Time Dependent Slip:

A Mathematical Study of Historic Displacement Near the Sunda Megathrust Subduction Zone

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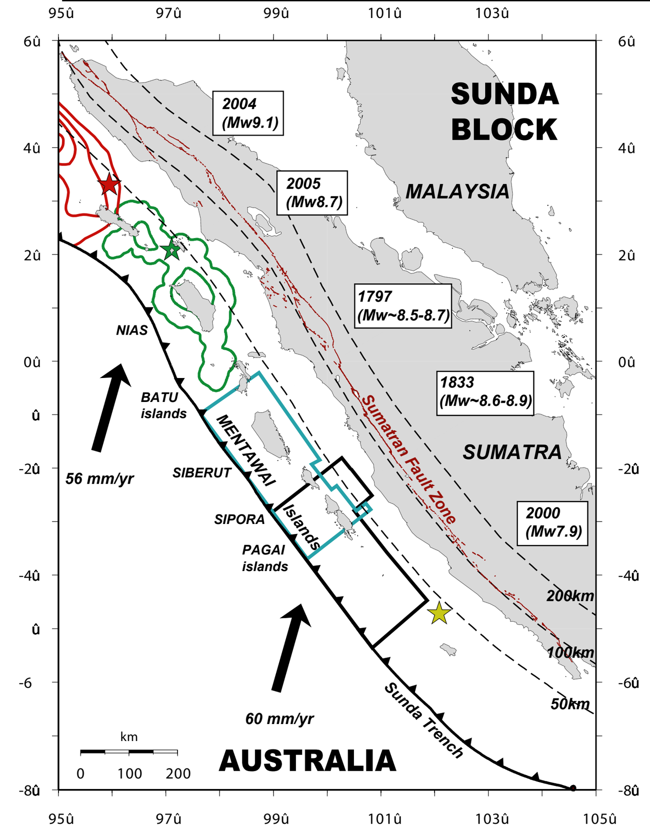
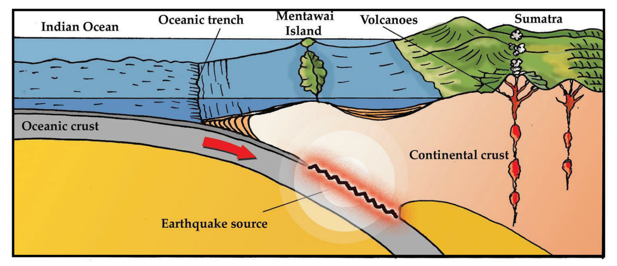
ABSTRACT

We invert displacement data using principal component analysis (PCA) and the Okada formulation for slip at depth on the fault in the Sumatra subduction zone. Though this work only deals with one dimensional displacement data, the method can be generalized to three dimensional displacements using GPS data. (Work in progress)





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 giant 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 when and where the next giant earthquake near the Sunda subduction zone is likely to occur.

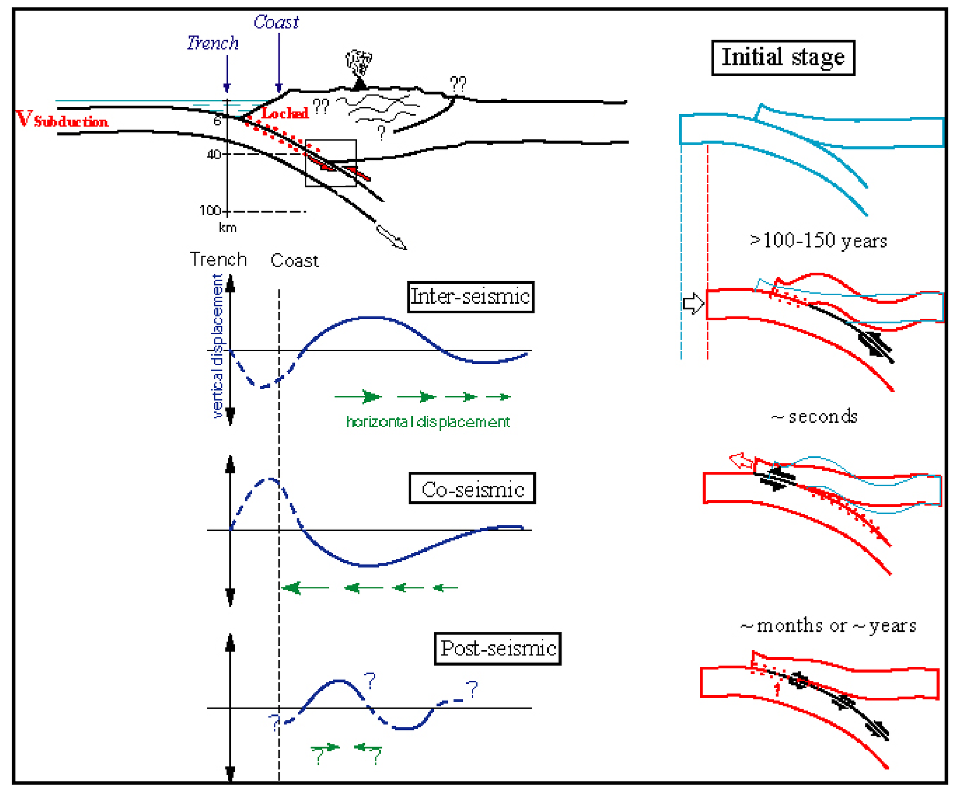
The earthquake cycle for two plates on the seductions on consists primarily of three phases:

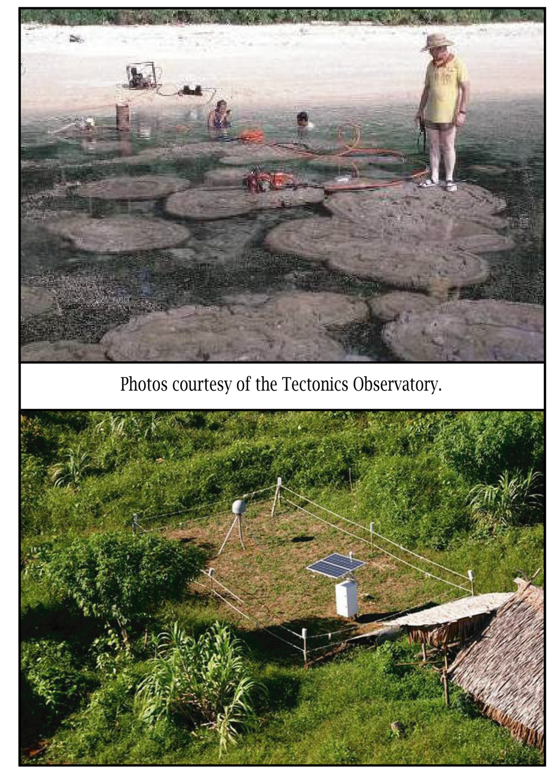
1. Inter-seismic Loading
   - As the subducting plate and the overriding plate converge, a section of the interface between the two plates locks and stress builds over time.

2. Co-seismic Events
   - The stress eventually becomes too much for the plates to bear a sudden and violent slipping between the two plates (i.e. an earthquake) occurs, releasing the stress that has built up.

3. Post-seismic Relaxation
   - After the earthquake the plates gradually return to a temporary state of equilibrium, often accompanied by gradually decreasing time-dependent slip.

A cartoon representation of this process and the resulting surface deformation are located in the figure on the right. This information implies that if we are able to figure out what the displacement at the surface has been we may be able to solve for what is happening at depth.

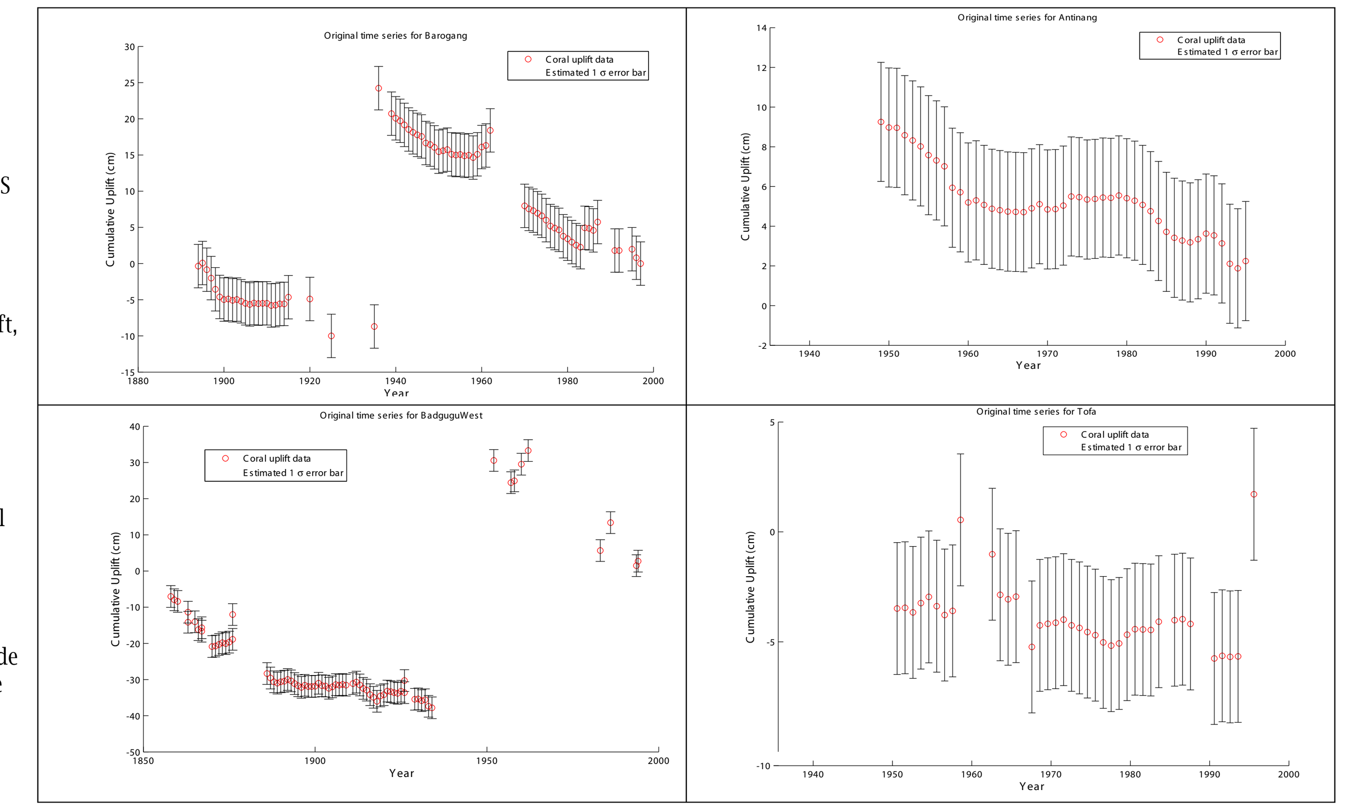


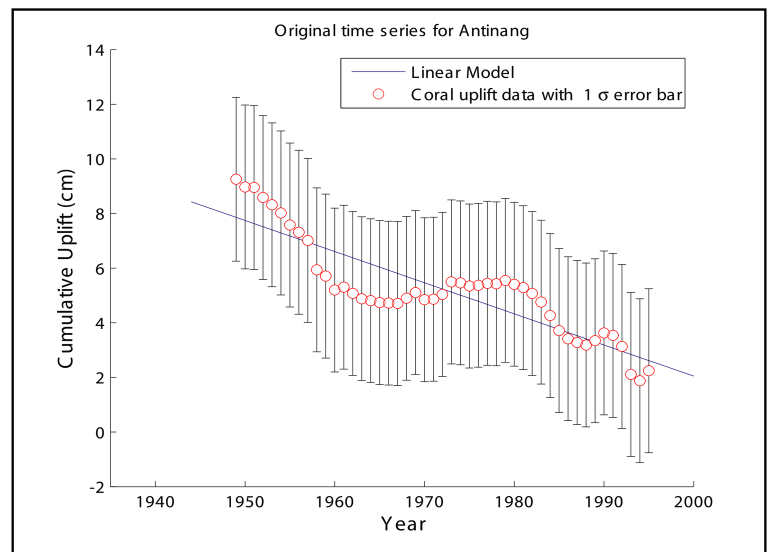


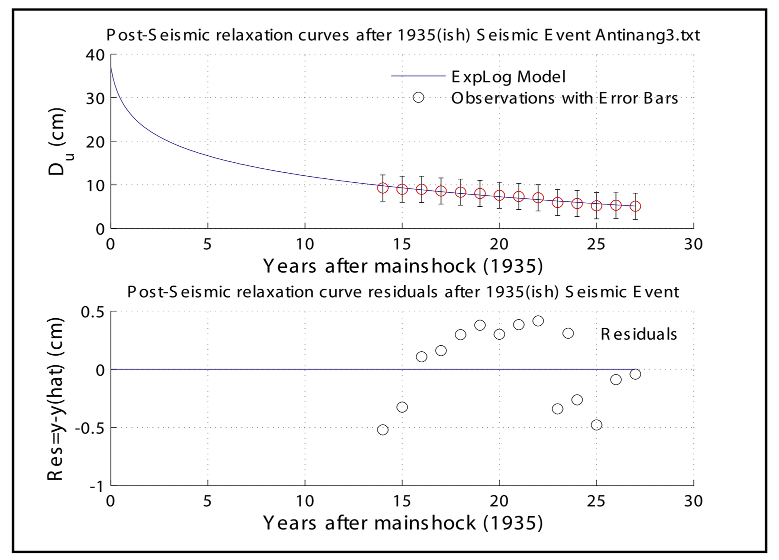
Photos courtesy of the Tectonics Observatory.

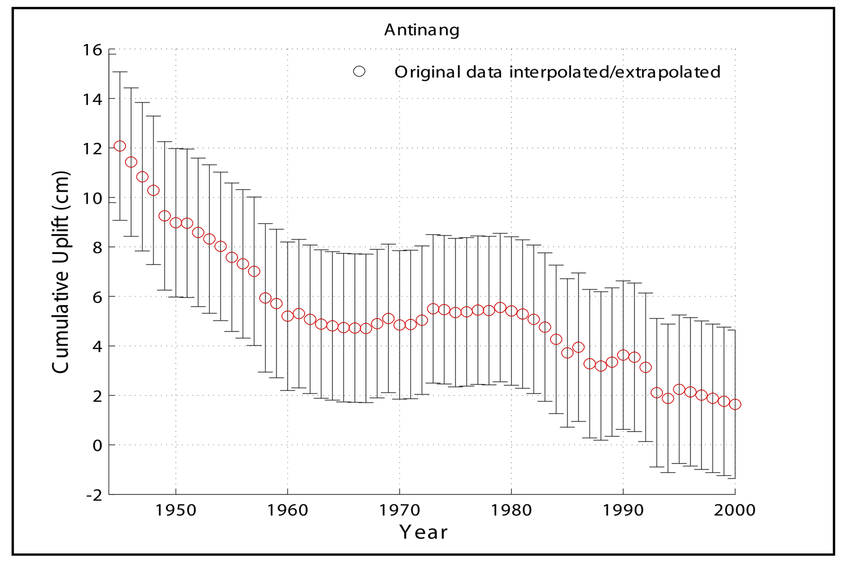
(Left)
The two primary methods used to measure surface displacement at this particular site are GPS, which directly measures displacement in every direction, and coral growth records, which is a proxy for vertical displacement. While GPS both is more precise and provides data in three directions rather than just one, we can only find data for time periods during which a GPS station was functioning and in place. Coral dies when it is exposed to air. Thus any changes in the lowest low tide of the year, for example due to tectonic uplift, may be reflected in how the coral grows from year-to-year. Because coral occurs naturally, coral growth records can provide over a hundred years of displacement data [5].

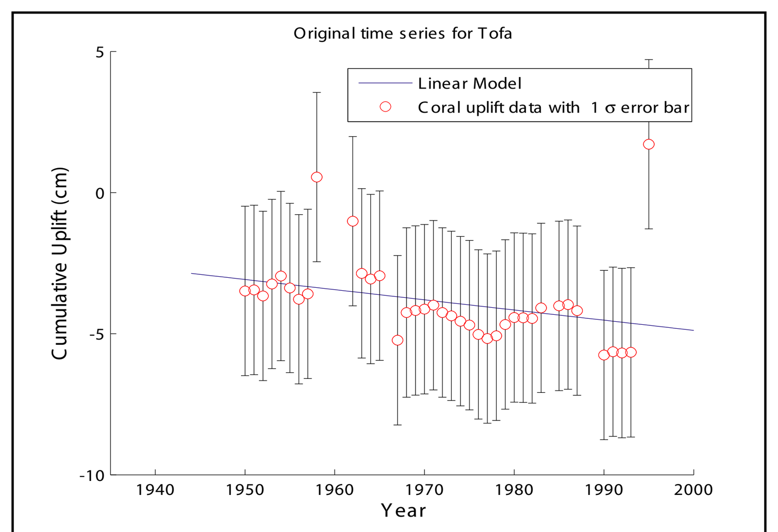
(Right)
After taking into account factors such as changes in sea level over time and idiosyncrasies related to working with a biological proxy, the position of the yearly growth rings formed by coral can be counted to determine the sea level relative to some part of the coral that can be dated using radioactive isotopes. What results are time series that provide a reasonably detailed record of vertical deformation over the last 40 to 150 years.

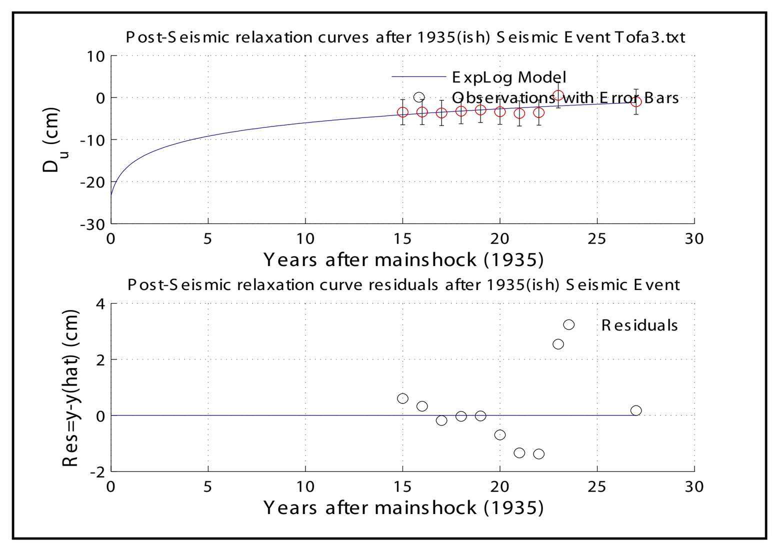


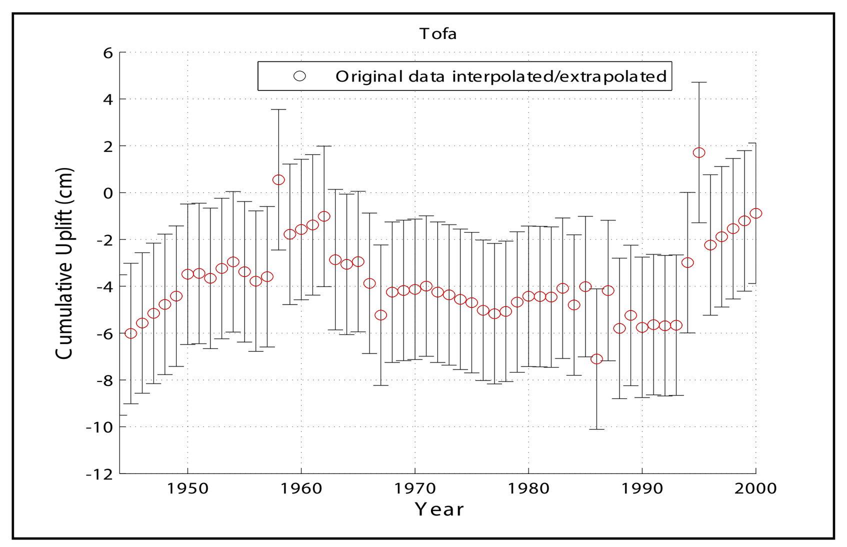


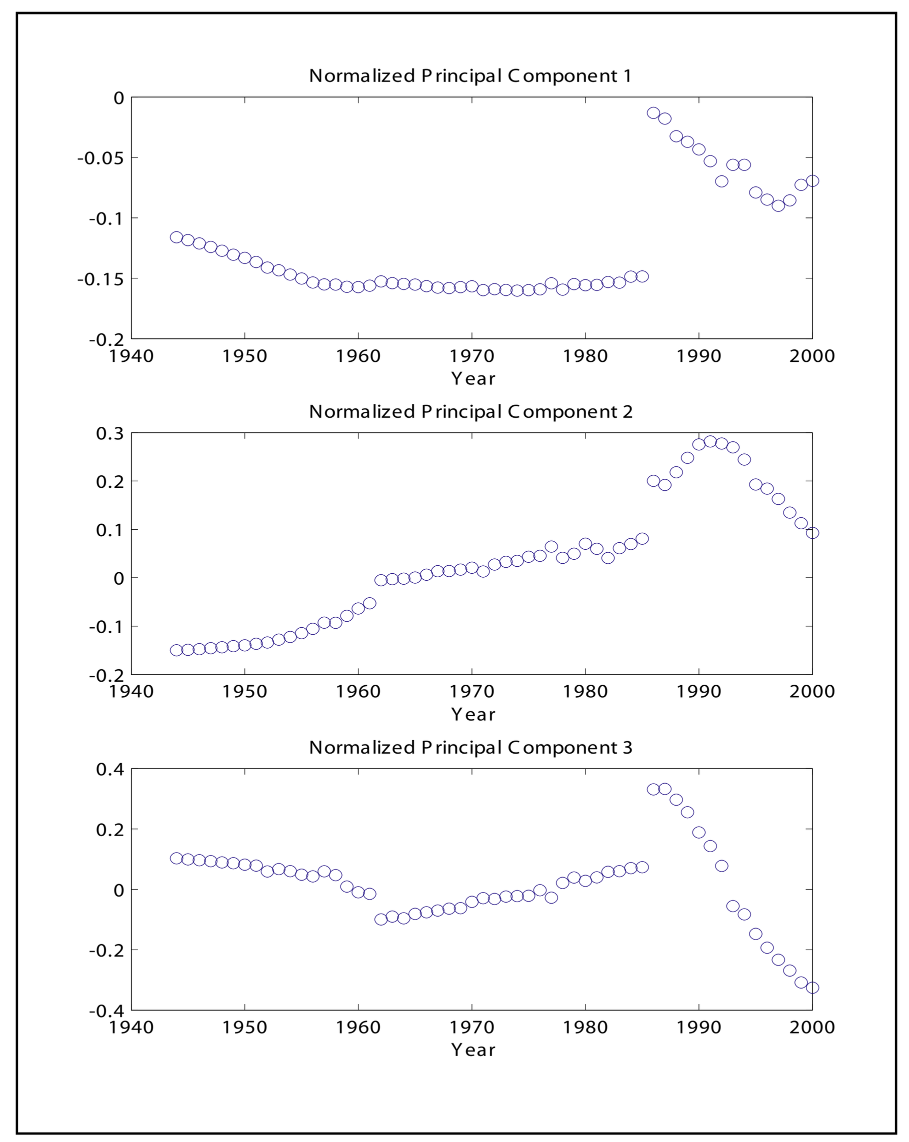


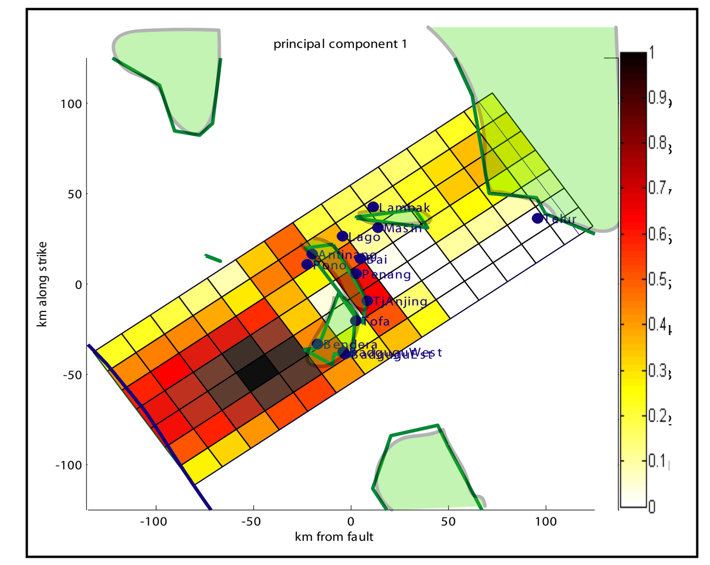


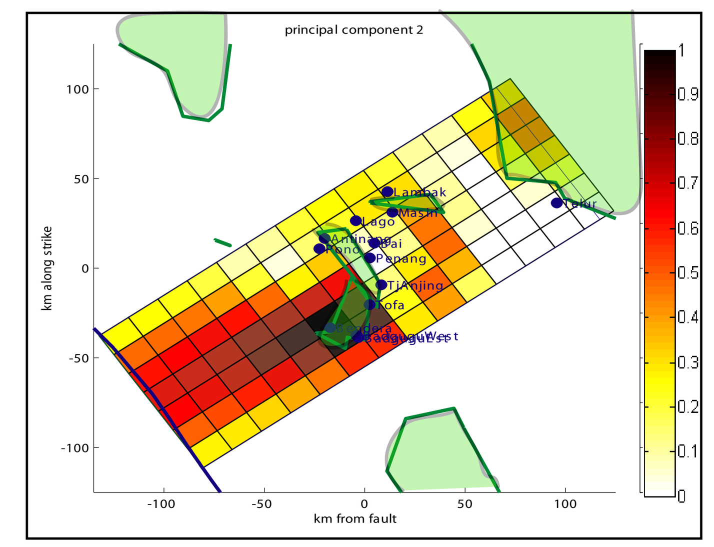


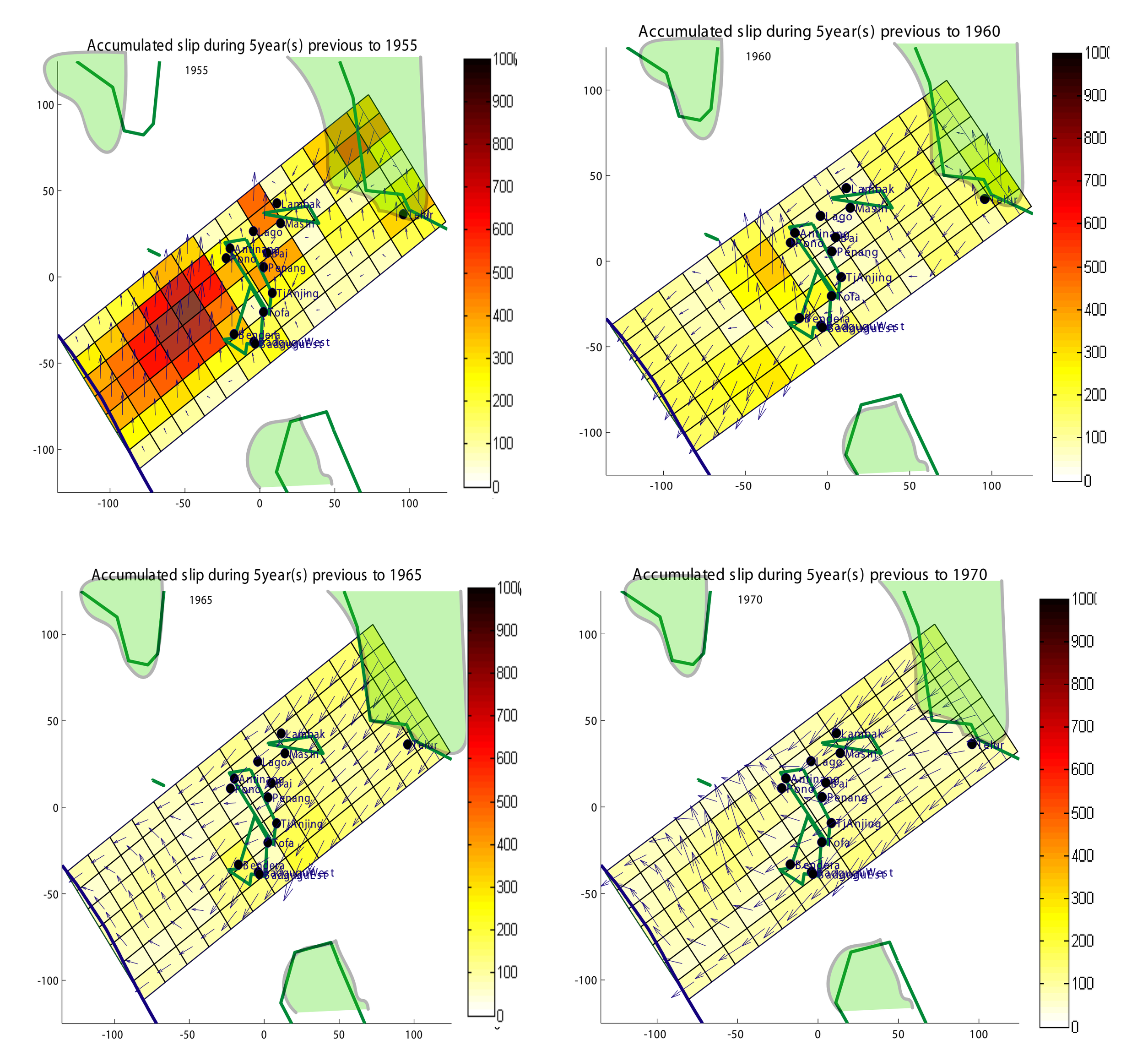












The most straightforward model is one that is linear with time. That is, the rate of displacement (vertical displacement in this case) at the surface is constant. This allows us to explain most of the first-order features of the data (no pun intended.) However, it is clear that there is some unexplained variability in the data.

The first step in investigating this variability is to fit the data using an assumed physical model, in this case the spring slider model from [8].

The physical model allows us to interpolate and extrapolated data so each of our datasets has the same distribution of "measurements" in time. In the case of the coral data, we make this an even distribution with one data point per year.

We then decompose all of our time series using a statistical technique called principal component analysis (PCA). The so-called principal component vectors are chosen and ordered such that the first principal component vector explains as much variability of the data as possible, the second principal component vector explains as much variability of the data as possible given that the variability associated with the first component has been removed, and so on.

This allows us to find the common patterns amongst the data (in other words, components not consisting of uncorrelated noise or signal,) and thus faithfully represent each time series as the sum of the first several pence will components. In this particular case, there are 14 principal component vectors total and the even the most troublesome stations (e.g. Antinang) are well-represented with the first six principal components. Some stations (e.g. Barogang) are well-represented with only one component.

Each of the principal components has a weight corresponding to each station. These weights represent how strongly each principal component is represented in the time series of that particular station. The vertical displacement resulting from the contribution of each component is proportional to each component's weight for that station. Using this information a given component we are able to invert the set of weights for each station using the Okada formulation and solve for a slip map that xplains the surface deformation we observe that the surface due to this component. In part the quality of the smoothing parameter used. If the smoothing parameter is set too low, the slip distribution will not be able to vary much with position. However if the smoothing parameter is set too high, the solution becomes very non-unique.

The figures above are examples of cumulative slip distributions over five-year periods, from 1950-1955, 1956-1960, 1961-1965, and 1966-1970. Notice how the direction and magnitude of slip over these time periods varies greatly. From examining all of the time series, it is clear that something out of the ordinary happened near 1960. Figures such as these will help unravel the mystery. Units are relative.

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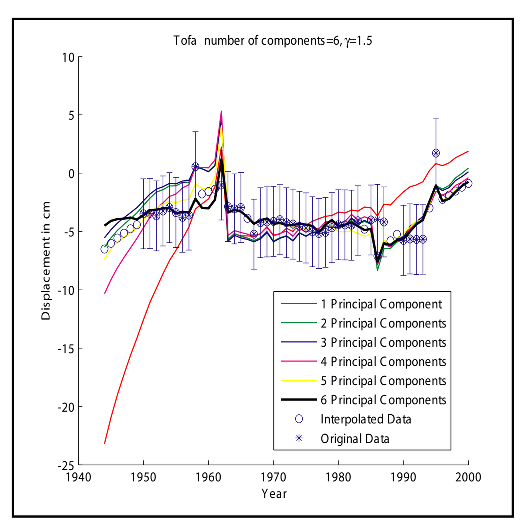

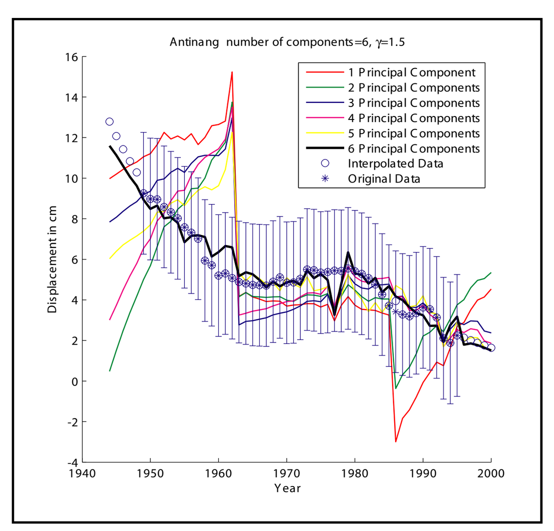

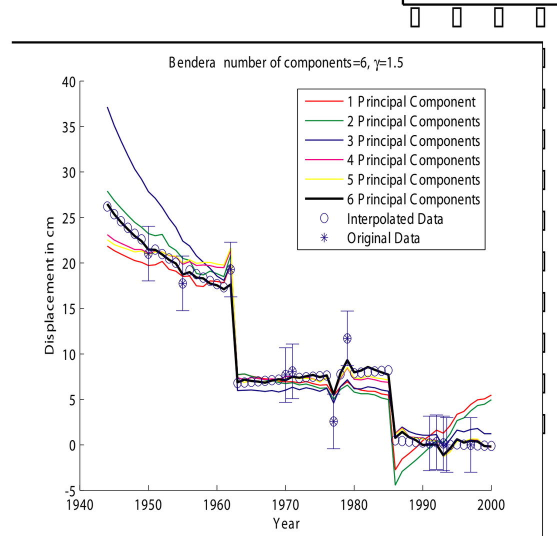

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An example of the how well the slip model agrees with the field data.