

# Paleoseismology: Why can't earthquakes keep on schedule?

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Our neighbors and the media ask us when the next large earthquake is due. In our response, we follow Shakespeare: "what's past is prologue." But projecting the past into the future is tricky because earthquakes, unlike tides and Halley's comet, don't follow a regular schedule, as shown by 1) the earliest multiple-event paleoseismological studies at Pallett Creek on the San Andreas fault (Sieh, 1978), 2) trenching studies on the Wasatch fault (Machette et al., 1992) and elsewhere, and 3) analysis of a 50,000-yr-long record of lake sediments in the Dead Sea graben (Marco et al., 1996). Lack of periodic behavior in earthquakes should not surprise us because Earth's crust is complicated, with many unknowns at depths where we cannot observe directly. But, like volcanism and changes in sea level, there ought to be broad geological patterns that can help us improve our ability to assess seismic hazards.

Seismicity variations are measured at different time scales, with the shortest being the decay in aftershocks after a major earthquake, following Omori's Law. Earthquake-generated changes in Coulomb failure stress (King et al., 1994; Stein, 2003; Lin and Stein, 2004) on individual faults or fault networks follow a slightly longer time scale of decades, with examples including the progression of earthquakes from east to west along the North Anatolian fault of Turkey from 1939 to 1999 (Stein et al., 1997; Barka et al., 2002) and the east-to-west progression of earthquakes on the North Tabriz fault, Iran, from 1721 to 1786 (Berberian and Yeats, 1999). In the San Francisco Bay area, the 75 yr before the great earthquake of 1906 were unusually active, whereas the next 75 yr were quiet, as if the 1906 earthquake cast a stress shadow over the entire region, from which it is only now (maybe) emerging. The great 1857 Fort Tejon earthquake produced a similar stress shadow in Southern California (Harris and Simpson, 1996).

These short-term variations could be very hard to work out in the prehistoric record, in part because of the uncertainties in late Quaternary dating techniques (for a reality check, see Noller et al., 2000). Furthermore, one rarely "dates" a rupture event, but instead brackets the event between the youngest sediments deformed along a fault and the oldest sediments not deformed (McCalpin, 1996; Yeats and Prentice, 1996). Large earthquakes that nucleated near the brittle-plastic transition, such as the 1977  $M$  7.4 Cauçete (Argentina), the 1989  $M$  6.9 Loma Prieta (California), and the 2001  $M$  7.6 Bhuj (India) earthquakes have relatively little surface expression, and might have been missed if those earthquakes had occurred thousands of years ago. Paleoseismology doesn't "see" all the big earthquakes.

A few decades ago, it was believed that if we knew plate tectonic rates, the slip rates of different faults within a diffuse plate boundary region would add up to the plate rate. However, as seismic networks improved in quality, it became clear that high seismicity does not necessarily equate to high slip rate based on geology. The Cascadia Subduction Zone has almost zero seismicity on the plate boundary. Much of the 1906 rupture zone of the San Andreas fault has low seismicity, and part of the Carrizo Plain has virtually zero seismicity on the 1857 Fort Tejon rupture. In the Ventura Basin, Southern California, the high-slip-rate Oak Ridge and San Cayetano faults have very low seismicity. Outside the United States, the Salt Range thrust–Potwar Plateau of Pakistan and the active reverse faults of central Otago, New Zealand, have few microearthquakes.

A comparison between slip rates based on geology and rates based on geodesy shows a similar lack of agreement. As summarized by Dolan

et al. (this issue, p. 855), the slip rate on the western part of the Garlock fault (California), based on geodesy is nearly half the rate based on late Quaternary geology. On the other hand, the geodetically based slip rate across the eastern California shear zone (ECSZ) in the Mojave Desert is close to twice the rate based on late Quaternary geology. Weldon et al. (2004) have shown that the long-term slip rate on the San Andreas fault at Wrightwood is considerably faster than the geodetic rate there, although the geodetic rate is in agreement with the geologically determined rate for the past 1100 yr.

How does one take these observations to the next level to improve long-range forecasting? Two events made the study by Dolan et al. possible. One was the establishment of the Southern California Earthquake Center (SCEC), which has as a major objective the understanding of fault networks beneath and around the Los Angeles Basin, where millions of people live in harm's way. Studying these faults has been a slow process because so much of Los Angeles is covered by houses, shopping malls, freeways, and uncooperative property owners that paleoseismic sites are few and far between. However, due to a concentration of effort, including work by James Dolan and his students, considerable progress has been made in Los Angeles, as summarized in the GSA Data Repository accompanying Dolan et al.'s paper.

The second event was an earthquake of  $M$  7.3 in 1992 in an unexpected place: the ECSZ in the Mojave Desert, unexpected because the long-term slip rate on faults in this area, aside from the San Andreas and Garlock faults, was known to be slow. Perhaps this earthquake should not have been such a surprise, though, because of a sequence of earthquakes beginning with the 1947 Manix earthquake of  $M$  6.2, followed by a southward-migrating progression of smaller earthquakes in 1965, 1975, and 1979. These were followed by several small events in early 1992, the largest of  $M$  6.1, close to a section of the San Andreas fault that had not sustained an earthquake in more than 300 yr. But instead of an earthquake on the San Andreas fault, as many expected, a group of faults ruptured along the ECSZ.

Unlike Los Angeles, the ECSZ has plenty of paleoseismic trench sites, and the SCEC expanded its mission to support trenches not only on the 1992 ruptures but also on other active faults that did not rupture in 1992, with many of these trenches excavated by Tom Rockwell and his students. This led to a paper by Rockwell et al. (2000) explaining the large number of earthquakes in a region characterized by low slip rates. The ECSZ is in the middle of an earthquake cluster, with earlier clusters in the middle Holocene (4.5–6.5 ka) and early Holocene (8.5–9 ka). This showed that the present earthquake hazard is higher in the ECSZ than the long-term average. ECSZ faults were essentially quiet in the period 2.5–4.5 ka, with very few earthquakes.

Conversely, other areas, now seismically quiet, might pose a much greater seismic hazard in the future than they do today. Conversations at annual SCEC meetings led SCEC scientists to redouble their efforts in Los Angeles, where the risk from earthquakes may be larger than anywhere else in the United States.

What they found was startling. Earthquakes are clustered in Los Angeles, also, but the Los Angeles faults were active at times when the ECSZ faults were quiet, a switching of Pacific–North America plate motion from one fault network to the other. Why? Dolan et al. present a model in which faults of the San Andreas system, including the Garlock and Los Angeles

Basin faults, suppress activity on the ECSZ, and vice versa. The switching might be related to fluctuations in loading rate at the base of seismogenic crust related to cycles of strain hardening (reducing slip rate) alternating with cycles of annealing (increasing slip rate). The southern San Andreas fault is active in both modes, a problem for the model because that fault has not sustained an earthquake in more than 300 yr.

The present-day quiescence is encouraging for the residents of Los Angeles, although there is no clue about when the mode of fault displacement concentrated in the ECSZ will shift, and when Los Angeles will start getting more than its share of earthquakes. Perhaps a cluster has already started, with earthquakes in 1971, 1987, and 1994.

What's next? To apply these ideas to other regions, one needs an extensive paleoseismic and geodetic data set to accompany seismic networks and records of historical seismicity. The best candidates might be Japan, Turkey, China, New Zealand, and Iran, all regions where much is already known about the distribution of active faults and fault networks, and more is being learned from paleoseismic studies. In New Zealand, for example, the Alpine plate-boundary fault appears to be quiet for the moment, except for the strike-slip faults of Marlborough, but the Range-and-Basin Province of northwestern South Island, with low long-term slip rates, was struck by large earthquakes in 1929 and 1968, and smaller ones in 1962 and 1991 (Anderson et al., 1993; Yeats, 2000). Parts of the Sierras Pampeanas in northwest Argentina, with earthquakes in 1893, 1944, 1952, and 1977, exhibit a seismic moment rate an order of magnitude higher than predicted by the geology (T. Rockwell, 2007, personal commun.).

In all of these examples, an interdisciplinary effort among geology, geodesy, and seismology is essential, as it has been for Southern California. In the meantime, Los Angeles residents can relax a little, but not much.

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