**TABLE OF HISTORIC EARTHQUAKES WITH SURFACE RUPTURE**

**Introduction**

Probabilistic hazard assessment of strong shaking accompanying earthquakes is better known than the hazard associated with rupture of the ground surface during an earthquake, particularly ground breakage beneath the foundation of an engineered structure. Surface rupture is regulated only in the states of California and Utah. This is unfortunate because where ground rupture from previous earthquakes is known and shown to be small, the ground-rupture hazard may be mitigated by engineering design (Bray, 2001; Bray and Kelson, 2006). This table shows that surface ruptures are surprisingly common, although their interpretation may not be straightforward, especially the conclusion that the surface rupture connects with the subsurface plane of major moment release or whether it is a secondary effect of folding, landsliding, or lateral spreading.

The surface effects of earthquakes were first summarized by Lyell (1875), who thought that earthquakes, like volcanic eruptions, demonstrated important concepts in the emerging field of geology. On the other hand, Montessus de Ballore (1925) and Richter (1958) discussed coseismic surface faulting as an insight to the physics of the earthquake process itself. Bonilla and Buchanan (1970) and Bonilla et al. (1984) tabulated world earthquakes known to have surface rupture to determine the relation of surface rupture length to magnitude. Like Richter, they wanted to use surface rupture to learn more about earthquakes. This table was expanded, with many additional case histories, including the 1992 Landers, California, earthquake, by Wells and Coppersmith (1994), again with the purpose of learning more about the relation of surface rupture to magnitude and rupture area. In this table, magnitudes of Wells and Coppersmith (1994) and, for the eastern Mediterranean-Middle East, Ambraseys and Jackson (1998) and Ambraseys (2009), have been used in preference to other sources, unless the other source revised a pre-instrumental magnitude based on geological data that resulted in a revision of earthquake moment (for example, Avouac et al., 1993, for the 1906 Manas, China, earthquake).

Information for this table comes from two sources: (1) the inspection of surface faulting by qualified observers shortly after the earthquake, and (2) the correlation, long after the earthquake, of surface geological features or observations in trench excavations with historical earthquakes, which I refer to as *historical paleoseismology*. Historical paleoseismology began with Lawson (1908), who, as part of the report he edited about the 1906 San Francisco earthquake, also reported on surface rupture accompanying an earlier earthquake in 1868 on the Hayward fault, near his office at the University of California, Berkeley. However, evidence for surface rupture length collected long after the earthquake may depend in part on shaking intensity that is strongest in the vicinity of a mapped active fault. Where recurrence intervals are short, so that the geomorphic and geochronological evidence might not be sufficient to correlate a surface rupture to a specific historical earthquake, the estimated rupture length is not solely dependent on geologic evidence, as illustrated by estimates for the 1838 San Francisco earthquake (Toppozada et al., 2002). Similarly, the Parkfield earthquakes prior to 1934 had reports of surface disturbance along the San Andreas fault, but because this was reported as ground cracks rather than fault displacement, it is possible that the earlier ground disturbance was not due directly to fault rupture. This problem is complicated because part of the Parkfield area is creeping (Toké et al., 2006); the displacements due to creep are not included in the table (*cf*., Toppozada and Branum, 2006). In the same vein, ruptures assigned to the 1861 San Ramon Valley, California, and 1934 Puerto Armuelles, Costa Rica, earthquakes might be due to secondary effects. The 1976 Guatemala earthquake on the Motagua fault was accompanied by surface rupture, but ground cracks in the alluvium near the Caribbean coast suggest that surface rupture might have continued east of the reach of the fault where offset is clear.

Inspection of surface faulting soon after the event began with a description of ground fissures on the Nauzad fault in Iran accompanying an earthquake of ML 7.0 on 10 January 1493 (Esfezari, 1493; *cf.,* Berberian and Yeats, 1999). In modern times, description of surface faulting began with the 1855 West Wairarapa, New Zealand, earthquake (*cf.*, Darby and Beanland, 1992), the 1861 Egion earthquake south of the Gulf of Corinth in Greece (Schmidt, 1875), and the 1887 Sonora, Mexico, earthquake (*cf.*, Suter and Contreras, 2002). Systematic study of coseismic surface faulting began in New Zealand with the 1888 Marlborough earthquake, in Japan with the 1891 Nobi earthquake, and in the United States with the 1906 San Francisco, California, earthquake, followed by the publication of descriptions of surface ruptures worldwide in the *Bulletin of the Seismological Society of America*. Yet even with inspection teams of trained observers, there may be controversy about whether disturbance of the ground surface is produced by tectonic rupture or by secondary effects (compare, for example, the accounts of the 1992 Erzincan, Turkey, earthquake by Barka and Eyidogan, 1993, and Trifonov et al., 1993). The 1989 Loma Prieta, California, earthquake is also included even though there is disagreement (compare Prentice and Schwartz, 1991, with Aydin et al., 1992) over the significance of presumed tectonic ruptures. Several listed earthquakes have surface ruptures recorded for a distance less than a few kilometers; these ruptures may represent secondary effects on a pre-existing zone of weakness.

A controversy has arisen over whether surface faulting is *primary*, part of the same rupture surface that includes the mainshock, or *secondary*, triggered on another fault by the earthquake simply because that fault was a zone of weakness and responded to differential shaking of competent blocks on either side. The 1983 Borah Peak, Idaho, earthquake may have primary rupture only in the Thousand Springs segment. Tectonic ruptures also were found to the north in the Willow Creek Hills and in the Warm Springs Valley, but geodetic data suggest that these may be secondary (Stein and Barrientos, 1985; Barrientos et al., 1987). Because the faulting in the Willow Creek Hills has the same sense as faulting in the Thousand Springs segment, both are included in the table. The 1979 Imperial Valley earthquake triggered up to 10 mm dextral slip on a 39-km-long section of the San Andreas fault more than 90 km away from the seismogenic Imperial fault (Sieh, 1982); this is not included in the table.

The largest earthquakes on Earth strike subduction zones, most of which are offshore and not available for inspection. Even when bathymetric mapping is conducted immediately after an earthquake, as was the case after the December 26, 2004 ***M*** 9.15 earthquake off Sumatra, evidence of surface rupture is ambiguous (Henstock et al., 2006). Some subduction-zone earthquakes are accompanied by secondary rupture on faults in the hanging wall of the subduction zone, presumably triggered by the subduction-zone earthquake. This is illustrated for the 1964 Alaskan earthquake (***M*** 9.2) and the 1995 Antofagasta, Chile, earthquake (***M*** 8.0), which was accompanied by minor surface rupture on the adjacent Atacama fault, based on DeLouis et al. (1997), who observed scarps after the earthquake that were not present just before the earthquake. The 2011 Tohoku-oki, Japan, earthquake was followed a month later by a normal fault on land (Kelson et al., 2011), which is included in the table. Because strong motion on the subduction zone extended to the trench, or close to it, generating a giant tsunami, the plate boundary itself might have ruptured at the surface during the earthquake. Alternatively, such faulting near the plate boundary may be secondary, rare only because surface rupture is largely underwater and difficult to confirm.

Displacements accompanying an earthquake may include coseismic slip and afterslip, as for the 1944 San Juan, Argentina, earthquake, where coseismic deformation of 30 cm on the La Laja fault was followed by another 30 cm of afterslip (Harrington, 1944). An earthquake in 2005 of *M* 5.0 south of Kabul, Afghanistan, was accompanied by 6.5 km of surface rupture on the Chaman fault; slow-slip surface rupture continued for at least a year over at least 50 km of the fault (Furuya and Satyabala, 2008). It would be challenging to distinguish coseismic slip from afterslip long after the event or for an earthquake in a remote, uninhabited area, where an expedition is necessary to describe the surface rupture.

It is now apparent that seismic faulting may warp the ground surface even though faulting is blind (does not reach the surface). These include the 1908 Messina Straits, Italy, earthquake of ***M*** 7.5, which Valensise and Pantosti (1992) interpreted as an earthquake on a blind normal fault. Two linear zones of reverse faults in basement rocks beneath salt of the Iranian Zagros are described as the blind Qir and Assaluyeh faults by Berberian (1995). These are expressed at the surface as broad, southwest-facing escarpments (Lacombe et al., 2006). The 1983 Coalinga, California, earthquake on a blind reverse fault is not included in this table, but a shallow aftershock on June 11 did rupture the ground surface, and it is included. Surface rupture accompanying the ***M*** 7.6 Kashmir earthquake of 2005 was recorded over a distance of about 70 km; these ruptures were not continuous but were separated from one another by unruptured ground (Kaneda et al., 2008). Despite these gaps in surface rupture, the entire length of the zone of faulting is included in the table.

Surface rupture reported in the table may be secondary, related to folding, rather than the surface expression of the main seismic fault, as illustrated for the 1980 El Asnam, Algeria, earthquake of ***M*** 7.3 (Philip and Meghraoui, 1983), the 1988 Spitak, Armenia, earthquake of ***M*** 6.8 (Philip et al., 1992), and the 1970 Uüreg Nuur, Mongolia, earthquake of ***M*** 7 (Baljinnyam et al., 1993).

Historical paleoseismology is most closely identified with the work of N.N. Ambraseys, J.A. Jackson, and their colleagues in the eastern Mediterranean, the Middle East, the Indian subcontinent, and Africa, M. Berberian in Iran, S. Stiros in Greece, Xu Xiwei and Deng Qidong in China, A. Sangawa of Japan, and T. Toppozada in California. Programs are underway in China, Japan, New Zealand, Iran, Turkey, Italy, Greece, and the United States to correlate surface ruptures based on paleoseismology with large historical earthquakes. Correlating the isoseismals of a historical, pre-instrumental earthquake to a fault conveniently located at the center of strong ground motion (e.g., Ambraseys and Jackson, 1998) must take into account errors in epicenter location, errors in dating the event, and even the possibility of more than one earthquake.

Recognition of pre-instrumental earthquakes on strike-slip faults relies only partly on construction of isoseismal maps; recognition of a linear zone of disturbed and disrupted ground is also necessary. This permits the recognition of rupture lengths of several pre-instrumental earthquakes on the North Anatolian fault (Ambraseys, 1970; 1975; Ambraseys and Finkel, 1988; Sengör et al., 2005), but generally does not permit the identification of the length of strike-slip offset because contemporary observers did not make observations near the ends of ruptures where offsets were small. The 1662 Kambun, Japan, earthquake of ***M*** 7.8 was originally described as a single earthquake, but a study of contemporary records shows evidence for two earthquakes separated by a few hours (Tsukuda, 2002). Even when paleoseismic trenching provides radiocarbon dates that bracket a trench displacement with a historical earthquake, an offset in a single trench excavation commonly does not provide enough control to establish ***M*** with confidence.

The correlation of fresh topographic expression of fault offset was used by Nakata et al. (1990) to determine the rupture lengths of the 1645 and 1796 earthquakes on the Philippine fault. On the other hand, trenching on the Median Tectonic Line fault of Japan showed that this fault ruptured during the late 16th century, (Okada et al, 1991), but this was probably not the historical 1596 earthquake producing strong damage in populated areas to the northeast. Similarly, tree-ring dating tied the “San Juan Capistrano,” California earthquake of 1812 to the San Andreas fault rather than coastal California, but there is controversy about the length of 1812 surface rupture despite an extensive trenching campaign (Sieh et al, 1989; Salyards et al, 1992; Fumal et al, 1993; 2002) and about whether surface rupture was due to two earthquakes in 1812, not just one (Toppozada et al., 2002). In the table, we follow Fumal et al. (1993; 2002) and assign 1812 surface rupture to a single earthquake on December 8. Trenching commonly does not yield evidence for strike-slip offset unless there are several closely-spaced trenches, including trenches parallel to the fault, that allow the mapping of offset features such as stream channels from one side of the fault to the other, which is now the standard of consulting practice in subsurface investigations for critical facilities.

Trenching is commonly able to provide evidence for maximum displacement on dip-slip faults, particularly normal faults that are less likely to be blind. Dip-slip faults produce a scarp, the height of which is more likely to be recorded by contemporary observers, as was the case for the 1899 Menderes Valley, Turkey, earthquake (Ambraseys and Finkel, 1987a). However, even for the 1861 Egion, Greece, earthquake, there is lively controversy over whether arcuate scarps with normal displacement are tectonic or are due to slope failure because the surface expression for both may be similar. This has been a particular problem for pre-instrumental (and even twentieth-century) ruptures in Greece (cf. Ambraseys and Jackson, 1990) and in Italy, particularly for the 1783 earthquake in Calabria described by Dolomieu (1784).

Another problem is the correlation of fresh geomorphic expression, such as the preservation of a free face, with isoseismal maps (cf. Armijo et al, 1991, for the earthquake that destroyed Sparta, Greece, in 464 BC, and Liu, 1993, for normal faulting accompanying the 1895 Tashkuergan earthquake in Xinjiang, China). The Pleasant Valley, Nevada, and Avezzano, Italy, earthquakes of 1915 were accompanied by vegetation-free zones near the base of the range front, formed during the earthquake (Wallace, 1984; Vittori et al., 1991), referred to by the Italians as *nastri di faglia*, or fault ribbons. In the central Nevada seismic zone, *nastri di faglia* mark the 1915 and 1954 surface ruptures, but not the middle Holocene rupture at the base of the Stillwater Range in northern Dixie Valley. *Nastri di faglia* are common in limestone terranes of Italy and Greece, and these are not easily correlated with historical earthquakes older than about 2000 years. Although the *nastri di faglia* near Sparta might have formed during the 464 BC earthquake, this has not been confirmed independently by dating, and the vegetation-free zone might be the product of more than one earthquake.

The Sumatran fault and Philippine fault are marked by isoseismals of large earthquakes that are distributed along most of their lengths, but these isoseismals are not considered sufficient evidence to include most of these earthquakes in this table. The danger of correlating isoseismal maps to a known Holocene fault is illustrated in the Apennines of Italy. Trenching on faults that ruptured the surface in the 1980 Irpinia earthquake showed that these faults did not rupture during the 1694 earthquake with an even larger meizoseismal zone centered on the same region as in 1980 (Pantosti et al, 1993). However, trenching the El Pilar strike-slip fault in Venezuela is suggestive of evidence for surface rupture accompanying earthquakes in 1684 and 1974 (Audemard, 2006).

Each historical earthquake is a separate problem and potential controversy, discussed in context in the discussions of surface ruptures in each region. For this reason, this table is a work in progress, subject to modification by newer earthquakes and also by paleoseismic investigations of older ones. The original version appeared under copyright in Yeats et al. (1997) and is modified here with permission of Oxford University Press. Because it appears online, it is offered as a wiki; modifications and updates by the earthquake community are invited.

**Explanation**

# Explanation: Date: year, month, day; dates after 1999 in italics; BC dates use negative symbol.

M: magnitude; assume Ml if not specified; other subscripts: b, body wave; s, surface wave; w, moment; t, tsunami. Roman numerals: MMI intensity for some pre-instrumental earthquakes

Name of earthquake

Location: latitude and longitude in degrees and tenths of degrees

Strike of fault

Type: RE, reverse; NN, normal; LL, left lateral; LR, left lateral and reverse; LN, left lateral and normal; RL, right lateral; RR, right lateral and reverse; RN, right lateral and normal; LV, left lateral; dip direction unclear; RV, right lateral; dip direction unclear; VV, dip slip, dip direction unclear.

Length (L). Total length of rupture zone in km, including unbroken sections.

Horiz. (H) Maximum lateral offset in meters

Vert. (V) Maximum vertical offset in meters

Name of fault or faults

Reference: Only last two numbers of year given in table. Years prior to 1900 underlined; year after 1999 in italics. See full references following table.

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(C, Chinese; J, Japanese; R, Russian)

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