Block Models of Present Day Deformation in Southern California Constrained by Geodetic Measurements

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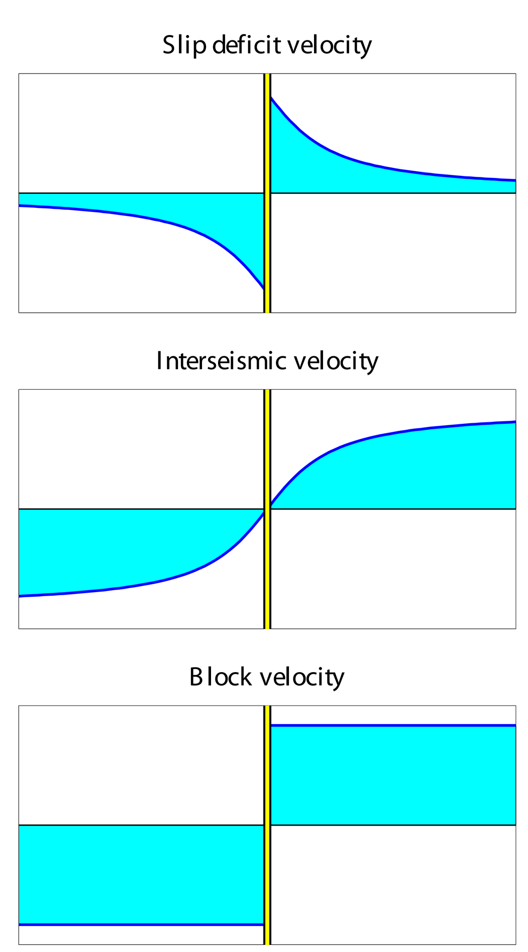
Introduction

From San Diego to Cape Mendocino, nearly all of coastal California lies along the plate boundary zone between the Pacific and North American plates. The relative motion between the two plates is accommodated by a complex network of faults, most of which quietly store energy to be released during earthquakes. In southern California, the 1992 Landers, 1994 Northridge, and 1999 Hector Mine earthquakes are recent examples. To better constrain seismic hazard potential we'd like to know fault slip rates so that we can try to estimate earthquake recurrence intervals.

The great quality and density of geodetic data manifest in the latest SCEC velocity field further motivated us to model present day deformation in the context of a block model. Simply put we divide the plate boundary zone into small blocks and estimate rotation vectors (Euler poles) for each. The block model approach accounts for elastic strain accumulation between block bounding faults and yields kinematically consistent slip rates, as well as far field motions. With this method the trade-off between locking depth and slip rate is heavily damped as geometric constraints limit the extent to which slip rates can vary. Slip rate uncertainties calculated by covariance propagation are typically less than 3 mm/yr. An important aspect of this type of modeling is that we estimate all of the slip rates at the same time, thus eliminating the need to use a priori models of, say, deformation associated with the San Andreas fault in order to estimate the present day slip rates on the faults in the Los Angeles basin.

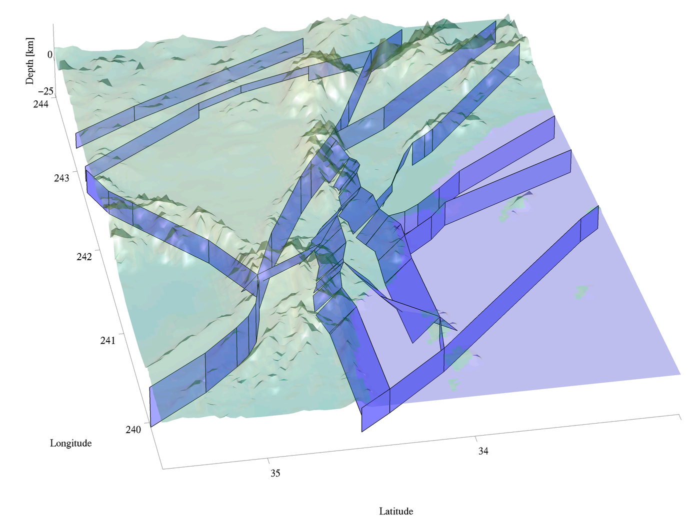
To relate block motions and fault slip rates to geodetic observations of secular deformation we follow the approach detailed by Savage and Burford (1972). For the two-dimensional case the total block velocity over geologic time is the sum of interseismic and coseismic contributions. This implies that all strain accumulated through the seismic cycle is released at some later time. Interseismic velocities can be expressed as the difference between the block velocity and a yearly coseismic slip deficit (see figure). To calculate the elastic contribution to the velocity field we use the finite dislocation solutions presented by Okada (1985). Each fault segment is subdivided into small pieces and projected, along with station coordinates, onto a plane using a locally tangent oblique Mercator projection. The elastic contribution is then rotated back to a ENU coordinate system. This approach allows us to work on spatially large models without worrying about the distortion due to a single map projection.

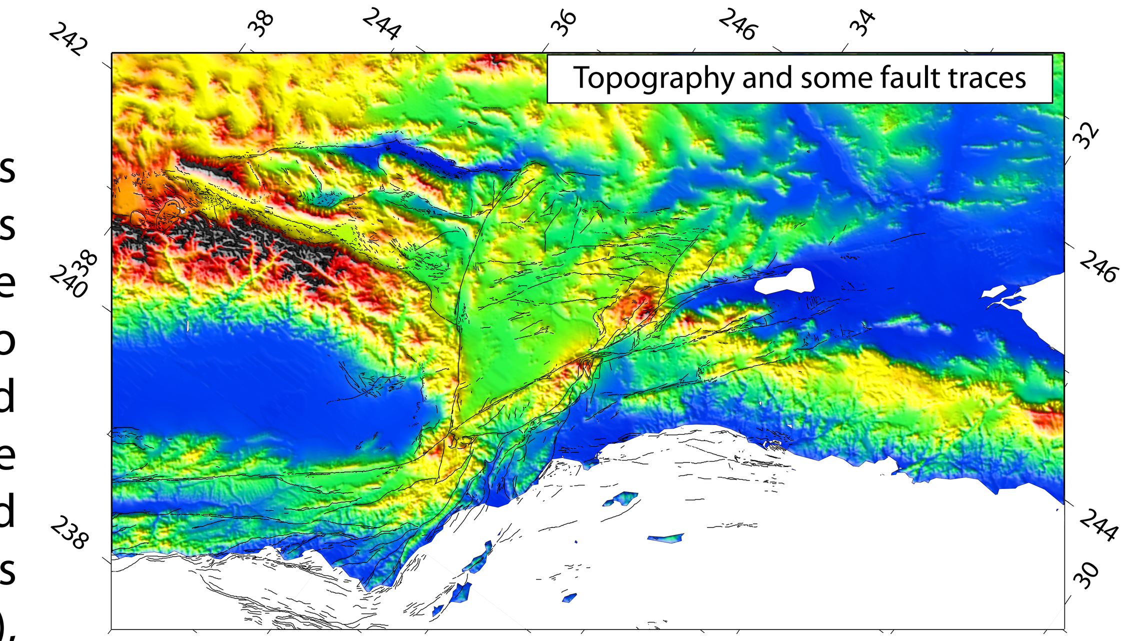


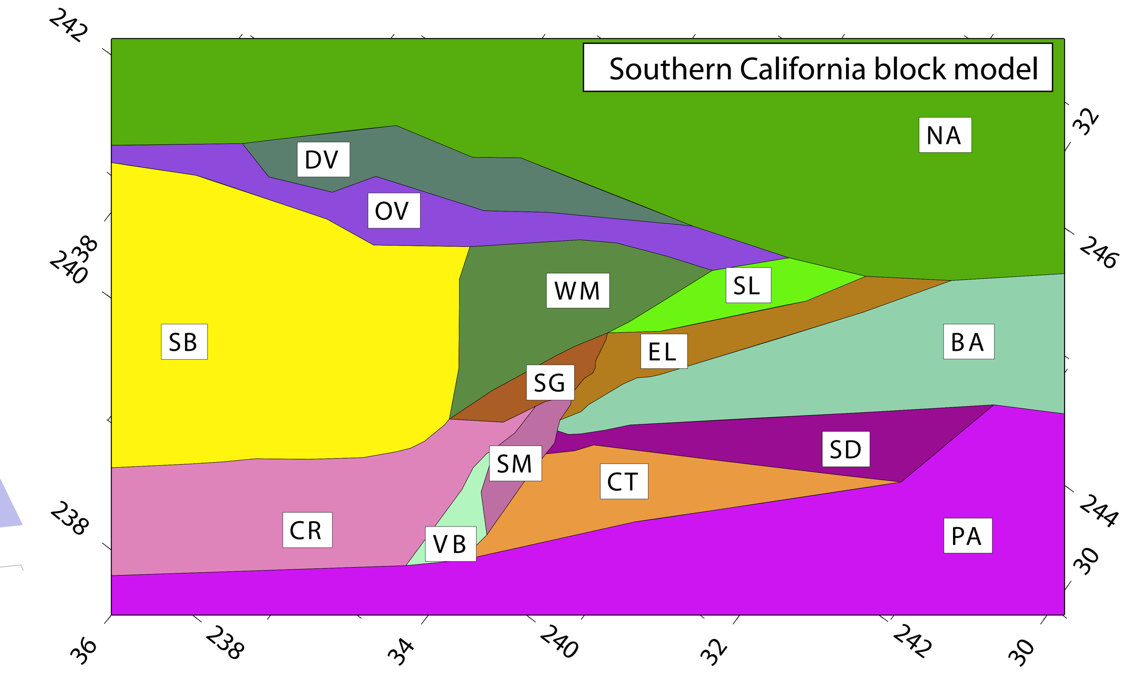
Block Geometry: connections and choices

Our preferred block model incorporates many of the major faults and is able to fit the geodetic velocities near the level of their uncertainties without being overly complicated. There are 16 blocks ranging in size from the large Pacific and American plates, to the very small blocks to the north of Los Angeles (LA). Most of the block boundaries correspond to well known faults. (e.g. San Andreas, San Jacinto, Garlock). Overall the block geometry has much in common with that presented by Bird and Kong (1994). The geometry at smaller scales closely follows previous work: McClusky et al. (2001) for the Eastern California Shear Zone (ECSZ)), Souter (1998) for the LA basin, Bennett et al. (1996) for the southern strike slip faults. In order to close all of the blocks we drew a few rather speculative boundaries. Examples include the connection of the ECSZ to the SAF and the offshore portion of the Oakridge fault to the western extension of the Santa Monica Mountains fault and the eastern termination of the Garlock at the Airport Lake fault.

A 3D view of the fault geometry near LA looking southeast along the trace of the SAF

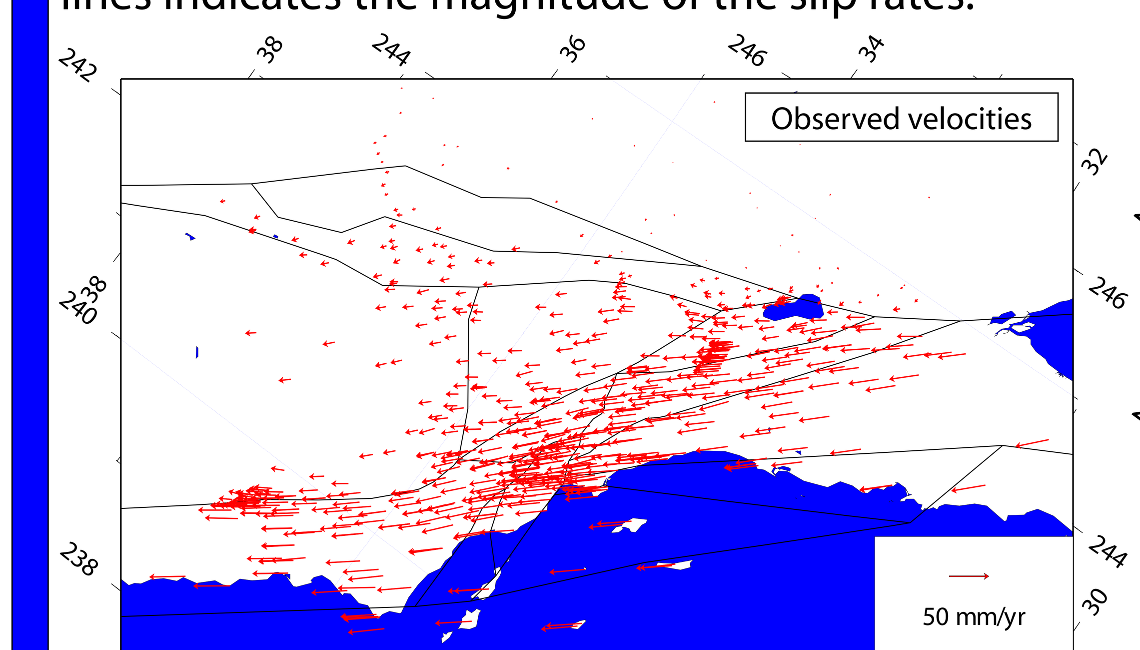


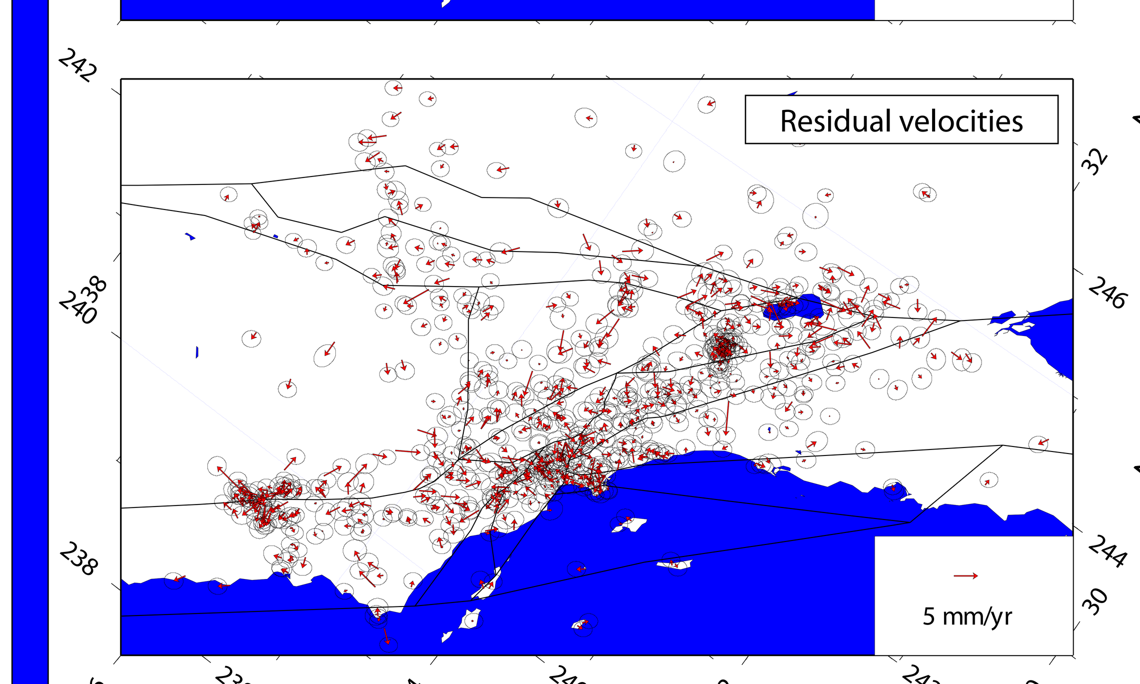


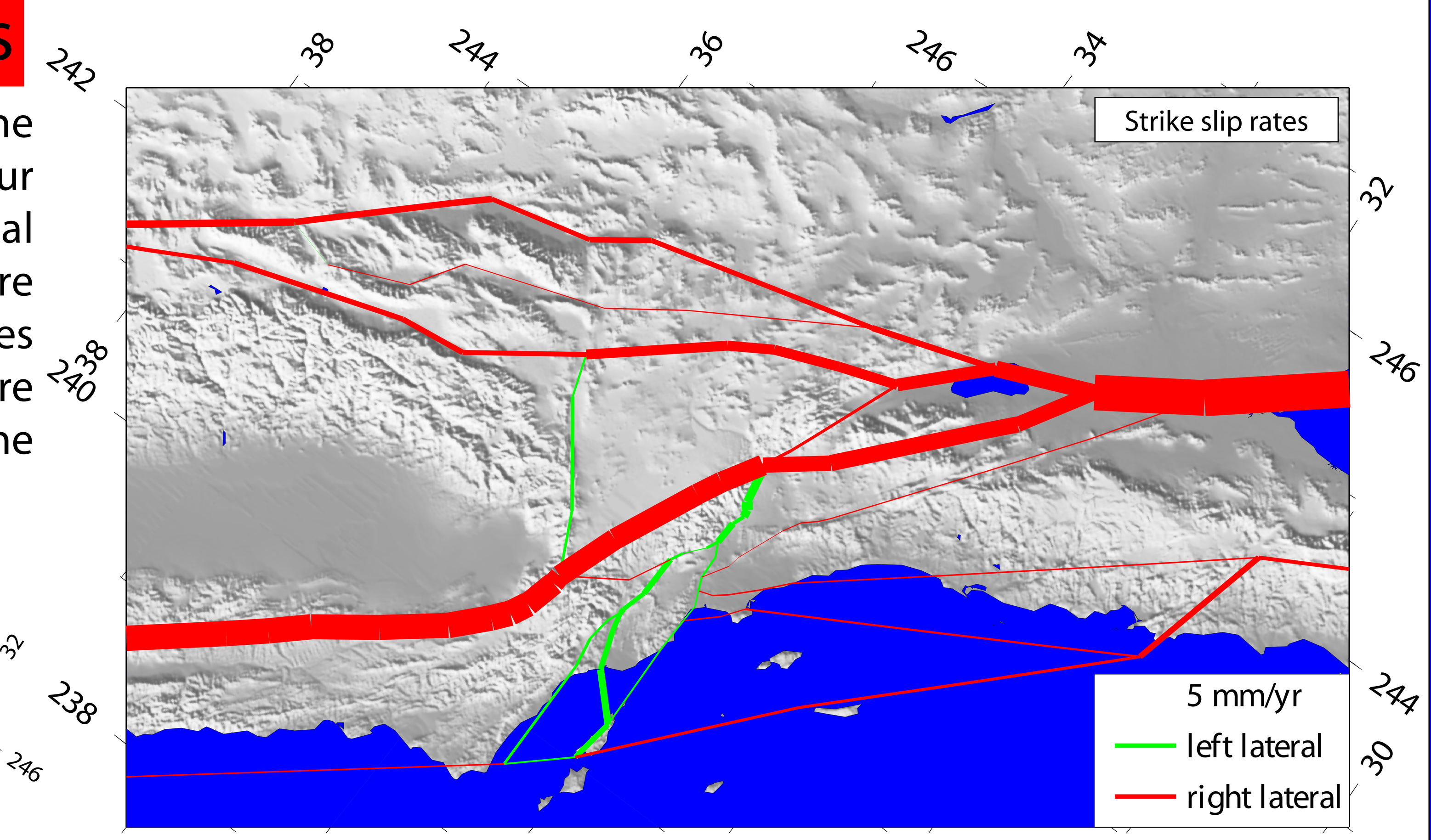


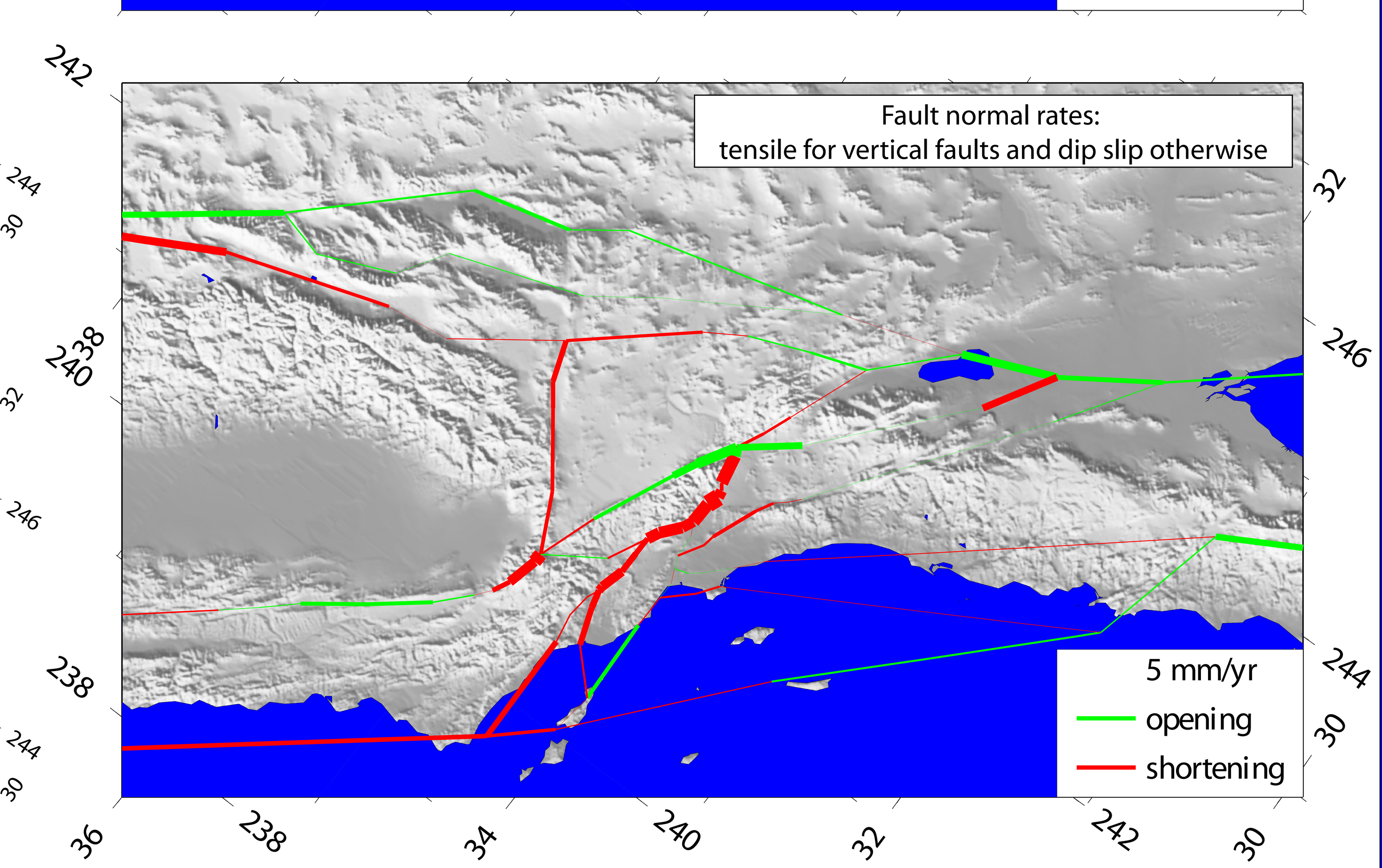
Residuals & estimated slip rates

The fit to the data is surprisingly good given the simplicity of the model. Of the 733 stations in our current inversion 67% of them have residual magnitudes less than 2 mm/yr. The residuals are shown below the with their 50% confidence ellipses from the observations. The slip rate estimates are shown in the figure to the right. The width of the lines indicates the magnitude of the slip rates.



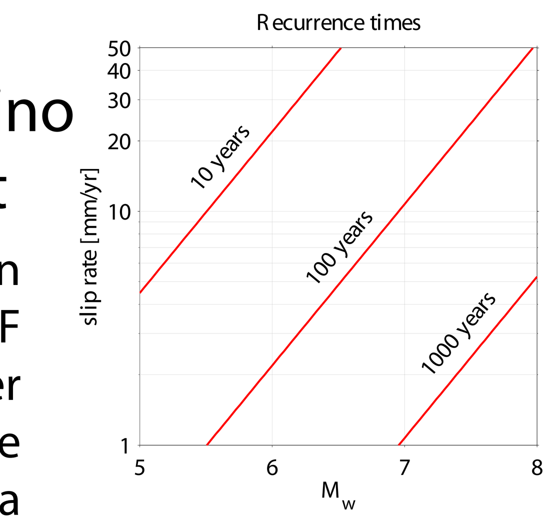






What's really interesting

A low slip rate on the San Bernadino segment of the San Andreas Fault



We find a very low slip rate (5 ± 2 mm/yr) on the San Bernadino segment of the SAF (SBSAF). This is a factor of five or six lower than the slip rate estimates on the rest of the SAF. We argue that this slip rate is a consequence of the local fault geometry. The combination of the ECSZ connection to the south and the reconnection with the San Jacinto fault to the north leaves very little motion to be accomodated here. A low slip rate is especially interesting in the context of paleoseismic estimates of recurrence times along this segment. Yule and Sieh (2000) found a mean recurrence interval of 330 years averaged over the last two millenia. Taken together this low slip rate estimate and the long recurrence interval suggest that earthquakes occur infrequently on this segment because it takes a relatively long time to accumulate enough strain to rupture. We can make a first order attempt to quantify the size of a typical earthquake by usingthe empirical scaling relations reported by Wells and Coppersmith (1994). The above figure shows the relationships between fault slip rates recurrence times and moment magnitudes. Based on this type of reasoning a typical earthquake on the SBSAF would be about M = 7.

Where's the shortening in the Transverse Ranges?

The string of faults from Oakridge in the west through the Santa Susana and Sierra Madre Mountains fault along the San Gabriel range front and finally to the Cucamonga fault that terminates along the Mojave segement of the San Andreas is where the Transverse ranges appear to be accommodating most of their present day shortening with dip slip rates of about 10 mm/yr. These same faults also have left lateral motion indicating the expulsion of the San Gabriels and Coastal ranges to the west-northwest. To the south the line of faults representing the Santa Monica Mountains, Hollywood Hills, and Raymond hills fault show very little motion. The Elysian Park Thrust and the east dipping Whittier fault to the south each show about 2 ± 2 mmy/yr of dip slip motion in fair agreement with the InSAR study by Bawden et al. (2001). Again this is mostly a consequence of the fault geometry. In this case it is the westward bend taken by the EPT and Whittier faults relative to the Elsinore fault zone.

Why is the southern Mojave so fast?

Running between the Airport Lake fault in to the north and the Salton segment of the SAF in the south the Calico-Blackwater fault defines the eastern boundary of the western Mojave block and veritably races along at about 11 mm/yr. This high rate is notable for two reasons: 1) it runs straight through the Landers rupture zone and may represent postseismic deformation, and 2) Peltzer et al. (2001) recently estimated a high slip rate on the segment of this fault north of the Landers rupture. Thus the postseismic relaxation argument makes sense only if it has affected an area much larger than the size of the coseismic fault plane. A fast slip rate on the Calico-Blackwater does make sense in the context of a complicated plate boundary zone that is trying to straighten itself out. In this high slip rate in the Mojave and on the San Jacinto fault to avoid the southern part of the Big Bend.