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VERIFICATION OF PRECARIOUS ROCK EVIDENCE FOR LOW GROUND ACCELERATIONS ASSOCIATED WITH STRIKE-SLIP FAULTS IN EXTENSIONAL REGIMES

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ABSTRACT

We use precarious rock methodology for verification of evidence for low ground accelerations associated with extensional strike-slip faults. Recent evidence from physical and numerical models and data regressions has indicated that ground motion for extensional strike-slip regions may be lower than for strike-slip faults with a large fault-normal tectonic stress component, and for thrust faults in general. Data from compressional strike-slip and thrust earthquakes dominate the data base used in most regression curves for ground acceleration, and in the calculation of current probabilistic seismic hazard maps. Therefore, estimates of ground accelerations on these seismic hazard maps may be too high for sites near extensional sections of strike-slip faults. This report discusses precariously balanced rock data from two areas near extensional sections of strike-slip faulting: (1) the region of the Honey Lake fault, California, with an active Holocene fault, and (2) the region just south of Beaumont, California, near the Hemet dilatational step-over in the San Jacinto fault. These are active strike-slip faults, with at least a few large earthquakes in the Holocene, and, in the case of the San Jacinto example, historic large earthquakes (M~7). Thus the precarious rocks at these sites are evidence of relatively low ground motions associated with extensional strike-slip faulting. The results of this study could be very important in developing more detailed seismic hazard maps in the future.

INTRODUCTION

Many expanding population centers are exposed to ground shaking from extensional sections of strike-slip faults. There are few near-source rock site strong motion data for large strike-slip earthquakes in such regions, and thus hazard maps, like the recent USGS-CDMG Probablistic Seismic Hazard Analysis (PSHA) maps (Frankel et al., 1996), assume attenuation curves for ground motion obtained from regressions on a data base which is dominated by trans-compressional strike-slip and thrust faulting. Recent regressions of strong motion data from extensional regions suggest somewhat lower ground motions for strike-slip faulting in extensional regions (Spudich *et al*., 1997; 1999), but there is very little data from near-source rock sites, and thus there is a large uncertainty. The uncertainty arises in part because of lack of knowledge of the effect of shallow sediments on recordings. For example, much of the data from the 1979 Imperial Valley strike-slip earthquake, which dominates the Spudich et al. (1997, 1999) database, was for deep sedimentary sites. Thus regressions and seismic hazard maps using the current database may overestimate the rock site ground motion for many extensional locations.

Although preliminary precarious rock estimates of constraints on ground motion at sites considered here are consistent with observed rock site values from the recent M=7.4 Izmit, Turkey earthquake (Anderson *et al*., 2000a,b), they are considerably lower than values from regression curves used in USGS-CDMG hazard maps. They are also somewhat lower than the median values from regression curves for extensional regions (Spudich *et al*., 1997; 1999).

Recent evidence from physical and numerical models has indicated that ground motion from extensional strike-slip earthquakes may be much lower than for strike-slip faults with a large fault-normal tectonic stress component (Brune and Anooshehpoor, 1998; Oglesby *et al.*, 1998, 2000, Shi, 1999, Day and Ely, 2002). The Day and Ely study was a finite-difference simulation of the Brune and Anooshehpoor (1998) physical model, and gave very similar results.

One of the main physical reasons for expecting low accelerations from strike-slip faults in extensional regions is the fact that in extensional regions the fault normal component of stress on the fault must approach zero near the surface (because the lithostatic stress approaches zero and the tectonic stress is extensional; Brune and Anooshehpoor, 1998; McGarr *et al*., 2000). Thus relatively little strain energy can be stored up at shallow depth near the fault trace.

In this study we focus on precarious rocks near two areas of extensional strike-slip faulting, the Fort Sage mountains region near the Honey Lake fault, an active Holocene fault, and the Beaumont region near the San Jacinto fault at the northeast edge of Hemet Valley, California, active in Holocene and historic times. The Honey Lake fault is inferred to have at least four major events in Holocene with a cumulative offset of at least 16 m (Wills and Borchert, 1993) (The nearby Fort Sage Mountains normal fault was site of the 1950 M5.6 Fort Sage Mountain normal faulting earthquake, and thus the studies proposed here could also provide some information on attenuation curves and hazard from normal faults). The San Jacinto fault is one of the most active faults in southern California, and was the site of at least two large earthquakes (M7 on December 25, 1899, and M6.8 in 1918) (Sanders and Kanamori, 1984).

BRIEF DESCRIPTION OF PRECARIOUS ROCKS METHODOLOGY

Peak ground acceleration necessary to topple a precariously balanced rock (through rigid-body rocking motion) can provide constraints on ground motion at that site for seismic shaking in the past. (The time scale for evolution and stability of these rocks is of the order of thousands years.) We use a pseudo-3D finite difference method developed by Shi *et al.* (1996) to estimate the dynamic toppling acceleration of precarious rocks from the dimensions and the value of the quasi-static toppling accelerations obtained in the field. The quasi-static acceleration is given by the ratio of the quasi-static toppling force (defined as a horizontal force whose moment through the center of mass about the rocking point exactly counterbalances that of the gravity) and the mass of the rock. For a rigid body, the quasi-static overturning force for a small α (the angle between the vertical and the line through the center of mass of the rock and rocking point) has the simple form $F \approx m\alpha g$.

As a further validation of the methodology we also used the shake tables in the Large-Scale Structures Laboratory at the University of Nevada, Reno, to study the rocking motion of rocks of various sizes and aspect ratios. The results indicate that, for input motions with time history shapes of various typical earthquake records, the peak toppling ground acceleration is, on average, about 30% higher than the quasi-static toppling accelerations (Anooshehpoor et al., 2004).

RESULTS AND DISCUSSIONS

Precarious Rock Evidence from the Honey Lake Strike-slip Fault

A spectacular zone of precarious rocks exists in the Fort Sage mountains, near (2-7 km distance) the strike-slip Honey Lake Fault Zone, California (Fig. 1). This fault has been interpreted to be the locus of a total of 16m of offset in Holocene time, a result of a few to several major earthquakes, with at least one major event in the last several hundred years (Wills and Borcherdt, 1993). The adjacent Honey Lake Basin is a major extensional feature. The rocks are thus strong evidence for low ground accelerations from this major strike-slip fault zone in an extending region. The appearance and geomorphic conditions of the rocks indicates they have been in precarious positions for thousands of years. The examples shown in Fig. 2 are a selection from more than 50 such rocks in a relatively small region. Some of the rocks are only 1 or 2 km from the trace of the fault. Estimates of toppling accelerations are about 0.3 g. (The rock in Fig. 2a was inadvertently toppled during field test.) Based on current attenuation curves it would appear that these rocks would be shaken down by ground motion from either an M=6.5 event on the Honey Lake fault (or an M =6 on the Fort Sage Mountains normal fault). The USGS-CDMG hazard maps for this region indicate a very high hazard, with 2500-year recurrence accelerations (2% in 50 yr probabilities) of over 0.8 g (Intensity X). The rocks suggest upper limit constraints on ground motion which is inconsistent with these maps.

The nearby Fort Sage Mountains normal fault was the site of the 1950 M5.6 Fort Sage Mountain normal faulting earthquake, and thus these rocks also provide support for low ground motions on the footwall of normal faults, further complementing the results of Brune (1999).

Precarious Rock Evidence from the San Jacinto Fault at the Northeast End of Hemet Valley, Near Beaumont, California

Another zone of precarious rocks associated with an extensional strike-slip zone occurs near Beaumont, California, a few km from the active San Jacinto fault (Fig. 3). The San Jacinto fault is one of the most active faults in southern California, and was the site of at least two large earthquakes (M7 on December 25, 1899, and M6.8 in 1918, Rasmussen, 1981, 1982). This part of the San Jacinto fault is at the northeast end of Hemet Valley, a trans-tensional step-over basin associated with a right step in the San Jacinto fault, and near the northwest terminus of the rupture zone of the M=7 San Jacinto earthquake (Sanders and Kanamori, 1984). The San Jacinto fault is one of the most active in Southern California, with a slip rate of about 1 cm per year, and thus likely has produced several large earthquakes during the time period represented by the precarious rocks.

Measurements of the quasi-static toppling accelerations of a selected number of these rocks (Fig. 4) are listed in Table 1. The measured toppling accelerations provide constraints of about 0.4g on ground motion at a distance of 5-7 km, suggesting ground accelerations associated with the 1899 and 1918 M~7 extensional strike-slip earthquakes, somewhat lower than the median of recent regression curves (Fig. 5). Although these values are again consistent with accelerations recorded in the recent Izmit, Turkey earthquake (Anderson *et al*., 2000a,b), they are considerably lower than predicted by current regression curves for the historic M= 7.0 San Jacinto Fault earthquake, and much less than indicated for the region by the USGS-CDMG 2% in 50 yr hazard maps (about 0.5 g).

Implications of Data from the Recent Izmit, Turkey, Earthquake

As mentioned earlier, most current attenuation curves for large earthquakes at near distances are based on very little constraining data. In fact they are extrapolations from data from smaller earthquakes at larger distances, a data set dominated by thrust faults and strike-slip faults in compressional regimes. Thus it is questionable how accurate they are for extensional strike slip regimes. The first rock site data for a large strike-slip earthquake recorded at the distances comparable to the precarious rocks in this study was provided by the recent M=7.4 Izmit, Turkey, earthquake (the Lucerne record for the Landers earthquakes was at a closer distance). The accelerations recorded at the sites Sakarya and Izmit were 0.42g at a distance of 4 km, and 0.23g at a distance of 5 km respectively. These values are significantly lower (almost one standard deviation) than the median values predicted by recent attenuation curves, and thus cast the validity of these curves into some question (Anderson *et al*., 2000a,b). Of course, one earthquake does not provide a sufficient sample for final conclusions, but rather emphasizes the uncertainty associated with current attenuation curves.

The accelerations recorded at SKR and IZT are consistent with our preliminary estimates of constraints provided by precarious rocks near extensional strike-slip earthquakes. This brings up the suggestion that the section of the North Anatolian Fault near SKR and IZT may be an extensional strike-slip fault, or at least dominated by extensional step-overs in the fault, and thus in a geologic setting similar to those of the precarious rocks discussed in this study. The earthquake occurred at the edge of the Sea of Marmara, which has the appearance of an extensional basin. Lettis et al. (2000) documented a series of step-over basins along the trace of the Anatolian fault which ruptured in the two 1999 earthquakes. These step-over basins look very similar to the San Jacinto fault and Garlock fault step-over basins discussed above. Seeber et al. (2000) operated a network of strong motion instruments after the 17 August 1999 earthquake and fortuitously recorded the M=7.2 12 November 1999 earthquake at a site of one of the step-over basins documented by Lettis et al. (2000), a site only about 100 meters from a step-over normal fault with over 2 meters displacement. The recorded ground acceleration was only about 0.1 g, a remarkably low value considering the fact that the station was located so near a large normal fault scarp, and that it was also less than 10 km from the strike-slip portions of the Anatolian fault which slipped in the M=7.2 earthquake. The Seeber et al. (2000) observation supports the propositions that (1) the footwall of normal faults have very low ground acceleration as proposed from previous precarious rock studies (Brune, 2000), and (2) that trans-tensional step-over regions of strike-slip faults have relatively low accelerations, as suggested in this study.

CONCLUSIONS

This report has presented precarious rock evidence for low ground motions associated with two extensional sections of strike-slip faults. The results support recent evidence from physical and numerical models, and data regressions, indicating that ground motion for extensional strike-slip regions may be lower than for strike-slip faults with a large fault-normal tectonic stress component. Estimates of ground accelerations on some current seismic hazard maps may be too high for sites near extensional sections of strike-slip faults. The results of this study could be very important in developing more detailed seismic hazard maps in the future.

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Table 1. List of measured parameters for selected precarious rocks near Beaumont, California.

Rock ID	Location	α_1	α_2	R_1 (cm)	R_2 (cm)	Toppling Azimuth
SJ01	33.8974, -117.0048	0.75	0.35	92	73	130
SJ02	33.8967, -117.0060	0.30	0.44	79	65	300
SJ03	33.9040, -116.9911	0.31	0.37	33	44	230
SJ04	33.9057, -116.9909	0.31	0.26	64	64	170
SJ05	33.9045, -116.9903	0.26	0.33	42	48	240
SJ06	33.8989, -116.9848	0.16	0.30	99	92	225
SJ07	33.8975, -116.9860	0.44	0.49	125	125	240

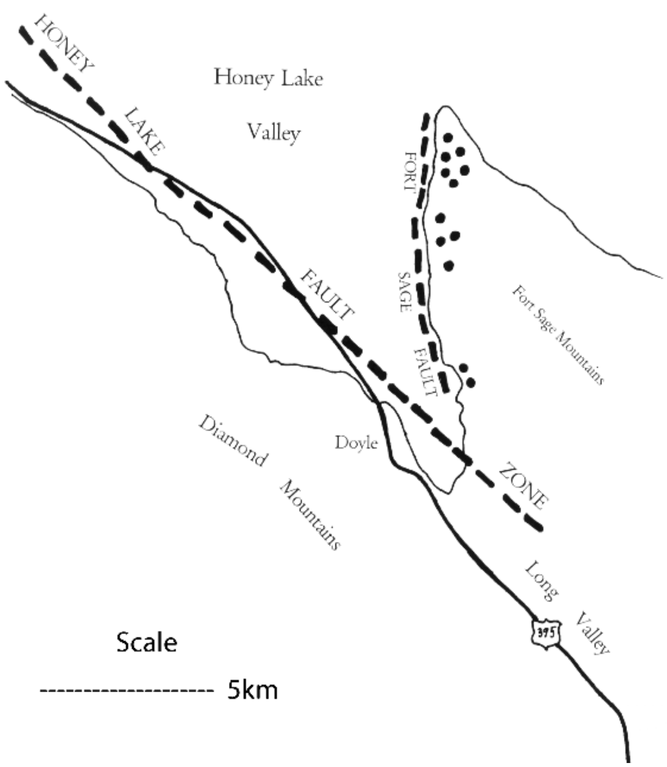

Figure 1: Honey Lake –Fort Sage Mountain fault zone in northern California. Black dots indicate approximate locations of precarious rocks.

Figure 2. Examples of precarious rocks in Honey Lake area.

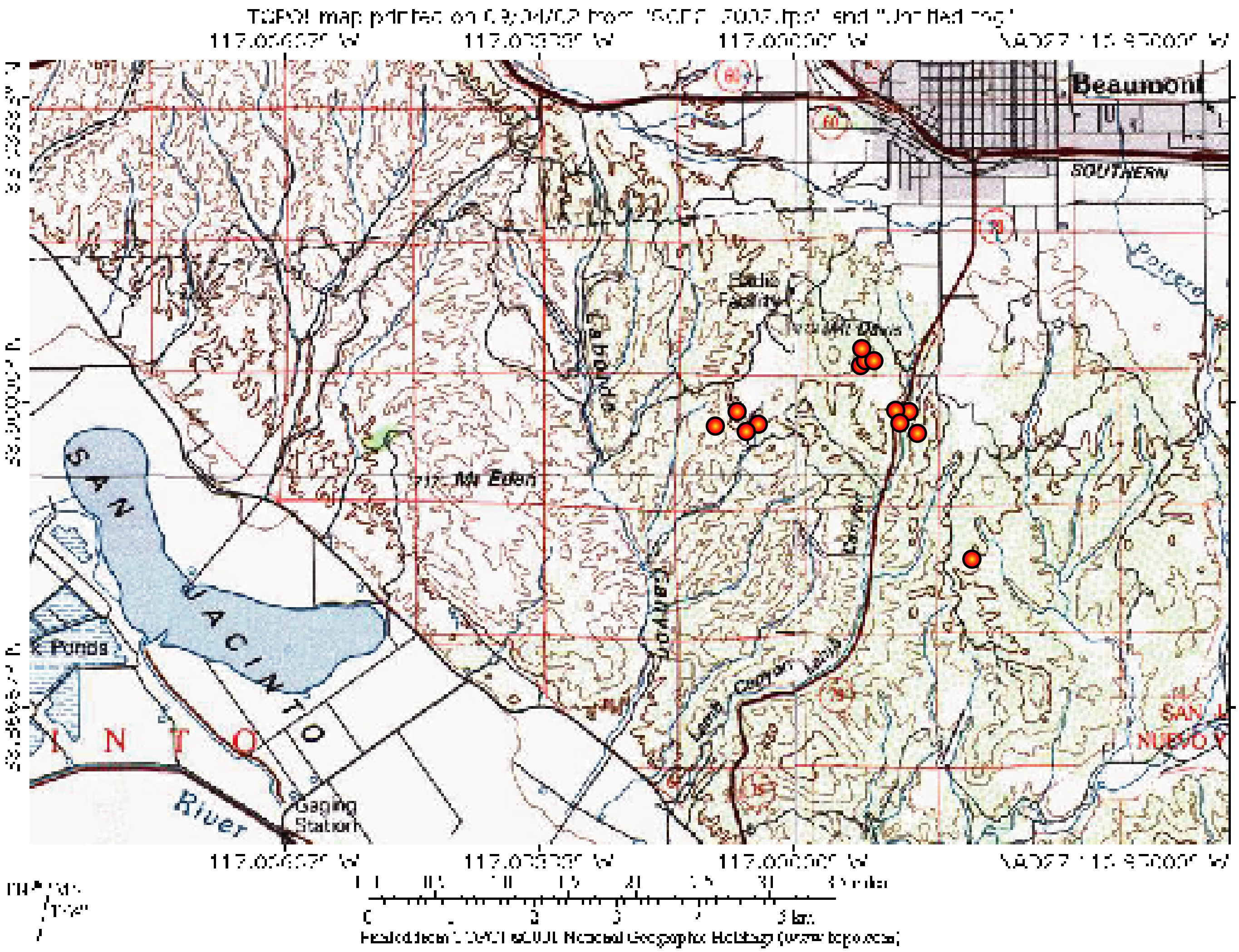

Figure 3. Map showing the location of surveyed precarious rocks near san Jacinto Fault in southern California, about . These rocks are about 5-7 km from the fault that produced 1899 and 1918 M~7 earthquakes.

Figure 4. Photographs of four precarious rocks near Beaumont, California. Rocks SJ01 and SJ02 are about 5 km from the fault. Rocks SJ06 and SJ07 are slightly farther, at about 7 km.

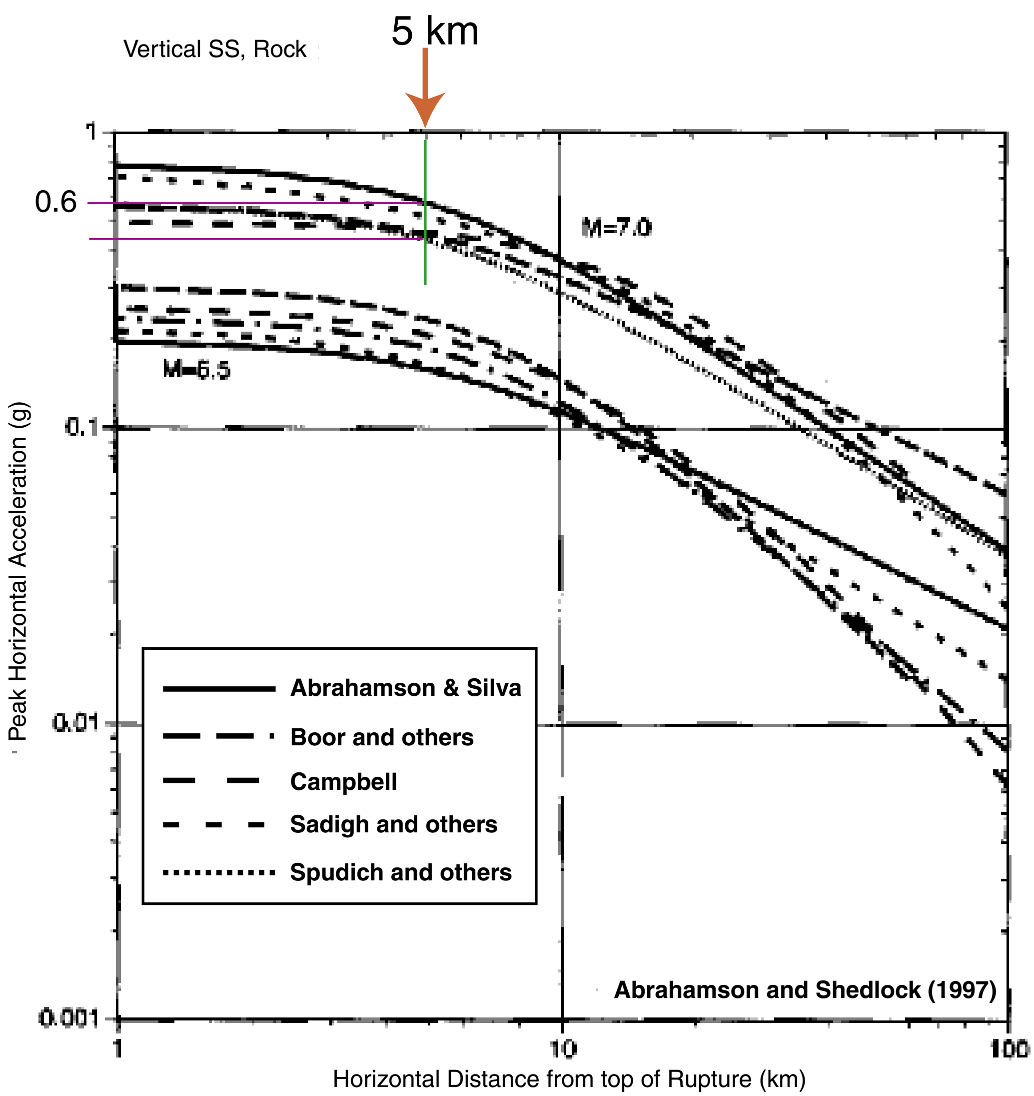

Figure 5. The measured toppling accelerations provide constraints of about 0.4g on ground motion at a distance of 5-7 km, suggesting ground accelerations associated with the 1899 and 1918 M~7 extensional strike-slip earthquakes, somewhat lower than the median of recent regression curves.