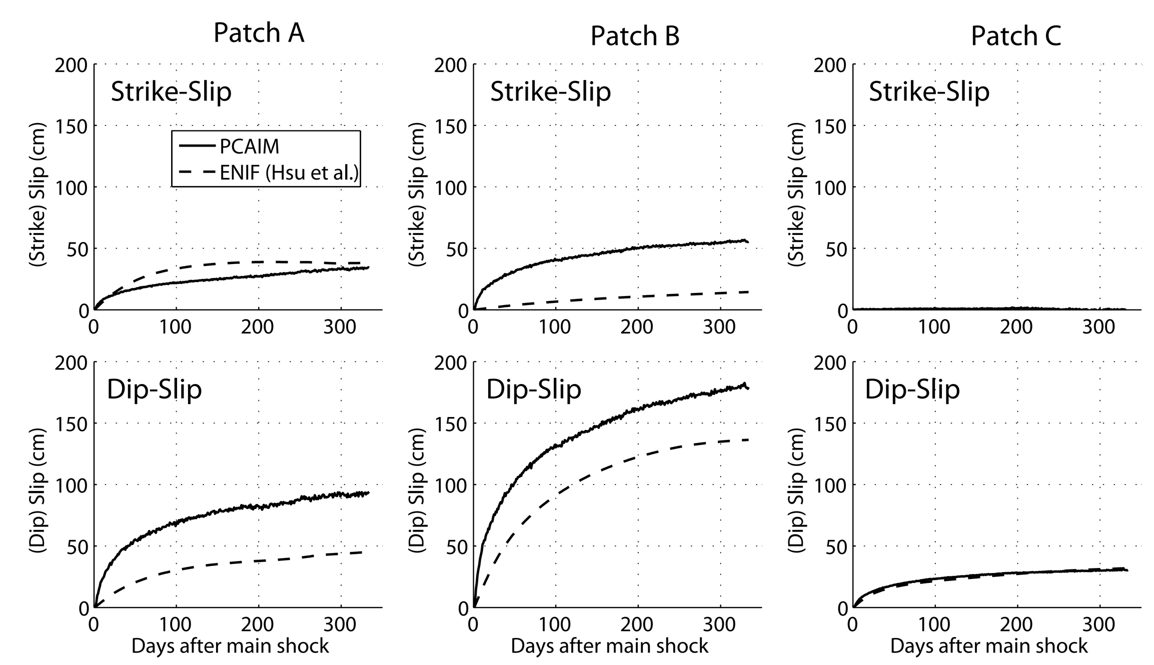

Figure 8

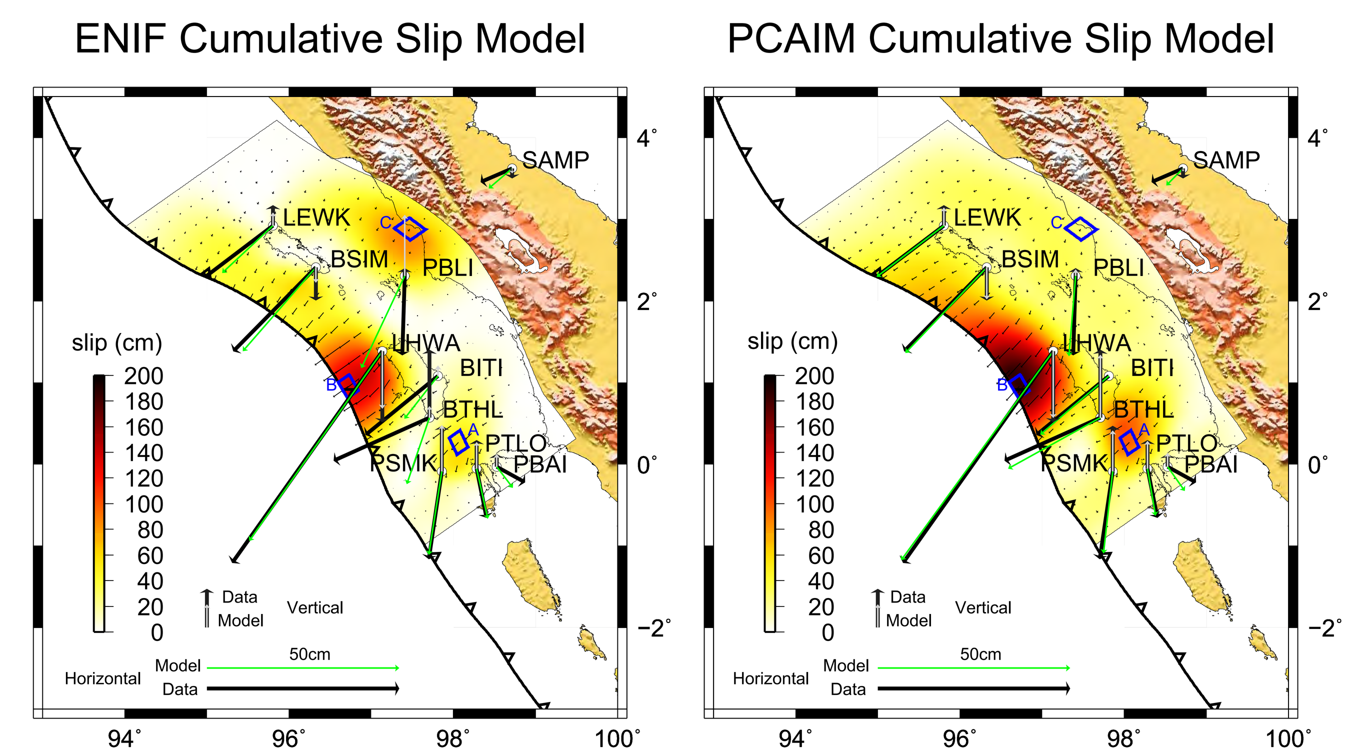

Figure 9

Cascadia 1999 Slow Slip Event

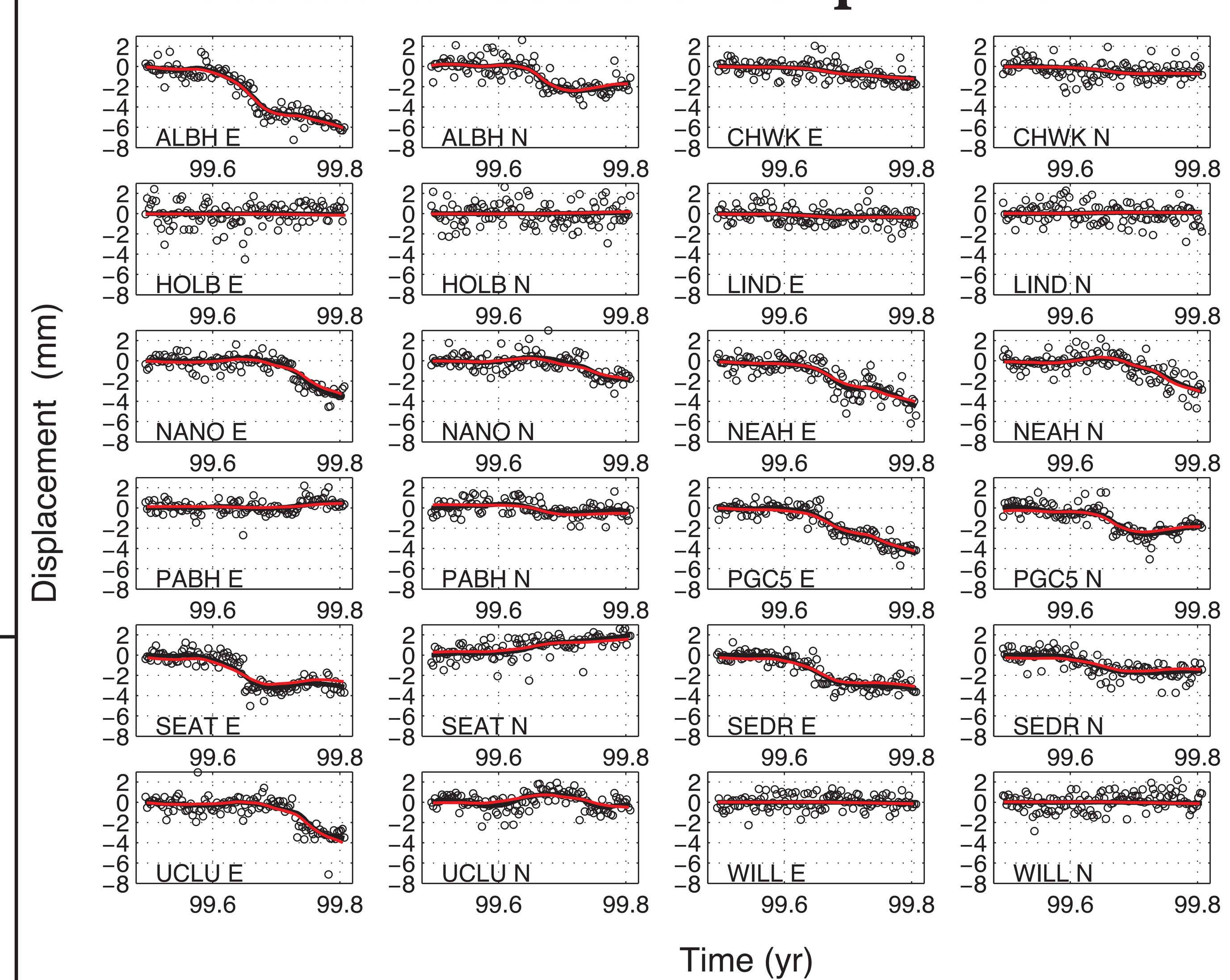

Figure 10

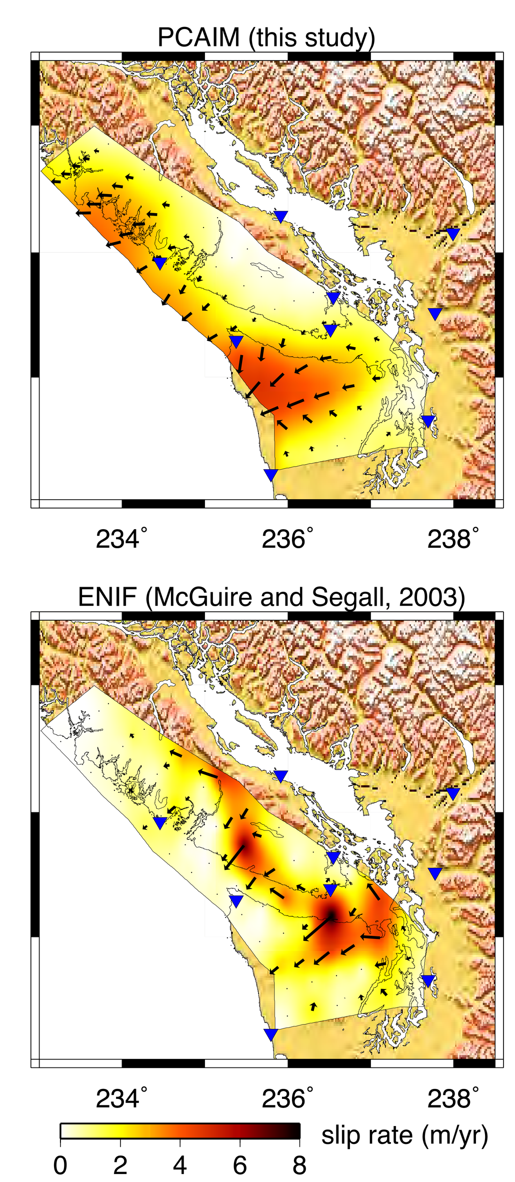

Figure 11

RESULTS AND DISCUSSION

Figures 7-9 show the results from the PCAIM and ENIF (Hsu, 2006) inversions of the Nias dataset. Both models show the same tendancy of slip in the same areas, and the fit to the data is excellent with both models. During early epochs PCAIM appears to do better because of its ability to capture rapid changes in position. The greater localization of slip in the ENIF model comes from using a slip penalty term, which the PCAIM model did not sue. This demonstrates the ability of PCAIM to invert post-seismic relaxation data for slip on a megathrust.

Figures 10-11 show the results from the PCAIM and ENIF (McGuire and Segall, 2003) inversion of the Cascadia dataset (Dragert et al., 2001). In figure 10 it is clear that both models (PCAIM in red, ENIF in black) fit the data equally well. Slip is more localized in the ENIF version and farther down-dip. This implies the range of possible models for the cascadia slow slip events may be larger than previously thought. However, this deficiency mainly stems from desiring to exactly mirror the data set used by McGuire and Segall. It should be noted the the PCAIM model used the ENIF predictions are input because of an inability to obtain the processed data.

CONCLUSIONS

In summary, we have created an analytic method through which it is possible to invert surface displacement time series for temporally changing slip distributions at depth using multi-source data. In this particular demonstration, we used three component GPS data, but there is no reason we must restrict ourselves to such data. Indeed, the PCAIM package in MATLAB that will be released by the end of the year on the Tectonics Observatory website will contain this ability. Several researchers have already used the joint inversion capabilities of PCAIM on EDM/InSAR timeseries and creep meter/GPS time series (Nina Lin and Marion Thomas, respectively, both of Caltech). Please e-mail the authors if you are interested in testing or using the software package.

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