

Annual Report, 1999

In "Rethinking Earthquake Prediction" Sykes, Shaw and Scholz (1999) re-examine and summarize what is now possible in predicting earthquakes, what might be accomplished in a few decades (given major efforts in monitoring and analysis), and what is likely to be inherently impossible based on our understanding of earthquakes as complex phenomena. We take predictions to involve a variety of time scales from seconds to a few decades. Earthquake warnings, their physical bases, likelihood (or not) of success and their possible societal uses differ for those time scales. Earthquake prediction should not be equated solely with short-term prediction--those with time scales of hours to weeks--nor should it be assumed that only short-term warnings either are or might be useful to society. A variety of "consumers" or stakeholders are likely to take different mitigation measures in response to each type of prediction.

A series of recent articles claim that earthquakes cannot be predicted and that exceedingly high accuracy is needed for predictions to be of societal value. We dispute a number of their key assumptions and conclusions, including their claim that earthquakes represent a self-organized critical (SOC) phenomenon, implying a system maintained on the edge of chaotic behavior at all times. We think this is correct but only in an uninteresting way, that is on global or continental scales. The stresses in the regions surrounding the rupture zones of individual large earthquakes are reduced below a SOC state at the times of those events and remain so for long periods. As stresses are slowly re-established by tectonic loading, a region approaches a SOC state during the last part of the cycle of large earthquakes. The presence of that state can be regarded as a long-term precursor rather than as an impediment to prediction. We examine other natural processes such as volcanic eruptions and climate change that, like earthquakes, are also examples of complex processes, each with its own predictable, possibly predictable and inherently unpredictable elements. That a natural system is complex does not mean that predictions are not possible for some spatial, temporal and size regimes. Long-term, and perhaps intermediate-term, predictions for large earthquakes appear to be possible for very active fault segments. Predicting large events more than one cycle into the future appears to be inherently difficult, if not impossible since much of the non-linearity in the earthquake process occurs at or near the time of large events. Progress in earthquake science and prediction over the next few decades will require increased monitoring in several active areas. We draw upon several examples of changes in the occurrence of moderate-size earthquakes and the evolution of stresses in California prior to large shocks on time scales of a few decades.

The analogy of grains of sand being added slowly to a sandpile (Fig. 1) has been used as an example of self-organized critical processes. For large earthquakes, as for large avalanches on a sandpile, it is important to distinguish regional and global effects. Large sand avalanches can

occur at various azimuths on the pile at any time (a "global" effect). Nevertheless, once a large slide occurs at a given azimuth on the sandpile (Fig. 1b) a long time is needed to restore that segment to the angle of repose through the slow addition of grains from above such that a large avalanche can reoccur at the same place. Small avalanches (Fig. 1c) affect only a small part of the slope at that azimuth. Large to great shocks along a major fault are akin to large avalanches along a given azimuth of the sandpile (Fig. 1b). This effect can be seen in the pattern of earthquakes in the greater San Francisco Bay area. A broad neighboring area in which stresses were lowered in the 1906 earthquake was very quiet for events of $M \geq 5$ for about 70 years after 1906. Shocks of that size were about 10 times more numerous from 1883 to 1906. Thus, the greater Bay area can be regarded as being at or close to a SOC state from 1883 to 1906 as manifested by the frequent occurrence of moderate to large earthquakes with a b-value close to 1.0, in analogy with the sandpile in Fig. 1d. Most of the Bay area was dropped below a SOC state for decades after 1906 akin to the azimuth of the sandpile in Fig. 1b that recently experienced a large avalanche.

Jaumé and Sykes (1999) summarize data on increases in the frequency of occurrence of moderate-size shocks and accelerating seismic moment release prior to large and great earthquakes including a number of examples from California. They find that the rate of moderate-size events in the Bay area since 1990 has returned to the low values for the period 1910 to 1975. Du and Sykes (2000) examined changes in the rates of moderate-size earthquakes before and after the 1992 Landers event. While moderate activity increased in the 10 years prior to Landers at distances of 80 to 160 km, no significant change occurred within 80 km, leaving us doubtful if the increase at larger distance was, in fact, precursory to Landers. Increases, such as those preceding the 1948 Desert Hot Springs and 1989 Loma Prieta events, were found, however, in the vicinity of faults of high long-term slip rate. The failure to find such changes close in during the decades before Landers is in accord with the idea that tectonic stress built up very slowly along that slow-moving fault. The increases at larger distance as well as the occurrence of the Landers sequence and the 1999 Hector Mines event may instead represent a regional buildup to a future great earthquake along the southern San Andreas fault.

Static stress changes can affect the occurrence of shocks of all sizes by moving nearby faults either closer to or farther from failure (e. g. Deng and Sykes, 1997*a, b*). While the Coulomb stress model has been used mainly for locked faults, Du and Sykes (in preparation) are applying static changes in stress and the rate and state-variable friction model to shallow creeping parts of faults. Figs. 2 and 3 show calculated changes in shear, normal and Coulomb stresses caused by the 1968 Borrego Mountain and 1979 Imperial Valley events. Many of the fault segments that crept aseismically after these and other large California events were moved closer to failure in terms of Coulomb stress. We are trying to ascertain the relative importance of dynamic and static stress changes in triggering fault creep.

Publications 1999-2000

Sykes, L. R., B. E. Shaw and C. H. Scholz, Rethinking Earthquake Prediction, Pure and Applied Geophys., 155, 207-232, 1999. SCEC # 467.

Jaumé, S. C. And Sykes, L. R., Evolving toward a critical point: a review of accelerating seismic moment/energy release prior to large and great earthquakes, Pure and Applied Geophys., 155, 279-305, 1999. SCEC # 468.

Du, W. X. and L. R. Sykes, Changes in frequency of moderate-size earthquakes and coulomb failure stress before and after the Landers, California, earthquake of 1992, to be submitted to Bull Seismol. Soc. Amer., March 2000.

Du, W. X. and L. R. Sykes, Triggered aseismic fault movements from earthquakes: static or dynamic effect?, in preparation, 2000.

Selected Previous Publications from a Total of 10 Supported by SCEC

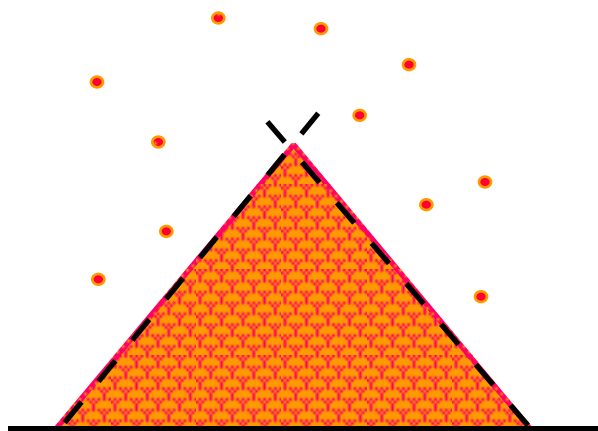
Deng, J., and L. R. Sykes, Evolution of the stress field in southern California and triggering of moderate-size earthquakes: a 200-year perspective, J. Geophys. Res., 102, 9859-9886, 1997a.

Deng, J., and L. R. Sykes, Stress evolution in southern California and triggering of moderate, small, and micro earthquakes, J. Geophys. Res., 102, 24,411-24435, 1997b.

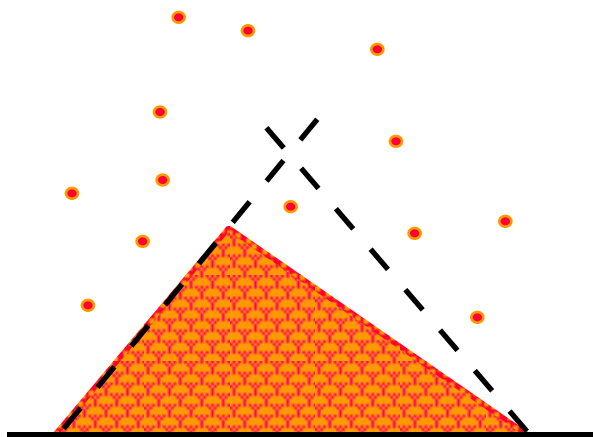
Sykes, L.R., Intermediate and Long Term Earthquake Prediction, in Earthquake Prediction: The Scientific Challenge, Proc. Nat. Acad. Sci. USA, 93, 3732-3739, 1996.

Caption for Fig. 1 on Page 4 (Next Page)

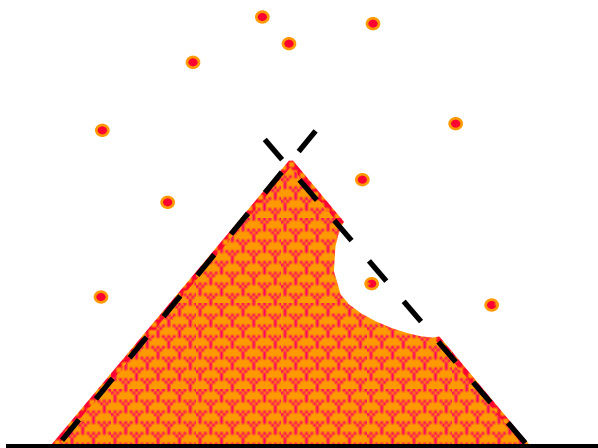
Grains of sand (small dots) being added slowly to a sandpile. a) All sides of sandpile have reached angle of repose whereby additions of sand result in instabilities, i.e. avalanches, of various sizes. b) A large avalanche has taken place along one small range of azimuths of pile taking that zone out of a self-organized critical state and incapable of being the site of a large avalanche for a long time (until grains of sand are added to it to bring its slope back to the angle of repose; large avalanches can still occur at any time along other azimuths. c) A small avalanche occurs along one azimuth but does not affect its entire downdip slope; small avalanches can still occur along other portions of slope either up or down dip of that small avalanche. d) moderate-size avalanches occur as a given azimuth approaches or reaches a state of instability prior to a large avalanche.



a



b



c



d

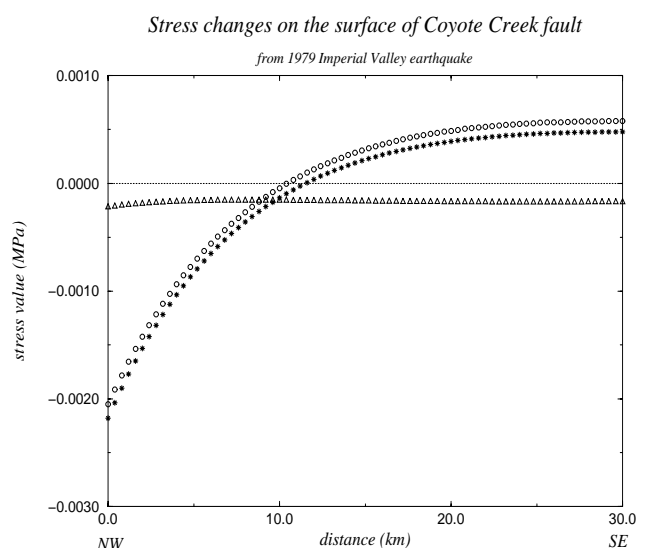
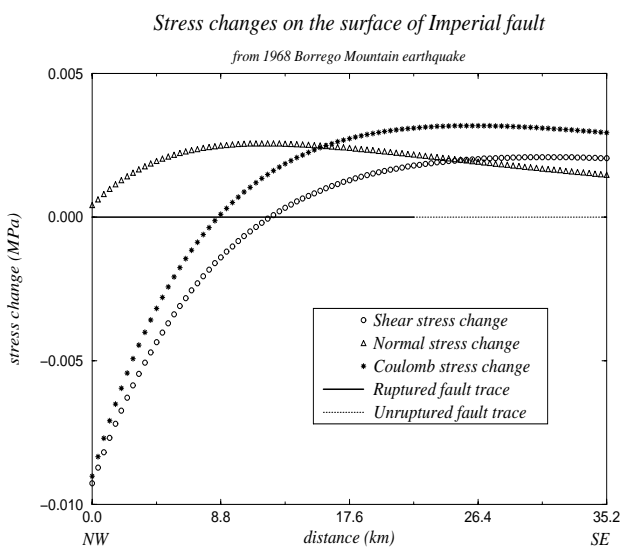
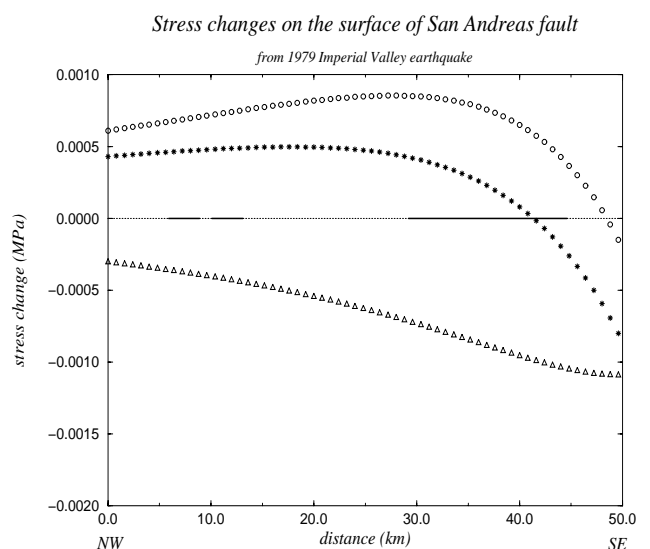
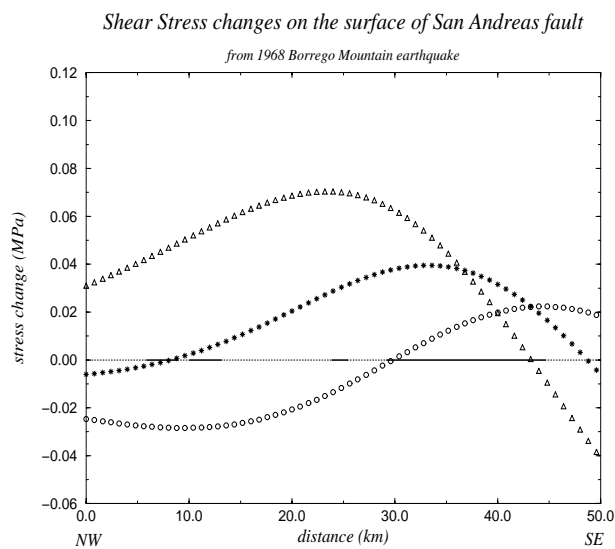
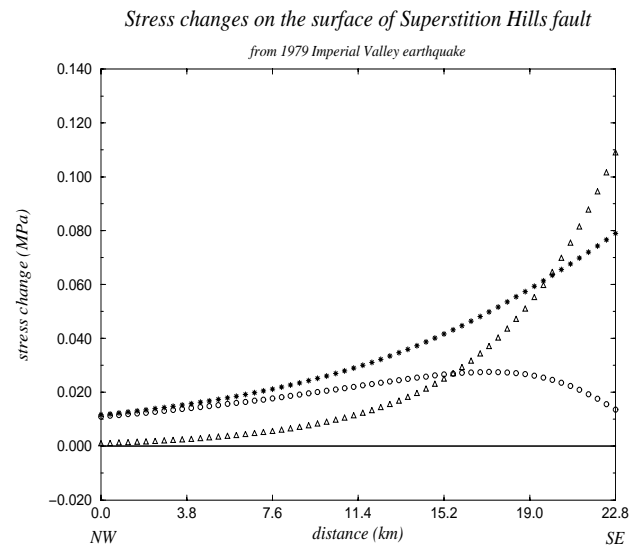
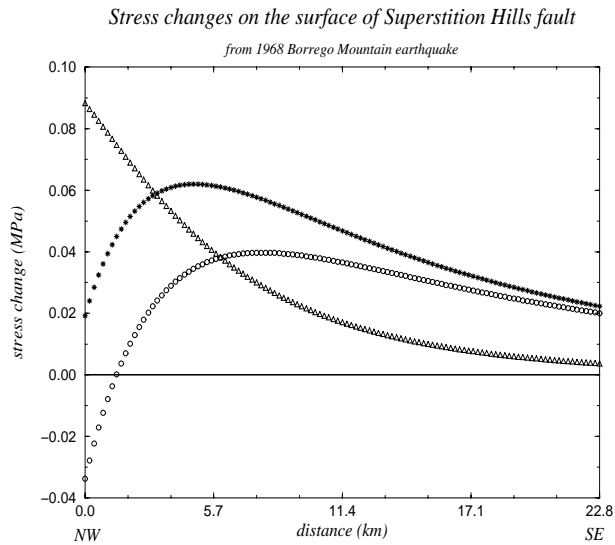


Figure 2. The static stress changes associated with the Borrego Mountain earthquake are resolved for the whole Superstition Hills fault, southernmost 50 km of the San Andreas fault and northernmost 35.2 km of the Imperial fault at depth of 0.5 km.

Figure 3. The static stress changes associated with the Imperial Valley earthquake are resolved for the whole Superstition Hills fault, southernmost 50 km of the San Andreas fault and Coyote Creek fault at depth of 0.5 km.