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New Constraints on Models for Time-Variable Displacement Rates on the San Jacinto Fault Zone, Southern California

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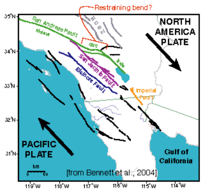
Introduction

Understanding how past- and present-day relative plate motion is apportioned among fault zones of the southern San Andreas system has been the subject of many recent studies. The San Andreas, San Jacinto, and Imperial faults are commonly assumed to form a closed system. But despite decades of investigation, appreciable disagreement remains regarding the relative rates of deformation among these fault zones at the plate boundary scale. South of the San Bernardino Mountains, the San Andreas fault zone trends oblique to relative plate motion. Unlike the Mojave and Indio segments of the fault zone to the north and south of San Bernardino, respectively, the segment traversing the San Bernardino Mountains do not form a through-going structure. Rather, it comprises a zone riddled with discontinuous and asynchronous fault strands bounding uplifted crustal blocks and pull-apart basins [Matti et al., 1985; 1992; Matti and Morton, 1993; Carena et al., 2004]. This complexity introduces additional difficulty in understanding how slip rates resolved along and between faults relate and how plate-boundary fault zones trade-off with one another in order to conserve the total relative plate motion, which is secular. We investigate the plausibility of new variable-rate fault models by combining basin deposit provenance, fault trenching, seismicity, gravity, and magnetic data sets from the San Bernardino area.



◀ The Pacific-North America plate boundary in southern California can be divided into a number of different fault zones, segments, and strands for which no universally agreed-upon nomenclature exists. We refer to the collection of fault zones that make up the Pacific-North America plate boundary in southern California as the greater San Andreas fault system. The San Andreas fault zone is the dominant component of this system. For convenience, we divide the San Andreas fault zone into 3 segments: the Indio, San Bernardino, and Mojave segments. The Indio segment represents the San Andreas fault south of Indio. The Mojave segment includes all fault strands north of Cajon Pass. For simplicity, we refer to the intervening fault strands including the often separately termed Coachella Valley segment, as the San Bernardino segment. Strands of the San Bernardino segment include the Wilson Creek, Mission Creek, Mill Creek, and San Bernardino strands. Other fault zones that are important to our discussion are the San Jacinto fault zone and the eastern California shear zone (ECSZ).

Why do we need new models?

Existing geodetic, geomorphic, and geologic studies yield apparently conflicting estimates of fault displacement rates over the last 5 m.y. in the greater San Andreas fault system of southern California.

Rates extrapolated from total measured displacement along a fault are significantly affected by inferred age of fault inception, which is still debated in some cases. Rates measured from geologic inference at certain sites are debated, and even robust rate estimations disagree from site to site (see table below). To throw in an additional complication, geodetically-determined rates do not always agree with geologically-determined rates. For instance, modern strike-slip loading rate estimates along the San Bernardino segment range between 1 and 5 mm/yr. These low geodetic rate estimates would appear to disagree significantly with geomorphology-based estimates for strike-slip displacement on the modern San Bernardino strand of the San Bernardino segment which range between 14 and 28 mm/yr since as recent as 6 ka [Weldon and Sieh, 1985; Harden and Matti, 1989]. Some faults within ECSZ also appear to exhibit this behavior [Oskin, et al., 2004]. There are a number of possible explanations for these discrepancies.

[after Bennett et al., 2004]

TABLE 1. AVERAGE FAULT-DISPLACEMENT RATES

Age to present (ka)	San Andreas (mm/yr)	San Jacinto (mm/yr)	Notes	References
0	2-5	~10		Becker et al., 2005; Meade and Hager, in press, 2004
6	25 ± 3		a,b	Weldon and Sieh, 1985
8	25 ± 3		a,b	Weldon and Sieh, 1985
10		9 ± 2	a,b,c	Rockwell et al., 1990
13	25 ± 3		a,b	Weldon and Sieh, 1985
14	19 ± 5	11 ± 7	a,b,c	Harden and Matti, 1989; Rockwell et al., 1990
15	25 ± 3		a,b	Weldon and Sieh, 1985
17		12 ± 7	a,b,c	Rockwell et al., 1990
30	28 ± 6		a,c	Harden and Matti, 1989
35	19 ± 3		a,b	Van der Woerd and Klinger, 2003, personal commun.
50		13 ± 7	a,b,c	Rockwell et al., 1990
90	14 ± 2		a,b,d	Harden and Matti, 1989
700		>10	e	Sharp, 1981; Dorsey, 2002
1500		19 ± 2	f	Sharp, 1967; Morton and Matti, 1993; Dorsey, 2002
5000	30 ± 2		g	Frizzle et al., 1986; Powell and Weldon, 1992

Note: (a) Displacement obtained from restoring offset geologic or geomorphic marker. (b) Age of offset marker determined by geochronologic age estimate (e.g., Carbon-14 or cosmogenic dating). (c) Age of offset marker determined by regional correlation of soil stratigraphy. (d) We choose the date of 90 ka from the possible choices of 65 ka or 90 ka reported by Harden and Matti, 1989. Qualitatively, the displacement-rate histories that we infer do not depend on this choice. (e) We do not use estimates for San Jacinto fault displacement rate for the 700 ka period because the reported rates are minima. (f) Total age of San Jacinto fault inferred from stratigraphic relationships and dated sedimentary deposits. (g) Total age of San Andreas fault inferred from regional palinspastic reconstruction.

Potential Solutions

1. Some data may be erroneous/not representative

Modeling of GPS may not accurately represent locking depth of faults or postseismic effects.

Geodetic estimates may be affected by the superposition of a large number of destructively interfering post-seismic strain transients [Pollitz, 2003]. However it is also possible that differences between geodetic and geologic rates are not entirely attributable to locking depth mismodeling or to earthquake-cycle effects.

Geologically inferred rates are subject to dating or interpretational error.

2. Data may be too sparse to adequately characterize slip rates

If right-lateral displacement is transferred from the San Jacinto to the San Andreas faults across the San Bernardino basin, geologic data sets may be rectified.

This type of slip transfer across the San Bernardino basin violates the subsurface structure model of Anderson et al. [2004].

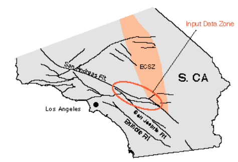
3. All data are correct, implying time-variable displacement rates

Some amount of the disagreement regarding the apportionment of deformation among these fault zones may signify temporal-variability of displacement rates on the faults.

This is not a new idea and has been suggested by such studies as Sharp [1981], Harden and Matti [1989] and Bennett et al. [2004]. We investigate two models, one includes GPS constraints, one does not.

Time-Variable Displacement Rate Models

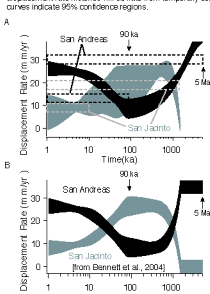
All existing data appear to be consistent with the notion that a change in the rate on one fault is matched by an equal and opposite change in the rate on the other, suggesting that the San Andreas and San Jacinto form a closed system with a conserved displacement rate totaling 35 mm/yr [Bennett et al., 2004]. A possible shortcoming of this model is that the San Bernardino and Indio segments of the San Andreas fault zone are assumed to exhibit the same behavior through time. It is likely, however, that the eastern California shear zone plays an important role in accommodating some fraction of the relative plate motion at the latitude of the San Bernardino segment. Here we explore 2 models, one that excludes other fault zones and geodetic data and one that allows for the inclusion of more than 2 faults and utilizes geodetic data.



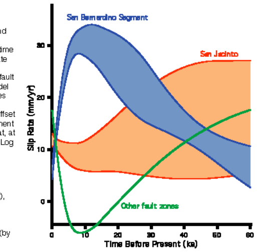
▲ Because potential faults include the San Andreas, San Jacinto, and Eastern California shear zone, our model area includes the intersections of these faults with each other.

Method and Results

We used an estimation technique that constrains history of instantaneous displacement rate with fault displacement rate average data. The technique is based on the theory of smoothing spline interpolation. Non-uniqueness is addressed by application of Occam's Razor---of the infinite number of possible rate histories that satisfy the rate average data, we select the simplest history that can explain the data to within their uncertainties. The nature of the smoothing spline technique is that the resulting displacement rate histories will deviate from temporally constant rates only if necessary to match the observed averages. Variable widths of displacement rate history curves indicate 95% confidence regions.

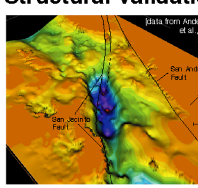


◀ Rate model of Bennett et al. [2004] which includes only the San Andreas and San Jacinto faults and does not use geodetic rates to constrain the present time period. Boxes represent a few of the rate averages used in the calculation. (A) Histories of displacement rate for each fault estimated independently. Note how model histories generally approximate averages such that rates are 50/50 above/below average rates since age of respective offset markers. (B) Histories of fault-displacement rates estimated subject to constraint that, at any given time, rates sum to 35 mm/yr. Log scale for time axis is necessary to simultaneously show variations across diverse time-scales.



▶ New rate model, which includes a shorter time period (from 60 ka-present), allows for more than 2 fault zones, and includes current GPS estimations. The data set is modified to only reflect the behavior of the San Bernardino strand (by excluding the 35 mm/yr rate for Biskra Palms: see highlighted data in table 1). San Jacinto rates come from the whole SJ fault zone (as shown in table 1). Geodetic slip rate estimates for the San Jacinto and San Bernardino strand are from Meade and Hager, JGR, in review, 2004 and Becker et al. [2005]. These data do not form a closed system. Another fault zone or fault zones (ECSZ?) are required to preserve the assumed 35 mm/yr total. If this is true, there would appear to be evidence for displacement rate changes on Myr, 100k yr, and 10k yr time-scales.

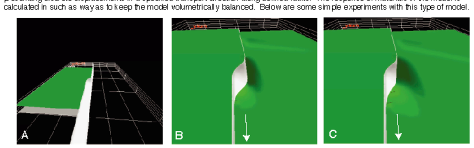
Structural Validation of Displacement Path



▲ The San Bernardino basin lies between the San Jacinto fault (SJF) and the San Andreas fault (SAF). The high-resolution strike-slip basin structural model of Anderson et al. [2004] allows us to trace the path and timing of strike-slip fault displacements in buried basement rocks. The figure shows a perspective view of the basement topography resolved from isostatic gravity signatures and shows a 2 km deep graben centered directly over the modern strand of the SJF. This observation indicates that displacements necessary to create the basin have been centered on the SJF for most of the basin's history. Linear magnetic anomalies, used as geologic markers, are offset ~25 km across the northernmost strands of the SJF, which matches offset estimations south of the basin. These offset anomalies indicate that the SJF and SAF are discrete fault systems that do not directly interact south of the San Gabriel Mountains, therefore spatial slip variability combined with sparse sampling cannot explain the conflicting rate data in this area.

Method and Initial Results

The detailed structure of the San Bernardino basin and estimated displacements on strike-slip faults can be utilized as constraints to quantitatively test models of strain accommodation in the basin. This type of approach is common in the study of thrust structures of orogenic belts. Upper-level structural details in thrust belts are known to have an intimate dependence on the morphology of lower level structures (e.g. the tilt of the basal decollement in a thrust belt strongly affects the possible thrust sequences above). The same has been shown to be true for pull-apart basins [Dooley and McClay, 1997]. Therefore, quantitatively modeling the development of this basin would not only provide important new insights into the viability of upper-crustal fault displacement rate histories but may allow us to constrain deeper structures. We are experimenting with 3-D Move, a program that allows geometrical manipulation of a volume by prescribing discrete displacements in a specified transport direction along defined faults. The response of materials in the model is calculated in such as way as to keep the model volumetrically balanced. Below are some simple experiments with this type of model.



▲ Simple block models. A) Input structure and fault geometry (hanging wall layers are not shown). Layers are included at the surface and at 20 km depth (representing the base of the brittle crust). Fault geometry was generated to give a step at the surface, but trend straight through the model at 20 km. The step is ~20 km wide. B) Structure of the surface layer after 25 km right-lateral strike-slip movement. Arrow shows direction of hanging wall movement (parallel to straight sections of the fault). C) Structure using an alternate material slip vector for the hanging wall.

Initial Observations

- **Material slip vector (faulting style) does not affect gross structure with large displacements, but may affect the extent of subsidence.**
- **Step between faults at the surface implies subsidence within and even beyond bounding faults, which reinforces our conclusion of no step existing between SJF and SAF across San Bernardino basin.**
- **The next step in modeling is to build and test a fault structure similar to the San Jacinto fault zone.**

Conclusions

Collectively, these data raise important questions about how complex upper crustal structures form, how they evolve, and how they relate to lithospheric-scale dynamics.

We still have the following pressing questions:

- Is our assumption that contemporary loading rates necessarily equal Holocene-Pleistocene displacement rates in error?
- Is our assumption correct that a decrease on the San Andreas implies an equally large increase on other fault zones, such as the eastern California shear zone or the San Jacinto fault zone?
- What changes to the tectonic environment would favor the formation of new displacement paths?
- Does our most recent rate model agree with paleoseismic evidence for fault zones other than the San Andreas fault and the San Jacinto fault such as in the ECSZ (e.g. Rockwell et al. [2000])?

Future Directions

Rheology: Discrepancies among geodesy-, geomorphology-, and geology-based strain models for the San Andreas and San Jacinto fault zones can be evaluated in the context of geodynamic modeling.

Geodesy: Improvements in geodetic (GPS) coverage in the general San Bernardino region is required to better resolve the modern allotment of plate motion among the San Jacinto, San Bernardino segment, and eastern California shear zone.

Structure: Further structural modeling of the San Bernardino basin will allow us to validate future calculated rate and rheologic models.

Geology: New paleoseismologic and geologic studies are needed to provide new rate constraints.

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