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**Constraints on Source Parameters for Great Earthquakes Provided by
Precarious Rocks in the Mojave Desert and San Gabriel Mountains**

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Technical Description

Great earthquakes along the San Andreas Fault and associated branch faults represent one the most important sources of hazard in California. Until the recent Izmit, Turkey, earthquake there have been no near-source on-scale recordings of such great earthquakes (the two great earthquakes, Fort Tejon, 1857, and San Francisco, 1906, occurred before modern strong motion instruments were deployed). Thus there are few data to constrain source parameters (use of Intensity data is very questionable). Most recent studies have relied on questionable extrapolations from smaller earthquakes, often not on the San Andreas Fault System. Scaling from smaller earthquakes and using off-fault earthquakes is questionable from a physical point of view, since scaling laws have not been established, and there are good reasons why large earthquakes might have different source parameters than smaller earthquakes (e.g. changing role of inertial terms and complexity), and why off fault earthquakes might have different source characteristics (e.g., different width of gouge, different healing states, different stress level). In fact, the rock-site accelerograms from the Izmit earthquake give values about one-half the predicted values in recent regressions(extrapolations) in the literature. Until this difference is understood there will remain serious questions about the validity of these regressions. For these reasons determining physical source parameters for great earthquakes along the San Andreas fault, while perhaps very difficult, is nevertheless of critical importance to understanding earthquake source physics and seismic hazard.

Precarious rocks are effectively upper-limit strong motion seismoscopes that have been in place thousands of years, thus providing upper limit bounds on the ground motion and associated source parameters appropriate for great earthquakes that have occurred on nearby faults. In the Mojave

Desert near Palmdale, and in the adjacent San Gabriel mountains, testable precarious rocks exist at distances of 15-35 km from the nearby San Andreas Fault, which has generated about 75 great earthquakes during the time the rocks have been in place. Thus the precarious rocks can provide an important constraint on source parameters of these great earthquakes. A preliminary estimate of the ground motion that would topple the rocks at a distance of 15 km is about 0.4 g (for a waveform appropriate for a great earthquake, e.g., with a response spectra similar in shape to that for the El Centro, 1949, earthquake, or similar to that implied by the recent USGS-CDMG hazard maps, Brune, 1999). This toppling acceleration estimate decreases to about 0.25 g at a distance of 35 km. In a concurrent study funded by SCEC we have further verified these preliminary estimates (Anooshepoor and Brune, SCEC 1999 annual meeting abstract).

In 1999 we proposed to investigate ranges of various source parameters and associated waveforms for great earthquakes which are consistent with our preliminary estimates of ground motion. Parameters in modern models of earthquake motion include:

- M_0 Seismic Moment (or Moment Magnitude)
- σ_s Static Stress Drop
- σ_d Dynamic Stress Drop (or Subevent Stress Drop)
- V_R Rupture Velocity
- r_s Radius of Largest Subevent (Composite Models)
- Earth Structure (For Green's Functions)
- Fault Geometry (Length, Width, Dip, Hypocenter)

Each of these parameters can play an important role in relating ground motion to the source physical parameterization. We considered reasonable ranges of the various source parameters which are consistent with levels of ground motion bounded by the precarious rock data. We assumed the total slip for great earthquakes gives an estimate of the seismic moment, which constrains the very long period spectrum of the seismograms. The next step is to choose various other source parameters such that the waveforms are consistent with the ground motion limits, e.g., dynamic stress drop (slip rise-time), rupture velocity, source complexity (asperity distribution). We used both simple half space models (2-D and 3-D) and layered models with calculated Green's functions for assumed velocity and attenuation structures. We estimated site effects from preliminary studies of precarious rock sites in S. California, and from an unpublished refraction study near Lovejoy Buttes by Gary Fuis (personal communication).

Assuming 10 m slip for the great earthquakes, ground motions for smooth, steady state rupture models are generally consistent with the precarious rock constraints unless the rupture velocities are forced to be nearly equal to the shear wave velocity in the crust (> 95%, which we think unlikely). We have verified this for both the steady-state model in a half-space (Anderson and Luco, 19xx) and the steady-state model in a layered model (Mendez and Luco, 19xx). Thus we conclude that the precarious

rocks are completely consistent with the low values of ground motion predicted by smooth rupture models in general. Given this, the precarious rocks provide a useful constraint only on the rupture complexity and rupture velocity, and on the associated high frequency model source parameters, e.g., dynamic stress drop (rise time), rupture velocity, and total energy release,-- parameters of critical importance to understanding the physics of the rupture process as well as seismic hazard.

Preliminary calculations for assumed dynamic stress-drop (sub-event or asperity stress-drop), rupture velocities, apparent stress, and total energy release, combined with constraints from heat flow measurements, lead to upper-limit constraints on dynamic stress drop (and apparent stress) as well as absolute stress. For the Zeng et al., (1994) complex source model the dynamic stress drop is less than about 75 bars (given current common interpretations of heat flow data along the San Andreas fault, this would imply absolute stresses less than 275 bars). However, this estimate is critically dependent on particular assumed values of other parameters listed above.

Our conclusions resulting from the studies carried out in 1999 are illustrated in Figure 1. In this figure several curves are shown to illustrate the effect of assumed dynamic stress drop in the composite model. About 30 different random value realizations of the model were carried out for each value of dynamic stress-drop. The response spectral values given in the figure correspond to typical median values.

Also shown are curves corresponding to the “standard” El Centro accelerogram used in many engineering design studies, and a similar response spectrum corresponding to the 2% in 50 yr spectrum values given in the recent USGS-CDMG hazard maps for the Lovejoy Buttes site. As can be seen from this figure the composite model response spectra consistent with the precarious rock data(lower curve, PGA about 0.4g) correspond to a dynamic(asperity) stress-drop of about 75 bars. In order to increase the spectrum to the values for the USGS-CDMG maps we need to increase the dynamic stress drop to about 100 bars. At this level the peak acceleration and response spectral values are no longer consistent with the precarious rock data(i.e., such seismograms would topple the rocks at Lovejoy Buttes). Thus the precarious rocks have the potential of providing bounds on the dynamic stress-drop modeling parameter for the last 75 earthquakes along the San Andreas fault, and this result in turn will have an important bearing on our understanding of fault physics.

Also shown in Fig. 1 are response spectral values at long periods from recent models of long period waves generated by earthquakes on the San Andreas fault by Olson et al.(1998?) and Graves(1999?), using finite element models. Predicted values at Lovejoy Buttes were provided by Olson(personal communication) and Graves(personal communication). The precarious rocks do not provide any constraint on ground motion values at such long periods, but the points show that if the response spectra are extrapolated to shorter periods assuming the same spectral shape as for the other curves, the values at high frequencies would be too high to be consistent with the precarious rock data. Thus the models are either giving too high values or the shape of the response spectra is different. This

illustrates the importance of the precarious rock data in providing constraints on the high frequency ground motion, and on the source model parameters which control high frequency ground motion.

The calculations for Fig. 1 assumed a layered structure for the Mojave desert provided by Gary Fuis(personal communication). The model used had a 100 foot thick low velocity weathered layer which amplified the peak acceleration values by about 30 %. The calculations also assumed typical Southern California attenuation and site effects(κ) values. It is not certain whether or not these values apply exactly to the Lovejoy Buttes precarious rock site, but we are carrying out a short refraction study as well as a site effects study to verify this(funded under separate SCEC projects). We operated high dynamic range digital seismographs at Lovejoy Buttes during the LARSE II passive experiment, as well as during the active experiment in Oct, 1999, and have also recorded several small events from the nearby section of the San Andreas Fault for use as Green's functions and constraints on attenuation and κ . The results should be available at the beginning of next years research.

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Figure Caption

FIGURE 1. Comparing various spectral acceleration curves for earthquakes of about $M=8$ and a distance of 15 km. The approximate precarious rock constraint for Lovejoy Buttes, Calif., is indicated by the median curve of Abrahamson and Silva, 1997, -the smooth green line. The blue smooth line corresponds to values obtained from the recent USGS-CDMG hazard maps for a probability of 2% in 50 years (average repeat time 2500 yrs). The lower irregular red line corresponds to a typical median spectrum for the composite source model of Zeng et al. (1994) for a magnitude of 7.9 and a dynamic (asperity) stress drop of 75 bars. The upper irregular purple line corresponds to the same model, but with twice the moment and a dynamic (asperity) stress drop of 100 bars, parameters chosen to raise the spectrum to approximately the level of the USGS-CDMG curve. The ground motions corresponding to this curve (and the USGS-CDMG curve) would topple the rocks at Lovejoy Buttes, i.e., are inconsistent with the precarious rock data. The dots at periods of 2-4 seconds period correspond to long period spectral values from recent finite element calculations of ground motion by Olsen et al. (1998-green dot) and Graves (1998-blue dots), and a value for the steady state model of Luco and Anderson (1983-red dot). These points are plotted to indicate that if spectral curves are estimated from these points by extending to shorter periods assuming the same general shape as for the other spectral shapes in the figure, the values at shorter periods would be too high to be consistent with the precarious rock data.

- Average Composite Source Model (Zeng et al., 1994), $M=7.9$, $\Delta\sigma_d = 75$ bars
- USGS/CDMG 2% in 50 YRS
- $M=8$, $d=15$, Abrahamson and Silva (1997)
- Average Composite Source Model, with Moment Twice of the Previous Case and $\Delta\sigma_d = 100$ bars
- Olsen et al. (1998), $M=7.75$
- Graves (1998), $M=7.75$
- Anderson and Luco (1983), Steady State, 10m

