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Three Dimensional Fault Characterization for Southern California Regional Earthquake Likelihood Models

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The objective of the Regional Earthquake Likelihood Models (RELM) project is to explore the uncertainty bounds on seismic hazard estimation in southern California by examining the implications of different approaches to modeling seismic moment release in space and time. This report summarizes progress in developing a geological earthquake source model that captures alternative tectonic interpretations and 3D geometries of faults. Differences in the geometries, slip rates, and even the existence of potentially significant active faults arising from alternative viable interpretations of the available data remains a major source of uncertainty in source characterization that propagates through to broad uncertainty distributions on hazard estimates. This is particularly true for source characterization in the Los Angeles Basin (LAB), Ventura Basin and Santa Barbara Channel (SBC), and the remainder of the Continental Borderland (south of the Northern Channel Islands), where we are focussing our effort. In these (and other) areas, basement-involved "thin-skinned" tectonic models (e.g. Davis et al., 1989; Shaw and Suppe, 1994, 1996; Seeber and Sorlien, 2000) not only incorporate major active low-angle thrust and regional-scale detachment sources but also imply significantly different down-dip geometries, and hence seismogenic potential, for high-angle surface faults from those implied by "thick-skinned" models (e.g. Yeats, 1993; Huftile and Yeats, 1995, 1996).

We are developing the model through a series of workshops and meetings involving SCEC and other scientists whose research results can be used to define and evaluate the various alternative sources incorporated in the model. The project, therefore, serves an important integrative function of bringing together SCEC scientists to exhange and critically discuss the results of their research. This forum also enables future (SCEC II) research priorities to be identified and focussed. Construction of the geological source model is facilitated by using a 3D fault data base and associated 3D visualization software. The structure of the data base is still under discussion; although it will be integrated with the broader USGS/SCEC(RELM) southern California fault data base, we anticipate that in order to fully serve its purpose the 3D data base must be capable of accommodating a more extensive set of fault attributes (including, for example, detailed seismic reflection and well picks, and structure contours), other 3D data sets (such as seismic velocity and stratigraphy), and perhaps more extensive quality metadata than that included the broader data base. Both John Shaw and the UCSB group (Kamerling, Sorlien and Nicholson) are currently producing impressive 3D visualizations using GOCAD software, which can interface with a broad range of data bases.

The basic issues and current state of knowledge underlying the alternative fault interpretations, construction of the source model, and the data base and visualization were discussed at a small planning workshop on Oct. 6, 2000. The workshop focussed on the LAB and to a lesser extent on the Ventura Basin and SBC. A workshop summary can be found on the RELM web page, http://www.scec.org/research/RELM. The current state of knowledge discussed at the workshop is summarized below. (A larger workshop was held on the Continental Borderland on Jan. 30-31, 2001, but is not included in this report.)

We divided the faults in the LAB, Ventura Basin and SBC into two broad categories according to the following hierarchy of constraints: (1) Seismological, geological and geodetic observations of mainshock/aftershock sequences; (2) direct surface observations (mapping, trenching, etc.); (3) subsurface observations (well picks, reflection picks, seismicity, etc.); (4) modeling results (balanced cross-sections, map restoration, etc.). Faults in each category are listed in Appendix A. Category 1 faults are those for which there is direct evidence for activity (i.e. Constraints 1-3, above), and Category 2 contains more speculative sources, based largely on Constraints 3 and 4.

Los Angeles Basin

Much of the discussion of faulting within the LAB at the Oct. 6 workshop was facilitated by reference to a large-scale N-S seismic transect through the Basin constructed by John Shaw, together with 3D views of interpreted blind thrust/reverse faults under the northern Basin. There is general agreement among the groups working in the northern LAB that active folding there formerly attributed by Davis et al. (1989) and Shaw and Suppe (1996) to a regional-scale, NW-striking Elysian Park thrust ramp is actually driven by a series of shallower, W-striking blind thrust/reverse faults, some of which are considered to be sources of significant earthquake hazard. Therefore, there is little or no evidence to support present slip on the Elysian Park thrust ramp. Geomorphic evidence (Jim Dolan, personal communication) also suggests that the ramp (and the Santa Monica Mountains thrust to the west) is either inactive or slipping at a very slow rate.

In the integrated interpretation of Shaw and Suppe (1996), the Elysian Park ramp is connected to the NE-dipping Compton-Los Alamitos thrust ramp (CLAT) to the SW by a décollement under the central Basin. Interpretation of cone penetrometer test (CPT) penetrations of late Quaternary aquifers, trenching of late Holocene sediments and a digital elevation model by Karl Mueller and Tom Rockwell indicate that the CLAT (at least at its SE end) has not slipped since about 15 ka, and suggests that it has either been inactive since at least 15-20 ka or that has been slipping at a very low rate (0.24-0.36 mm/yr) since 330 ka. According to the décollement model, inactivity of the CLAT would also imply that the Elysian Park ramp is inactive. The reverse argument - that lack of evidence in the northern Basin for activity on the Elysian Park ramp implies that the CLAT is inactive - can also be made. However, Shaw and Suppe (1996) also proposed an alternative, equally viable interpretation in which the CLAT is the upper ramp of a northward-propagating thrust wedge, with no linkage to the Elysian Park ramp. In this interpretation, the question of the activity of the CLAT rests, at present, solely Mueller and Rockwell's data. Karl Mueller suggests that if the thrust is still active, then the apparent lack of slip over the last 15 ka may imply that, even at the low interpreted rate, it has accumulated sufficient strain to generate an M7+ earthquake. If the CLAT can be considered active, then the implications of it cross-cutting the Newport-Inglewood fault within the seismogenic crust need to be addressed, and specifically the mechanical viability of a vertically segmented fault capable of generating an earthquake at least as large as the 1933 M6.3 event. A preliminary sensitivity study in 1997 (Foxall 1997 SCEC Annual Report) suggested that the hazard in the LA area is particularly sensitive to segmentation of the Newport-Inglewood fault. This is also an important issue with respect to proposed low angle thrusts under the Inner Borderland.

Based on apparent progressive tilting of Quaternary strata above the Quaternary-Pliocene fold along the Compton-Los Alamitos trend, Chris Sorlien has proposed a listric model for active blind thrusting under the LAB. This listric fault is the eastern end of the mega-fault proposed by Seeber and Sorlien (2000) to underlay the entire length of the Santa Monica Mtns.-Channel Islands anticlinorium . Sorlien asserts that the activity of this listric fault would not be precluded by Mueller and Rockwell's interpretation.

Major differences remain in interpretation of the geometry and style of the Palos Verdes fault at depth. Shaw favors a vertical near-surface fault shallowing to about 45°SW dip , with oblique slip on the deeper plane partitioned to essentially pure strike-slip on the shallow Palos Verdes and dip-slip on separate reverse/thrust faults. Rockwell favors a subvertical Palos Verdes fault through the seismogenic thickness, and admits the possibility of separate thrust faults. A very preliminary interpretation by Bob Yeats and Chris Goldfinger of results from a mid-Oct., 2000 Oregon State University (OSU) cruise suggests that the Palos Verdes fault horsetails northwards under Santa Monica Bay into two thrusts near Redondo and Santa Monica Canyons, respectively, and does not continue to the north to intersect the Dume-Anacapa fault. They tentatively suggest the 3 mm/y slip rate can be consumed by thrusting.

Ventura Basin and Santa Barbara Channel

With the exception of Bob Yeats, there was a substantial measure of agreement among the participants of the Oct. 6 workshop on the probable existence of a N-dipping Channel Islands thrust under the SBC, although Shaw and Suppe (1994) and Seeber and Sorlien (2000) proposed this structure based on markedly different data interpretations. The slip rates estimated for the two models are similar, in the range 1.3-2.6 mm/yr. Shaw and Suppe's average rate is since ~3Ma. The Seeber and Sorlien rate is a tentative estimate since ~400ka for central-west Santa Cruz Island; the rate appears to die of rapidly to the east.

It is not clear how the south-vergent Channel Islands thrust relates to the north-vergent offshore Oak Ridge fault of Huftile and Yeats (1996) and the UCSB group (e.g., Sorlien et al., 2000; Sorlien and Kamerling, 1998, 2000). It seems that there is some convergence between the Shaw and Suppe (1994) and UCSB interpretations of the offshore Oak Ridge-Mid Channel/Blue Bottle structures. Characterization of the onshore Oak Ridge fault by Yeats and his colleagues (e.g. Yeats, 1988) is generally accepted. However, there are significant differences between their interpretation and that of Sorlien et al (2000) and Sorlien and Kamerling (1998, 2000) regarding the left-lateral rate on the NE-striking segment of the fault near the coast, in the mechanism and amount of slip transfer offshore, and in the activity of the shallow portion of the offshore fault.

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Appendix A: Fault Categories

See main text for explanation of categories.

Los Angeles Basin

<u>Category 1</u>

Cucamonga
Sierra Madre
Santa Susana
Northridge
Elsinore
Whittier
Palos Verdes
Newport-Inglewood
Malibu Coast[3]
San Jose
Raymond
Verdugo
Hollywood
Santa Monica
Chino
Puente Hills –Sa. Fe Springs seg./Carmenita[1]
San Gabriel

<u>Category 2</u>

Compton-Los Alamitos thrust
Elysian Park thrust ramp
Elysian Park fault (Oskin et al., 2000)
Las Cienagas
San Joaquin Hills thrust
San Vicente
Dume[2]
Listric LAB/Santa Monica Mtns. thrust
Coyote thrust

Ventura Basin & Santa Barbara Channel

<u>Category 1</u>

San Cayetano
Sisar-Lion Mtn.
Padre Juan
Oak Ridge – onshore
Simi
Red Mtn
N. Channel
Santa Cruz Is[3]
Santa Rosa Is.
Holser

<u>Category 2</u> (not complete):

Sulphur Mtn.
Del Valle
Channel Is. thrust
Pitas point
Offshore Oak Ridge – Mid Channel

Notes:

(1) Bob Yeats suggests that the western and eastern segments of the Shaw and Shearer (2000) Puente Hills thrust should be considered Category 2 sources, since only the central Santa Fe Springs segment is imaged directly.

(2) Yeats feels that the Dume fault should be considered Category 2, since he and Chris Goldfinger do not see a fault at the base of the continental slope in the seismic. Chris Sorlien's view is that the Dume fault is very ill defined; west of Pt. Dume it is associated with a large fold scarp but its surface expression further west is subdued. It is not clear whether east of Pt. Dume it can be connected with the Santa Monica fault at the coast. In his new mapping Sorlien has the Anacapa as a segment of the Malibu Coast-Santa Cruz Island fault (see Note (3)).

(3) It is unclear whether the Santa Cruz Island and Malibu Coast faults are continuous, or whether there is a left stepover between them. Based on seismic, Sorlien favors the former, while Yeats favors the latter, based on a somewhat more restricted data set. Eldon Gath has solid evidence for the activity of the Malibu Coast fault, but suggests that the fault is complex and that mapping of the currently active fault is incorrect .