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Minimum Earthquake Magnitude Associated with Coseismic Surface Faulting

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ABSTRACT

Rupture of the ground surface by faulting associated with shallow earthquakes is an important element to consider in the evaluation of fault activity. Observational data compiled in this report indicate that the minimum earthquake magnitude associated with reported sudden surface faulting is about M, 5. Considering that the epicentral areas of many earthquakes of M, 5 or less were not searched for evidence of surface faulting, the actual minimum magnitude may be smaller. A combined empirical and theoretical analysis suggests that under ideal conditions, coseismic surface faulting of a few millimeters associated with earthquakes having moment magnitudes as small as 3 could be recognized by simple field methods. Several factors such as dimensions, depth, and orientation of the rupture surface together with observational conditions affect the development and subsequent recognition of surface faulting.

Surface displacements ranging from a few millimeters to several decimeters have accompanied earthquakes having magnitudes between 5 and 6. The larger fault displacements and the earthquakes can damage structures, and that possibility should be considered in regions where shallow earthquakes of that size can occur. The generally small and short surface ruptures associated with such earthquakes may leave very little evidence in the topography, stratigraphy, or near-surface structure, especially if the displacements are consistently small and the recurrence intervals for earthquakes are long. Such conditions may explain why so few active faults have been recognized in some regions of infrequent shallow earthquakes, such as eastern North America.

INTRODUCTION

Surface faulting can have a profound effect on the siting, design, and performance of a wide variety of engineering projects. Because surface faulting is relatively common during large shallow-focus earthquakes but rare or absent during small ones, a recurring question concerns the minimum earthquake magnitude at which coseismic faulting may rupture the ground surface. This report lists 31 events (i.e., earthquakes and associated surface faulting) that bracket the minimum earthquake magnitude associated with reported coseismic surface faulting, summarizes important factors that affect the development and recognition of faulting at the ground surface, and discusses some practical implications of this information and its interpretation.

Faulting can occur in different modes that depend primarily on the speed of its occurrence, or characteristic rise time. Rise time can be defined as the time for 90 percent of the slip to occur at a point on the fault (Sibson, 1983, p. 743). Sibson lists five modes ranging from coseismic slip to steady creep, but the faulting discussed in this study is classed in only two modes: coseismic slip, in which the faulting occurs suddenly (a rise time of a few seconds) at the time of the earthquake, and tectonic creep, in which the faulting occurs gradually (rise time of minutes to days, or steady creep).

FACTORS AFFECTING THE DEVELOPMENT AND RECOGNITION OF FAULTING AT THE GROUND SURFACE

Several factors that have an influence on whether faulting will both reach the ground surface and be correctly recognized as faulting are listed in Table 1. Most important are the size of the earthquake and the depth at which the faulting occurs. The subsurface displacement on the fault, the area of the fault surface, and the shear modulus of the rock control the size of the earthquake. As shown diagrammatically in Figure 1, the area of the fault surface (as part of earthquake size) in relation to depth and its shape and orientation determine whether the rupture can possibly reach the ground surface. Even if it theoretically can, however, it still may be absorbed or diffused in near-surface rock or unconsolidated materials in such a way as to conceal it (Bonilla, 1970, pp. 58-59). If the fault ruptures do reach the ground surface, they may or may not be recognized as faulting for various reasons, some of which are listed in Table 1. Observational factors which affect the recognition of faulting include vegetative cover, the thoroughness of the field examination, and the timing of the examination in relation to the action of several agents that can modify or conceal minor faulting, such as rainfall, burial by eolian or other sediment, and freeze-and-thaw action. The character of the surface fractures such as length, size of displacement, sense of displacement, and fracture pattern in relation to topography are important in distinguishing faulting from fractures that may accompany earthquakes but are caused by sliding, shaking, sackung (gravitational spreading of ridges; Radbruch-Hall et al., 1976), subsidence, or liquefaction. A common final step is the investigator's conclusions as to the origin of the fractures. Because of these factors and the fact that no search for faulting was done following many small earthquakes that occurred in past decades, the record of surface faulting associated with small to moderate earthquakes that is discussed below is surely incomplete, and may include some non-tectonic fractures.

OBSERVATIONS OF SURFACE FAULTING ASSOCIATED WITH SMALL TO MODERATE EARTHQUAKES

Tocher (1958) showed that every earthquake of magnitude greater than 61/2 that occurred between 1906 and 1957 with epicenter on land in Nevada or northern California was accompanied by surface faulting, and that the smallest shock having surface faulting was of magnitude 51/4. Since then, many examples of surface faulting associated with earthquakes of magnitude less than 6 have been reported worldwide, and include strike-slip, normal-slip, and reverse-slip types. All of the reported surface faulting associated with earthquakes of magnitude less than 6 for which I have been able to find documentation are listed in Table 2 or discussed below. Events are listed in Table 2 and discussed in the order of increasing earthquake magnitude. Local magnitude (M_L), equivalent to the original Richter magnitude, is used if available and if not the body-wave magnitude (m,) is used; these magnitude scales are appropriate for short-period ground motion (Nuttli, 1985), which is typically associated with small- to moderate-sized earthquakes. The references column in Table 2 gives sources for the descriptions of the ruptures, followed if necessary by sources for the earthquake magnitudes, focal depths, and intensities. Some of the listed events have unusual or equivocal aspects; these events and some that are not listed in Table 2 are discussed below.

The 1981 Lompoc, California, faulting occurred in a diatomite quarry that had been active for about 30 years, but quarrying had stopped in 1979 near the site of the future fault. A combination of artificial unloading and tectonic stresses evidently produced this bedding-plane faulting that was primarily reverse slip but accompanied by a substantial strike-slip component (Yerkes et al., 1983). It is a special case because the faulting was not wholly of tectonic origin.

Part of the Imperial, California, fault is subject to tectonic creep, and the 1966 faulting on it probably represents a period of accelerated creep triggered by earthquakes rather than coseismic faulting. Surface fracturing known to be associated with tectonic creep occurred on the Imperial fault in 1977, and its length was apparently similar to the 1966 rupture (Goulty et al., 1978).

Table 1. *Factors affecting the development and non-instrumental recognition of coseismic surface faulting.*

1. Earthquake size
    - Magnitude or seismic moment, related to:
        - fault displacement
        - area of rupture surface
        - shear modulus of rock
2. Depth of rupture surface
3. Dip of rupture surface
4. Shape and orientation of rupture surface
5. Absorption by near-surface materials
6. Observational factors
    - Vegetation
    - Topography
    - Thoroughness of field examination
    - Time of field examination relative to:
        - Rainfall
        - Burial by sediment
        - Freeze-and-thaw
        - Activities of man
        - Other modifying agents
7. Character of fractures
    - Length
    - Continuity
    - Size of displacement
    - Type of displacement
    - Consistency of slip direction
    - Fracture pattern
    - Relation to topography
    - Relation to known faults
    - Relation to landslides
8. Investigator's decision on origin of fractures
    - Landslide
    - Sackung
    - Subsidence
    - Liquefaction
    - Vibratory fractures
    - Tectonic fractures
        - Creep (gradual displacement)
        - Coseismic (sudden displacement)

Surface faulting associated with earthquakes of magnitude less than 6 occurred in 1922 and 1983 just north of Lake Taupo in New Zealand. The area is within the Taupo volcanic center, a possible caldera, where a pumice eruption having a source in Lake Taupo occurred in A.D. 131 (Cole, 1979). In 1922, ruptures formed along four parallel traces which, in effect, formed a graben centered near Whakaipo Bay on Lake Taupo (Grange, 1932). Eiby (1966) stated that the faulting occurred on June 10 at the time of the largest of a group of earthquakes; however Grange (1932) maintained that the faulting occurred over a period of months, and cited observations of increasing subsidence of the shore of Whakaipo Bay, from about 0.09 m on June 27 through 1.4 m in September to 3.7 m in December of 1922. The magnitude of the largest earthquake was estimated to be > 5 by Eiby (1968) and <6 by Clark and others (1965); the mean of these two estimates is used in Table 1. The second episode of faulting north of Lake Taupo occurred in June, 1983. On the morning of June 23, following several earthquakes of Modified Mercalli intensity 4 to 5, fractures were found at one of the fault scarps where faulting had occurred in 1922. Following several more earthquakes, these of Modified Mercalli intensity 3 to 4, the fractures became more prominent and propagated northward (Hull and Grindley, 1984; Otway et al., 1984). The largest earthquake of the series was of magnitude 3.9 (Hull and Grindley, 1984). Judging by the published evidence, the 1922 and 1983 faulting occurred progressively over time periods that ranged from hours to months, and therefore is considered in this report to have occurred in the form of tectonic creep.

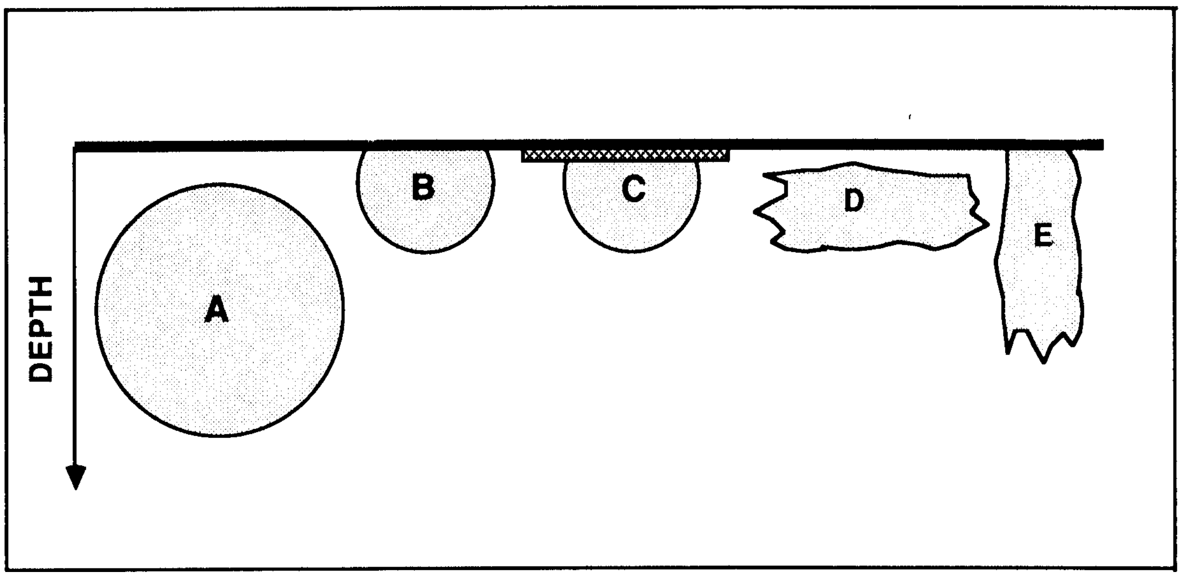

Figure 1. Vertical section diagrammatically showing how depth and configuration of rupture surface can influence surface faulting. The shaded areas represent the area of fault rupture in events labelled A -E, and the ground surface is represented by the heavy line. Event A is much larger than B but in contrast to B the rupture does not reach the ground surface because of its greater depth. The rupture in event C is similar to B in size and depth but the near-surface material represented by the cross-hatched area absorbs or diffuses the rupture, concealing it from the field investigator. Not shown are rupture surfaces having a low dip that could be of the same size as B and C and lie at shallower depths yet not reach the ground surface. The rupture in event D is the same size as and its lower edge is at the same depth as B and C but because of its shape it does not reach the ground surface. The rupture in event E, of essentially the same size and shape as in D but having a greater depth at its lower edge nevertheless reaches the ground surface. The irregular shapes of D and E are more realistic than the regular shapes of A-C. A factor not shown on the diagram is that for a given earthquake magnitude or seismic moment, the area of the surface rupture varies in relation to the shear modulus of the rock and the average displacement on the fault.

The 1978 Stephens Pass, California, ruptures were associated with a swarm of earthquakes, the largest of which was of magnitude 4.6. The ruptures first appeared after the magnitude 4.3 earthquake of August 12, 1978 along a pre-existing fault scarp and in most places they formed a series of grabens; however, the investigators (Bennett et al., 1979) were unable to measure any net vertical slip across the zone of ruptures. The distribution of hypocenters in relation to the scarp and the preliminary focal mechanism solutions both suggest normal faulting. The possibility that the fractures may have formed by earthquake-induced collapse of lava tubes was investigated by magnetic and gravity surveys; however, the results were inconclusive because the observed gravity anomalies could represent concealed lava tubes, but the magnetic anomalies probably do not (Bennett et al., 1979).

Table 2. Surface faulting associated with small to moderate earthquakes.*

Earthquake Magnitude	**Maximum Surface Displace-ment (m)**	**Fault Type**	**Surface Length (km)**	**Remarks**	**Date: Yr.Mo.D.**	**Location**	**Event Symbol**	**Depth**	**Intensity (MM)**	**References**	**Mode**
M_L 2.5	0.25	R	0.6	Bedding-plane slip, trigered by quarrying	1981.04.07	California, Lompoc	CA81	<5	-III	Yerkes et al., 1983	E
M_L 3.6	0.015	S	10	Ruptures probably reflect accelerated tectonic creep	1966.03.04	California Imperial Valley	CA66A	~3	V	Brune and Allen, 1967	CR?
M_L 3.9	0.05	N	1.2	Progressive faulting over several hours	1983.6.22 through 1983.6.23	New Zealand, Taupo	NZ83	1-4	IV-V	Hull and Grindley, 1984; Otway et al., 1984	CR?
M_L 4.3 m_b 4.3 Ms 4.1	0.3 ?	N	GT 2	Origin of fractures uncertain	1978.08.13	California, Stephens Pass	CA78	2	V	Bennett et al., 1979; PDE	E
ML 4.7 m_b 4.9 Ms 4.6	0.2 ?	N ?	10.4	Ruptures may reflect accelerated tectonic creep	1975.01.23	California, Brawley	CA75A	4-8	VII	Sharp, 1976; Johnson and Hadley, 1976; PDE; Coffman, 1979	PC
M_L 4.5 to 5.0	0.5	S	~3	Earthquake swarm. Tectonic creep	1966.04.11 through 1966.09.06	Japan, Matsushiro	JA66	1-9	VII	Tsuneishi and Nakamura, 1970; Hagiwara and Iwata, 1968	CR
m_b 5.1 Ms 5.6	0.040	S	~6		1966.10.09	Sudan, Jebel Dumbeir	SU66	?	VIII	Qureshi and Sadig, 1967; Ambraseys and Adams, 1986	C
m_b 5.1	0.25	?	~6	Rupture very poorly documented	1968.9.24	Turkey, Kigi	TK68	~14	VII	Ambraseys, 1975; Lander, 1969	PC
M_L CA 5.2 m_b 4.9	?	?	~7	Fractures in four groups, along monoclines. Origin uncertain	1982.10.01	California, Ridgecrest	CA82	8	VI	Roquemore and Zellmer, 1983; Stover, 1985; PDE	E
M_L 5.2 m_b 5.3 Ms 5.4	0.56	R	3.3	Main shock (Ms 6.5) 14 km away, did not have associated surface faulting	1983.06.11	California, Coalinga, Nunez fault	CA83	5	VI	Rymer et al., 1985; Hart and Mcjunkin, 1983; Stein and King, 1984; PDE	C
ML 5.2 m_b 5.5	GE 0.003	S	GE 0.3	Fractures at two localities0.3 km apart. Some fractures in rock. On active Clarence fault	1973.04.23	New Zealand, Molesworth	NZ73	?	?	Wood, 1973; Kieckhefer, 1977; PDE	PC
M_L 5.2 m_b 5.5 Ms 5.6	0.1	S	3.2		1979.03.15	California, Homestead Valley	CA79A	~1-4	VIII	Hill et al., 1980; Hutton et al., 1980; PDE	C

Earthquake Magnitude	**Maximum Surface Displace-ment (m)**	**Fault Type**	**Surface Length (km)**	**Remarks**	**Date: Yr.Mo.D.**	**Location**	**Event Symbol**	**Depth**	**Intensity (MM)**	**References**	**Mode**
M_L 5.3 m_b 5.1	0.015	S	6.6		1975.05.3	California, Galway Lake	CA75B	6	IV	Hill and Beeby, 1977; Bonilla et al., 1984; PDE	C
M_L ? 5.4	~0.1	S ?	~2	Discontinuous fractures	1931.03.31	Nicaragua, Managua	NI31	?	?	Sultan, 1931; Freeman, 1932; Brown et al., 1973; Leeds, 1973; Lomnitz and Hashizurne, 1985	PC
m_b 5.4 Ms 5.8	0.2	S	19.5		1977.12.9	Iran, Bob-Tangol	IR77	?	?	Berberian et al., 1979; Ambraseys et al., 1979; Bonilla et al., 1984; PDE	C
m_b 5.4	?	N ?	~10	Rupture poorly documented	1972.7.2	Iran, Mishan	IR72	?	?	Berberian and Tchalenko, 1976; PDE	PC
M_L 5.5 m_b 5.3 Ms 5.9	0.025	S	4-6	Discontiuous fractures	1980.01.24	California, Livermore Valley	CA80	12	VII	Bonilla et al., 1980; Bolt et al., 1981; PDE	C
m_b 5.5 Ms 4.9	0.005	N ?	GE 1.3	Discontinuous fractures, West side consistently down	1983.03.31	Colombia, Popayan	C083	~5	VII	Lomnitz and Hashizurne, 1985; PDE	PC
M_L 5.5	1.8	N	9.7	Probably progressive faulting over several months	1922.6.10 through 1922.12.?	New Zealand, Taupo	NZ22	?	VII	Grange, 1932; Eiby, 1966; Clark et al., 1965; Eiby, 1968	CR
M_L 5.5	0.05	S	38	Tectonic creep occurred prior to and after the earthquake	1966.6.27	California, Parkfield	CA66B	1-12	VII	Brown and Vedder, 1967; Wallace and Roth, 1967; Cloud, 1967; Eaton et al., 1970	CR
m_b 5.5 Ms 5.1	0.1	N ?	9	Rupture poorly documented. On previously known normal fault 3 km NE of Chanmagua	1982.09.29	Guatemala, Chamnagua	GU82	12	?	Person, 1983; White, 1985; Burkhart, 1965; PDE	PC
M_L 5.6	?	S	3 ?	Possibly tectonic creep	1951.01.23	California, Superstition Hills	CA51	?	VII	Dibblee, 1954; Allen et al., 1965	PC

Earthquake Magnitude	Maximum Surface Displace-ment (m)	Fault Type	Surface Length (km)	Remarks	Date: Yr.Mo.D.	Location	Event Symbol	Depth	Intensity (MM)	References	Mode
m_b 5.6 Ms 6.2	0.38	S	~12	Parallel trace 300 m away had 0.26 m displacement	1972.12.23	Nicaragua, Managua	NI72	1-8	IX	Brown et al., 1973; Ward et al., 1974	C
M_L 5.7 m, 5.7 Ms 5.0	0.7	R	3.4		1970.03.10	Australia, Calingiri	AT70	5	VII	Gordon and Lewis, 1980; Bonilla et al., 1984; PDE	C
m_b 5.7	0.4	N	~4	Rupture very poorly documented	1966.10.29	Greece, Acarnania	GR66	~12	VIII	Ambraseys, 1975; Lander, 1967	PC
M_L 5.7	0.6	N	8.7		1950.12.14	California, Ft. Sage	CA50	?	VII	Gianella, 1957; Bonilla et al., 1984	C
M_L 5.7 m, 5.8 Ms 5.6	-0.055	N	~4	Initial surface length and displacement poorly known; both increased over several months	1975.08.01	California Oroville	CA75C	6	VII	Clark et al., 1976; Hart et al., 1977; Morrison et al., 1976; Hart and Harpster, 1978; PDE; Langston & Butler, 1976	C
M_L 5.7 m_b 5.4 Ms 5.7	0.005	S	14.4	Ruptures probably reflect accelerated tectonic creep	1979.08.06	California, Coyote Lake	CA79B	6	VII	Lee et al., 1979; Armstrong, 1979; PDE	CR
m_b 5.8 Ms 5.8	0.6	?	-7.5	Preliminary data	1986.3.30	Australia, Marryat Creek	AT86	~10	VI	Person, 1987	C
M_L ? 5.9	0.8	S	30	Rupture very poorly documented	1946.5.31	Turkey, Ustukran	TK46	?	?	Ambraseys, 1975	PC
m_b 5.9 Ms 5.7	0.4	R	~3?		1969.07.24	Peru, Paria-huanca	PE69	?	?	Deza, 197 1; Philip and Megard, 1977; Lander, 1970; PDE	C

Abbreviatons used are: C, coseismic slip; CR, creep; E, mode or origin equivocal; GE, greater than or equal to; GT, greater than; rn, body wave magnitude; MM, modified Mercalli; M_L, local magnitude; Ms, surf ace-wave magnitude; N, normal slip; R, reverse slip; S, strike slip; PC, probably coseismic slip; PDE, U.S. Geological Survey, Preliminary Determination of Epicenters, issue corresponding to date of earthquake. Question mark indicates uncertainty about ite m to left, or no reliable information.

The 1975 Brawley, California, faulting was associated with a swarm of earthquakes of which 75 had an M, of 3 or greater. The earthquakes occurred along only 4 km of the 10 kin total length of surface ruptures, prompting Johnson and Hadley (1976) to suggest that the ruptures originated by creep. However, the time of faulting at a road was fixed within a one-hour interval that included the largest shock, and all of the faulting may have occurred suddenly at that time (Sharp, 1976). The coseismic displacement is not certainly known. The given displacement was measured across a zone about 60 in wide (Sharp, 1976).

The fractures that occurred near Ridgecrest, California, in 1982 are of uncertain origin and relation to the seismogenic fault. Although the fractures were on monoclines in a strike-slip fault zone, they showed only separation of the walls; no strike-slip or dip-slip displacement was reported (Roquemore and Zellmer, 1983). The fractures were in four separate groups within a zone about 7 km long, and the longest group was over 2 kin long. The focal depth of the associated earthquake was given as about 8 km and the magnitude as M, 4.9 to 5. 4 (Stover, 1985); the mean of these magnitudes is listed in Table 1.

Complete documentation of the event of July 2, 1972, in Iran is not at hand. A report by Berberian and Tchalenko (1976), based on a field reconnaissance at an unspecified time and information from local inhabitants, gives a rupture length of about 10 km and a displacement of 4 in. The given displacement is questionable however, because the published photos of the scarps show two distinct slopes, indicating that the scarp formed in more than one event; also, a 4-m displacement is more appropriate to an earthquake having a magnitude larger than 7 (Bonilla et al., 1984), rather than one of magnitude 5.4. Because of the uncertainty, no value for displacement is listed in Table 2.

The 1982 Chanmagua, Guatemala, rupture has not been described in detail and perhaps does not represent faulting. The reported length of 9 km (Person, 1983) favors faulting as does its vertical displacement and occurrence along a mapped normal fault (White, 1985). The fault on which the rupture occurred displaces tuff of Tertiary or Quaternary age (Instituto Geografico Nacional, 1966). Other faults in the region display suggestive evidence of Quaternary displacement (Burkart, 1965) but whether this particular fault affects Quaternary deposits is unknown.

The 1979 Coyote Lake, California, ruptures occurred on a segment of the Calaveras fault where creep averages about 0.01 in per year (Savage and Burford, 1973). The maximum reported earthquake-related slip of 0.005 m in 1979 thus could represent a period of rapid creep. The hypothesis of accelerated creep is supported by the fact that some surface fracturing occurred a few days after the earthquake (Armstrong, 1979) outside the initial rupture zone (Lee et al., 1979) and outside the aftershock zone (Reasenberg and Ellsworth, 1982).

Some surface faulting known to be associated with earthquakes having magnitudes less than 6 are not in Table 2. Events associated with active rifting or concurrent volcanism such as have occurred in Iceland, Ethiopia, and Hawaii are not listed. The surface fractures related to a ML 5.9 earthquake in North Palm Springs, California, in July 1986 were probably tectonic, but the surface displacements on them were vanishingly small and they apparently were not directly connected to the seismogenic fault. The earthquake focal mechanism was strike-slip, and the focal depth was 11 km (Jones et al., 1986). Discontinuous surface fractures were found along about 9 km of the active Banning fault but, although a weak en-echelon arrangement of the fractures suggested a right-lateral component, the right-lateral slip, if any, was < 1 mm (Sharp et al., 1986). Tectonic creep had been occurring on the Banning fault near the east end of the 1986 fracturing, and Sharp and others (1986) suggested that the fracturing may have resulted when the earthquake vibrations reached surface layers that had not yet responded to minor, pre-earthquake subsurface creep. Other analyses, using elastic dislocation theory, suggest that the fractures were confined to the shallow subsurface and could have resulted from a small change in near-surface stress resulting from the stress changes on the much deeper seismogenic fault rupture (Wesson et al., 1986). Because the North Palm Springs fractures of 1986 seem to have been only indi rectly related to the earthquake, they are not listed in Table 2.

MINIMUM EARTHQUAKE MAGNITUDE ASSOCIATED WITH COSEISMIC FAULTING

Examination of Table 2 and the preceding discussion of selected events shows that the origin and mode of faulting is not always obvious. Some events are not well described, others are of uncertain origin, and in still others the distinction between tectonic creep and coseismic slip is problematical; thus classification of several of the events requires judgment based on a variety of objective and subjective factors, including the elapsed time between the event and the field examination, the number of data points, the existence and magnitude of afterslip, and the mode of characteristic slip on the fault. My interpretation of the mode of faulting for each event, to the extent feasible with the available information, is given in Table 2.

The smallest earthquakes with reported coseismic surface faulting have been of about magnitude 5 (Table 2, Figure 2). The mode of faulting for each of the coseismic slip events in Table 2 is shown in Figure 2 by a symbol whose horizontal position indicates the earthquake magnitude. The figure clearly shows that reported coseismic surface faulting events are relatively common above magnitude 5, and rare below that magnitude. The arrangement of events in Figure 2, in the order of increasing magnitude, gives first priority to the M_L magnitudes and second priority to the m_b magnitudes listed in Table 2. If first priority is given instead to the m_b magnitude determinations, the minimum magnitude for reported coseismic surface faulting is also about magnitude 5.

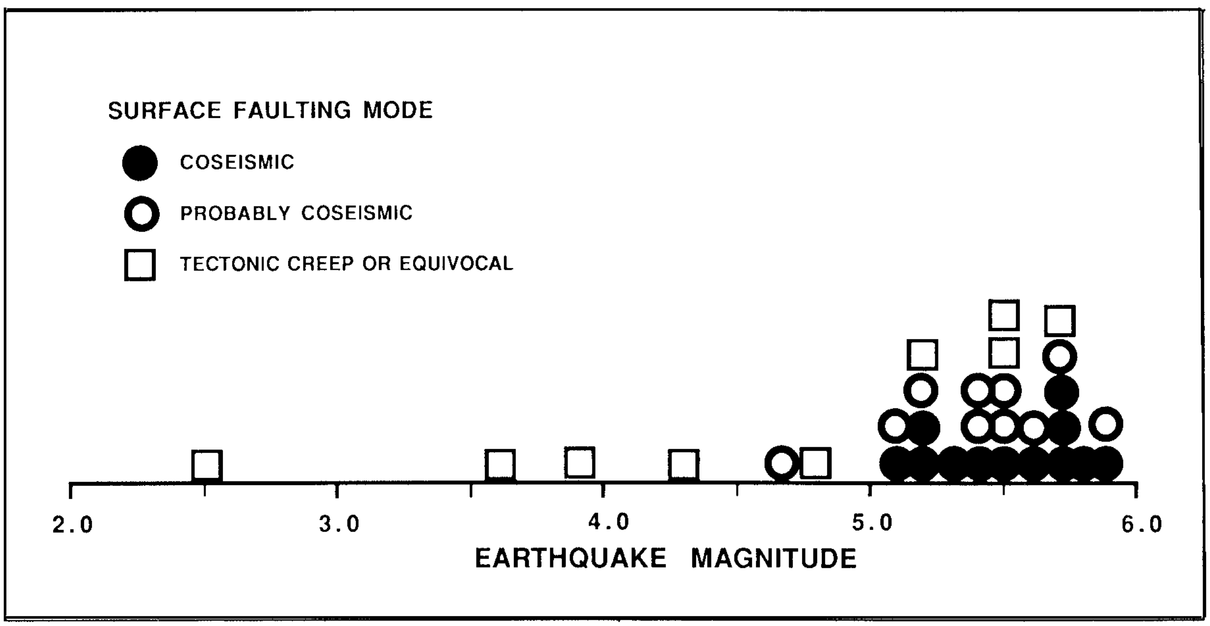

Figure 2. Diagram showing mode of surface faulting in relation to earthquake magnitude for each of the events in Table 2.

Although the minimum earthquake magnitude associated with reported coseismic surface faulting is about magnitude 5, the actual minimum may be smalle r. As discussed previously in this report, the identification of minor surface faulting can be difficult. Based on my experience and that of several colleagues, the lower limit of non -instrumental detection of surface faulting under very favorable circumst ances is about I mm of displacement. Furthermore, the historical record of surface faulting is incomplete because the epicentral areas of many small earthquakes were not searched for faulting.

What size of earthquake can be expected in association with surface displacements of a few millimeters? Correlations of magnitude with displacement for the events in Table 2 are very poor and do not give a reliable estimate. Figure 3 shows the relation of earthquake magnitude to maximum surface displacement based on the coseismic and probable coseismic slip events listed in Table 2. The graph shows that the displacements corresponding to a given magnitude have a very wide range, and least-squares regressions of this data are not statistically significant at the 95 percent confidence level. A rough estimate of expected magnitude can be made, however, using the following combined empirical and theoretical analysis. For an average displacement of 1 mm, the maximum displacement can be imprecisely estimated at about 3 mm (Bo nilla et al., 1984, p. 2403). A reasonable corresponding surface rupture length is about 1.3 km, based on a least-squares regression of the data on coseismic events in Table 2 which yields log L = 1.03 ± 0.13 + (0.37 ± 0.11)log D, in which L is length in k m and D is maximum displacement in m. Assuming a downdip width equal to the surface length and the commonly used shear modulus value of 3 x 10^{11} dynes/cm^2, the seismic moment (equivalent to μdA, in which μ is the shear modulus, d is average displacement and A is area of the fault surface) of such an event would be about 5.07 x 10^{20} dyne-cm. The equivalent moment-magnitude, using the equation of Hanks and Kanamori (1979), is 3.1. Using a smaller shear modulus, 1. 7 x 10^{11} dynes/cm^2, which was considered appropriate for the upper 10 km of geologic section at the site of the 1979 Imperial Valley, California faulting (Archuleta, 1982, p. 1953), the indicated moment -magnitude is 2.9. Thus the analysis suggests that under ideal conditions coseismic surface faultin g associated with magnitudes of about 3 may be detectable by simple field observations. Ideal conditions include a fault plane at shallow depth having a steep dip, timely and detailed field examination, good exposures, and situations in which possible comp action, liquefaction, landsliding, and other surficial effects of earthquakes can be evaluated.

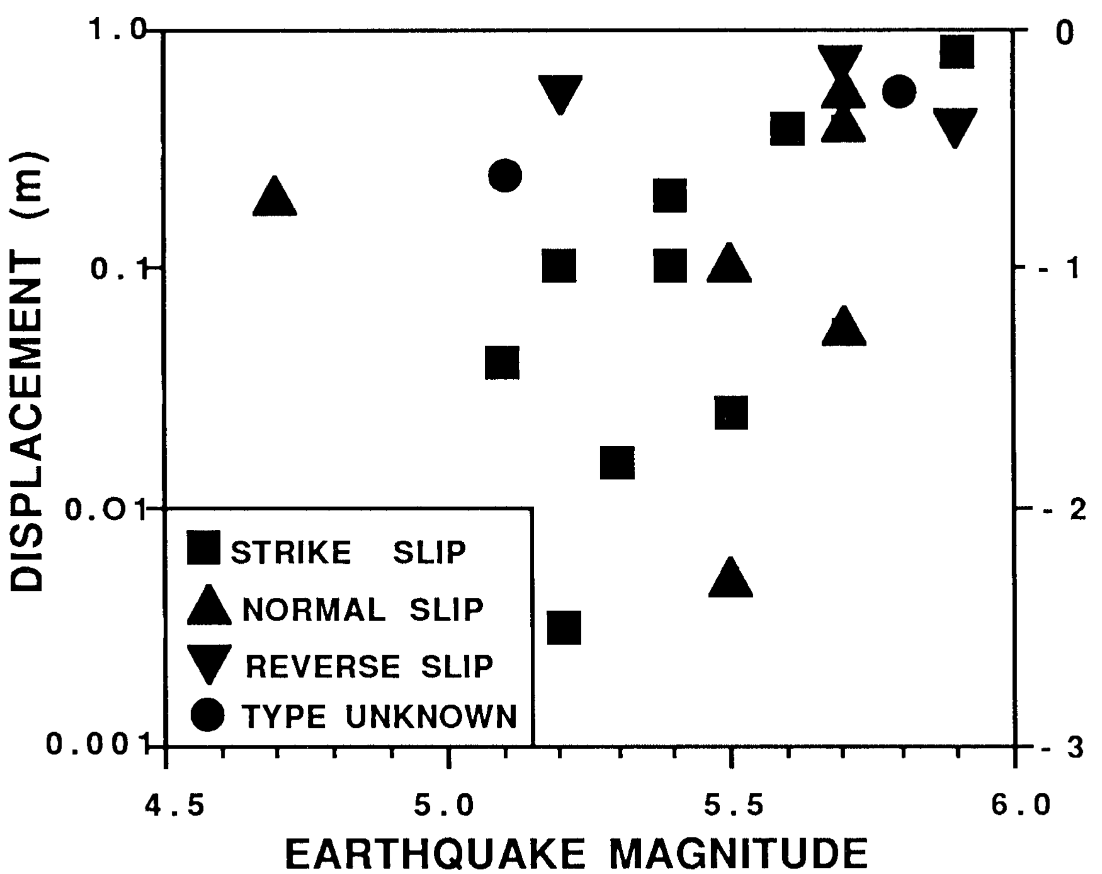

Figure 3. Plot showing maximum surface displacement in relation to earthquake magnitude for the coseismic slip events listed in Table 2. Symbols indicate fault types.

DISCUSSION

The data compiled in this study are representative of surface faulting in general in that the three principal fault types are included, and the geographic distribution and tectonic settings of the events are quite varied. Compared with a group of 53 coseismic surface faulting events associated with earthquakes of M > 6 that occurred in various parts of the world, the strike-slip coseismic faulting in the M < 6 group constitutes the same proportion, but normal-slip events are over-represented and reverse-slip events are under-represented (Table 3). A detailed description of the geographic and tectonic settings is beyond the scope of the study, but a few general comments can be made. A large fraction of the events, 45 percent of the whole set and 36 percent of the coseismic slip events, occurred in California. The settings of the coseismic slip events in California include the San Andreas strike-slip fault system, thrusts on the east side of the Coast Range, Basin-Range structures, and the Sierra foothills fault system. The settings of the 64 percent of coseismic slip events that occurred outside the United States include strike-slip fault systems, normal fault systems, volcanic areas, and the border zone of a major ancient shield.

Table 3. *Frequency of occurrence of fault types in coseismic surface faulting events.*

	M < 6 (This Study)		M > 6 (Bonilla et al., 1984)	
Fault Type	Number	Percent	Number	Percent
Strike slip	10	50	27	51
Normal slip	7	35	11*	21
Reverse slip	3	15	15**	28

*Includes normal oblique slip.
**Includes reverse oblique slip.

The scope and data base of this study permit little discussion of the effects of depth on the development of surface faulting in addition to that of Figure 1. The focal depths of mainshocks given in Table 2 can be assumed to vary greatly in accuracy because many are based on recordings made at distant stations, and a few on local stations; furthermore, the vertical position of the initial rupture (the focus) within the area of the fault rupture is seldom known and may vary considerably. The depths based on aftershocks have the usual uncertainty regarding how the aftershocks relate to the faulting at the time of the main shock -for example, the data for the Oroville, California, event (CA75C) and the 1984 Morgan Hill, California, earthquakes strongly suggest that the aftershocks were outside the area of initial rupture (Lahr et al., 1976; Cockerham and Eaton, 1987), and Cockerham and Eaton give references to two other aftershock series that apparently had a similar relation to the seismogenic rupture. For the 13 coseismic faulting events listed in Table 2 that have focal depth data, no trend is apparent between focal depth and frequency of events.

The findings of this study have application to the evaluation of potential damage to structures from both earthquake vibrations and faulting, and to the evaluation of the activity of faults. Shaking from earthquakes in the 5 to 6 magnitude range can damage structures, particularly if the structures are close to the energy source, and can cause landslides. The larger fault displacements can also damage structures, and the generally minor evidence of surface faulting associated with these earthquakes makes it difficult to identify faults that generate such earthquakes. These topics are briefly discussed in the following paragraphs.

The range in reported maximum Modified Mercalli Intensities of the earthquakes in this data set that were accompanied by coseismic surface faulting is from IV to IX, and the majority (73 percent) have Intensities of VII or greater (Table 2). The effects at the higher levels, briefly stated, are that Intensity VII causes damage to weak masonry such as adobe, Intensity VIII does some damage to reinforced masonry of good workmanship, and Intensity IX seriously damages reinforced masonry of good workmanship (Richter, 1958, pp. 136-138).

A factor in the range in intensities listed in Table 2 is proximity of the seismogenic fault to the reported damage. An evaluation of this factor is outside the scope of the study, but its importance is shown by the three examples that follow. The moderate-sized (magnitude in, 5.6) earthquake of 1972 that had its hypocenter at shallow depth directly under the city of Managua, Nicaragua, produced damage of Intensity IX (N172, Table 2). An earthquake that occurred on the outskirts of the city of Santa Rosa, California on October 1, 1969 had no recognized surface faulting but the energy source was shallow, having a reported focal depth of 2 kin and aftershock depths of 1.4 to 14 km (Lander, 1970). This earthquake had a magnitude in, of only 5.2 (average M,, based on two stations, was 5.4 and Ms was 4.8), but the intensity was VII to VIII, and damage was estimated at $6-10 million (Lander, 1970). The El Salvador earthquake of October 10, 1986, was not accompanied by coseismic surface faulting (Rymer, in press), but its focus was at shallow depth directly below the city of San Salvador (U.S. Geological Survey, 1986). This earthquake, whose magnitude was only in, 5.0 and Ms 5.4 (U.S. Geological Survey, 1986), caused intensity VIII damage to a wide area in the city (Harlow, 1987), and the recorded horizontal acceleration and calculated velocity at one site reached peak values of 72 percent g and 56 cm/sec respectively (Shakal et al., 1986, Table 1).

In addition to damaging buildings, the shaking from earthquakes in the magnitude 5-6 range can cause ground failure related to liquefaction and landslides (Youd and Perkins, 1978; Keefer, 1984). These effects can occur as much as 20 to 60 km from the fault rupture zone for magnitude 6 earthquakes, the maximum distance being related to type of failure (Keefer, 1984, Figure 3).

The fault displacements associated with moderate-sized earthquakes are capable of damaging structures. Examples are the Nicaragua faulting of 1931 (N131, Table 2) that broke a 12-inch water main (Sultan, 19 3 1), the Colombia faulting of 1983 (CO83, Table 2) that ruptured four water mains of unspecified diameter (Lomnitz and Hashizurne, 198 5), and the California faulting of March 1979 (CA79A) that broke the foundation of a house in two places (Bonilla, 1979). These particular events all had small displacements, one decimeter or less. Figure 3 and Table 2 show that several of the coseismic faulting events, o f reverse-slip, normal-slip, and strike-slip types, had displacements of several decimeters. Displacements of this size are capable of damaging important structures, including gravity dams and arch dams (Swiger, 1978).

Surface faulting associated with earthquakes in the magnitude 5 to 6 range is difficult to identify immediately after the event, and evidence of a prehistoric faulting event that may have occurred hundreds or thousands of years ago is even more difficult to identify. Most of the ruptures are less than 10 kin long, many are less than 5 km long, and the ruptures are commonly discontinuous; thus the evidence of a prehistoric rupture presents a small target for the investigator. Besides being of limited extent, the evidence is apt to be subtle. Fi eld evidence of the smaller displacements, some of only a few millimeters, will be very obscure, particularly for strike-slip faulting. The geomorphic expression will be minor and could be rapidly destroyed, and both stratigraphic offsets and scarp-related deposits will be hard to recognize. These difficulties in recognition of prehistoric surface faulting are particularly severe if the fault displacements in successive earthquakes are all similar in size (the "characteristic earthquake" model of Schwartz and Coppersmith, 1984), are small, and the recurrence intervals for earthquakes and faulting are long. Such conditions may explain why so few active faults have been recognized in some regions in which earthquakes typically occur at shallow depths but are infrequent, such as eastern North America.

CONCLUSIONS

From the information and interpretations in this study the following conclusions are drawn:

1. At least 22 earthquakes that occurred in the period 1931-1983 having magnitudes less than 6 were, or probably were, accompanied by coseismic surface faulting.
2. Presently available data indicate that the minimum earthquake magnitude associated with reported coseismic surface faulting is about magnitude 5. The actual but unreported minimum may be considerably less than 5.
3. Shaking from earthquakes having magnitudes between 5 and 6 can damage structures, particularly if the structures are near the seismogenic fault.
4. Surface faulting that may accompany earthquakes in the magnitude 5 -6 range can damage structures.
5. Faults that only produce infrequent earthquakes having magnitudes less than 6 may be very hard to identify using near-surface geologic methods. Investigations of faults possibly having such characteristics need to be comprehensive and detailed. Examination of geomorphic and geologic features of sufficient age to display the cumulative effects of several possible faulting events may be necessary to determine the state of activity of a fault. The investigations, including trenching, should be done at several sites along the fault.

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