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Restoring California, part I: 0~18 Ma

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ABSTRACT

We are computing incremental stepwise restorations of maps of faults and outcrops in the western United States and northern Mexico using kinematic F-E program RESTORE (v.4) and datasets of: fault traces, fault offsets, timing constraints, paleomagnetic rotations (including a major contribution by Bruce Luyendyk), restored sections, and paleostress directions. The eastern edge of the model is fixed to stable North America, and the western edge is free. Three model parameters were tuned to match GPS velocities in the first (neotectonic) timestep. This report covers only the southern California part of the model in timesteps back to 18 Ma. Early results include:

(1) The model Garlock fault has neotectonic rates of 3.7 (W), 5.8 (central), and 4.1 (E) mm/a, and total sinistral offsets since initiation at 11 Ma of: 44 (W), 52 (central), and 39 (E) km, somewhat less than the geologic estimate of 64 km (central) from Andrew et al. [2015]. Under-fitting of geologic offsets is common in this model, except where offsets have small uncertainties.

(2) The restraining left-step of the San Andreas fault at San Gorgonio Pass began to form as soon as the southeastern San Andreas initiated at 6 Ma. Left-slip of 15 km on the Pinto Mountain fault (associated with general clockwise rotation of the region to its S) contributed to this. In our model, post-6 Ma shortening of 8 km on the Dillon thrust fault was another cause.

(3) We are able to nearly close the Gulf of California, and restore the Pelona Schist antiform opposite to the Orocopia Schist antiform at 6 Ma by about 240 km of San Andreas offset, as many authors have advocated. A remaining problem is that faults in the Orocopia area only back-rotate ~25 degrees--much less than the ~90 degrees that would be needed to align them with faults in the Pelona area.

(4) The Western Transverse Ranges (Santa Ynez, Santa Susana, & Santa Monica Mountains) have rotated clockwise since 18 Ma, as shown by many paleomagnetic studies. However, our model rotation is only ~70 degrees [as in *Hornafius et al.*, 1986; also similar to *Wilson et al.*, 2005] rather than ~120 degrees [as in *Nicholson et al.*, 1994]. This implies that the sinistral faults now defining the N and S margins of the WTR formed at azimuths of ~020, consistent with stress directions just slightly counterclockwise from present.

INPUT DATA

The scope of the data reported here is: western U.S.A. and northern Mexico, from 49°N to 20°N, and from the Great Plains in the East to the outer edge of the continental borderland (trench or paleo-trench) in the West, and back to at least 85 Ma (Late Cretaceous).

***Fault traces: 2,384 fault traces were digitized. Many were from large-scale maps in the literature, or from the Geologic Map of California [*Jennings et al.,* 2010]. The Tectonic Map of North America [*Muehlberger,* 1992] helped us to include all important faults, even nameless ones. For all California faults that were modeled in the UCERF3 project of 2013, digitized traces from SCEC CFM were preferred.**

***Fault offsets and age-constraints: The authors surveyed the geologic literature for offset components (throw or heave, including trace-parallel and trace-perpendicular components of heave) and associated uncertainties, age-constraints, literature citations, and notes. Where reported offsets disagreed, we exercised editorial judgement to average them, or to select one alternative. Where sufficient piercing-points of different ages were reported, some faults have multi-chapter offset goals (e.g., one dextral heave since 1.6 Ma, a different heave during 6.0-1.6 Ma, and a third heave during 22-6 Ma). Faults without reported offsets are assigned generic values: dextral 18.9±12.6 km; sinistral 8.2±4.1 km; high-angle thrust throw 1.7±1.7 km; low-angle thrust heave 13.6±9.1 km; high-angle normal throw 2.5±1.9 km; low-angle detachment heave 12.2±8.1 km. All of these default offsets are medians of measured offsets on faults of the same class in the western US, and the default sigmas roughly describe the spreads of those distributions. For some faults whose offsets lacked age constraints, the authors selected likely age ranges from data on nearby faults of the same class, or tectonically connected faults.**

***Paleomagnetic declination and inclination anomalies: A southern-California database of 23 selected paleopoles was contributed by Bruce Luyendyk. Another 232 paleopoles (across all of western North America) were obtained from the IAGA Global Paleomagnetic Database v.4.6, selecting for primary magnetizations of only volcanic rocks with ages no greater than 85 Ma.**

***Restored cross sections: Data from 90 cross sections were obtained from the geologic literature: locations, present lengths, restored lengths, uncertainties, and restoration ages.**

***Paleostress azimuths (σ_{1h}): 433 azimuths of most-compressive horizontal principal stress [many from *Bird,* 2002] were compiled with uncertainties, locations, and ages. Note that indicated azimuths are passively rotated during reconstruction. Due to the shortage of data, trace azimuths and rakes of active faults (already in our model) were also used as stress-direction indicators. Interpolation of stress directions to other points was by the algorithm of *Bird & Li* [1996].**

***Geologic Map of North America [*Reed et al.,* 2005; *Garrity & Soler,* 2009] was a "passive passenger" carried along during the reconstruction (as a set of vector-graphic objects) and displayed in output maps, but not directly influencing the calculation.**

ALGORITHM

Program RESTORE (v.4) is available at: http://peterbird.name/oldFTP/Restore/. Associated programs include ORBWIN for editing F-E grids, and RETROMAP (v.4) for plotting input & output files.

(1) The surface of the Earth in the model domain is covered by a F-E grid of ~20,800 nodes and ~41,200 spherical-triangle 2-D finite elements. Major faults are surrounded by narrow "fault corridors" of small elements, but there are no special "fault elements."

(2) All offsets (from the datasets listed above) are converted to rates, by dividing each offset by the length of the relevant time window for that datum. Offset uncertainties yield rate uncertainties.

(3) A weighted least-squares criterion is used to find the 2-D surface field of horizontal velocities that matches the datum rates as closely as possible, considering their uncertainties. This involves iterated solution of ~80,000 simultaneous linear equations, using 16-fold parallel processing.

(4) Extra terms added to these equations require that deformation of the crust between model faults is {a} minimized; and {b} approximately aligned with interpolated principal stress directions and senses.

(5) Boundary conditions are simple: Fixed zero displacement on the Eastern side; free on all others.

(6) Crustal velocities are multiplied by a timestep of 0.2 m.y. and applied as displacements to all datasets.

(7) The velocity calculation is repeated at the (older) end of each timestep to determine accelerations and apply a correction. (This is the "predictor/corrector" method of time-integration.)

(8) Whenever the F-E grid becomes too deformed, program RESTORE stops and requests manual intervention to re-draw deformed parts of the F-E grid. This was necessary about every 0.8 m.y..

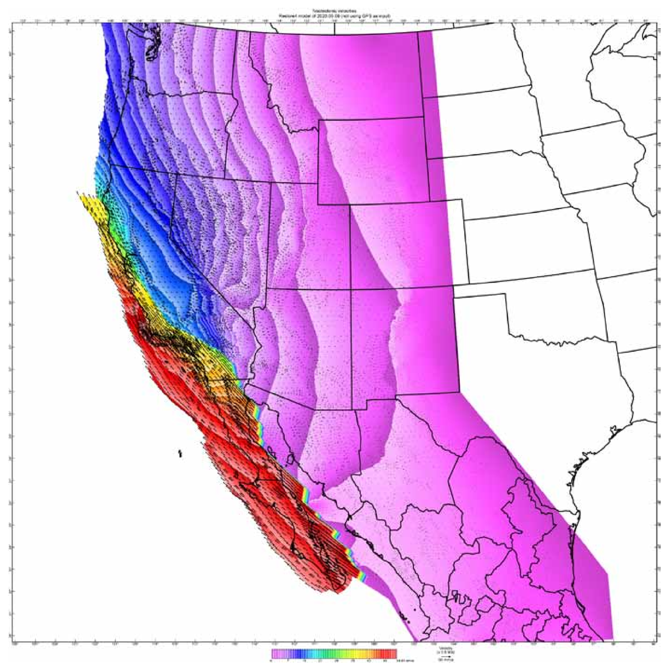
Relevance to SCEC objectives?

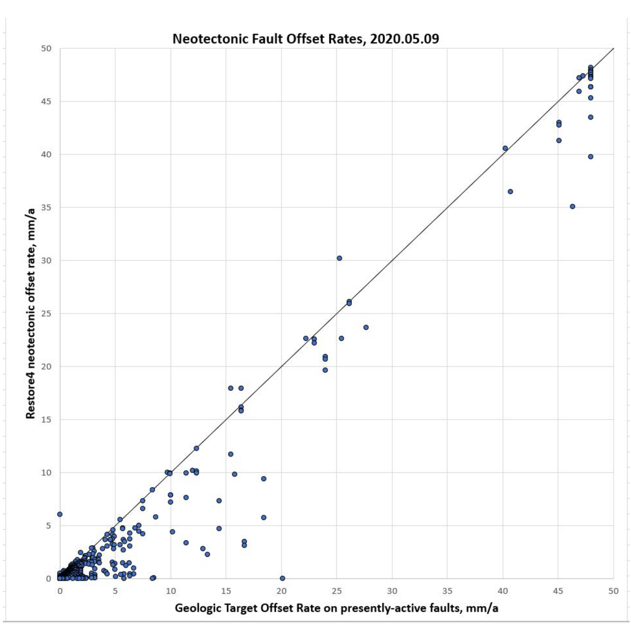
***Natural experiment in the natural laboratory: We can watch the fault systems evolve through time, as many faults rotated in opposite directions to stress fields, and components turned off and on!**

***Importance of "Off-fault" deformation: In southern California neotectonics, 1/3 of permanent strain is NOT on the major mapped & modeled faults [*Bird,* 2009]. Was this fraction higher in the geologic past? We will be able to provide detailed estimates through time.**

***Community Models: Current attempts to build a Community Thermal Model (CTM) and a Community Rheology Model (CRM) depend on a correct understanding of the tectonic and geologic history.**

NEOTECTONICS:





PALEOTECTONICS: