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The Maximum Background Earthquake for the Basin and Range Province, Western North America

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Abstract The maximum background earthquake (MBE) is the largest earthquake not associated with significant primary surface rupture. The MBE is estimated for the Basin and Range province considering 22 earthquakes from the province and a simple physical model of a circular rupture in the seismogenic zone. In the Basin and Range province, the number of historical earthquakes in the magnitude range 6 to 6.6 without significant surface rupture is clearly greater than the two events below magnitude 6.6 with primary surface rupture. Based on the historical record, the MBE for the Basin and Range province is magnitude 6.6, but given the various uncertainties involved, the usage of a magnitude value of 6.5 may be more reasonable for seismic hazard studied.

Introduction

The western United States is a region where many faults can easily be identified as seismogenic sources, allowing a straightforward estimation of seismic hazard using techniques such as magnitude versus fault length relationships. Less apparent is the significant hazard posed by background seismicity not directly linked to specific fault sources. This note addresses the size of the largest background earthquakes, sometimes called floating or random earthquakes. These events occur without significant surface rupture, and are generally not preserved in the geologic record. A compilation of historical earthquakes with magnitudes (*M*) 6 to 7 that occurred within the Basin and Range province is used to constrain this maximum background magnitude.

The Basin and Range province of the western United States and northern Mexico (Fig. 1) is an actively deforming region of Cenozoic extension (Stewart, 1980). Twenty-two historical earthquakes from this province (Fig. 1) were considered in this study (Tables 1, 2, and 3). Due to variation in reported magnitudes, three types of magnitude scales are principally used; surface-wave (M_s), local (M_L), and moment (M_w) magnitudes. Over the magnitude range being considered, *M* 6 to 7, these different magnitude scales yield similar values (Kanamori, 1983), and the values reported herein are considered a single data set. In addition, magnitudes of some of the earlier events are reported without reference to magnitude type; these are designated (*M*) in Table 1. Although no systematic study has been undertaken to evaluate errors and variability in the magnitude values used in this study, these values are thought to be accurate to within about 0.3 magnitude units based on the spread of reported magnitude values for some of these (and other) events.

Three main types of surface rupture are considered in this study following Slemmons and dePolo (1986): primary, secondary, and sympathetic surface rupture. Primary surface rupture is fault displacement that is believed to be directly connected to subsurface seismo-

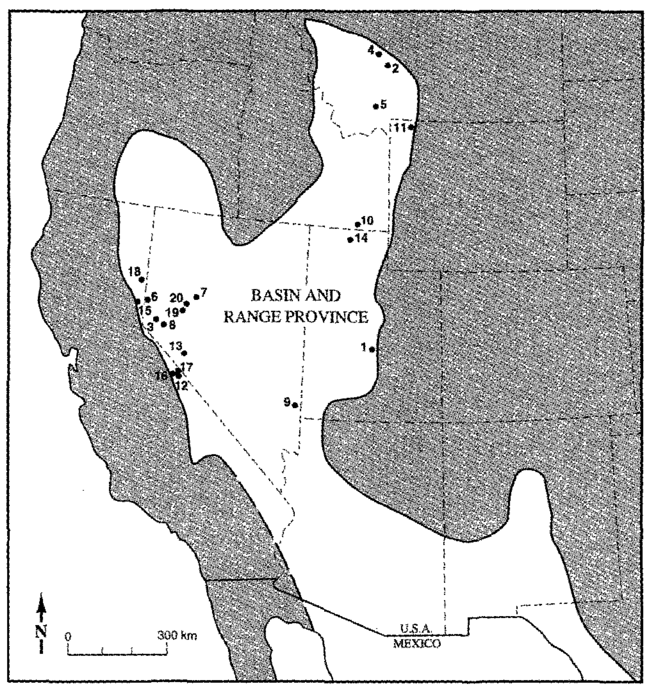

Figure 1. The Basin and Range province of western North America and the locations of earthquakes considered in this study. The numbers correspond to those listed in the location column of Tables 1, 2, and 3.

genic displacement, whereas secondary surface rupture has a branching or secondary relation to the main seismogenic fault. Primary surface rupture can be further subdivided into "minor" (incompletely expressed subsurface rupture) and "significant" (representative of subsurface rupture). Sympathetic surface displacement is triggered slip along a fault that is "isolated" from the main seismogenic fault.

Maximum Background Earthquake (MBE)

Floating and random earthquakes are terms used to

Table 1
Earthquakes $M \geqq 6$ in the Basin and Range Province Since 1920 without Surface Rupture.*

Date	Location	Magnitude	References
29 Sep. 1921	Elsinore, UT (1)	M_L 6	Richins (1979)
1 Oct. 1921	Elsinore, UT (1)	M_L 6	Richins (1979)
28 June 1925	Clarkston, MT (2)	M_w 6.6	Doser (1989a), Pardee (1926)
25 June 1933	Wabuska, NV (3)	M_L 6	Slemmons *et al.* (1965)
19 Oct. 1935	Helena, MT (4)	M 6.3	Doser and Smith (1989)
31 Oct. 1935	Helena, MT (4)	M 6	Doser and Smith (1989)
23 Nov. 1947	Virginia City, MT (5)	M 6.3	Doser and Smith (1989)
29 Dec. 1948	Verdi, NV (6)	M_L 6	Slemmons *et al.* (1965)
23 May 1959	Dixie Valley, NV (7)	M_L 6.3	Gawthrop and Carr (1988)
23 June 1959	Schurz, NV (8)	M_L 6.3	Slemmons *et al.* (1965)
22 Sep. 1966	Clover Mtn., NV (9)	M 6.1	Beck (1970)
27 Mar. 1975	Pocatello, ID (10)	M_L 6.0	Richins (1979)
30 June 1975	Yellowstone, MT (11)	M_L 6.1	Pitt *et al.* (1979)
23 Nov. 1984	Round Valley, CA (12)	M_L 6.1	U.C. Berkeley Seis. Stat. (1989)

*Numbers in location column correspond with locations in Figure 1.

Table 2
Earthquakes $M \geqq 6$ in the Basin and Range Province Since 1920 with Associated Secondary Surface Ruptures, but without or with Only Minor Primary Rupture.*

Date	Location	Maximum Surface Offset (cm)	Magnitude	References
30 Jan. 1934	Excelsior Mtn., NV† (13)	13	M_L 6.3	Callaghan and Gianella (1935), Doser (1988), dePolo *et al.* (1989)
14 Mar. 1934	Hansel Valley, UT† (14)	50	M_s 6.6	Shenon (1936), Doser (1989b)
12 Sept. 1966	Boca Valley, CA (15)	5	M_L 6.0	Kachadoorian *et al.* (1967), Bolt and Miller (1975)
25 May 1980	Mammoth Lakes, CA (16)	20	M_L 6.1	U.C. Berkeley Seis. Stat. (1989), Clark *et al.* (1982)
25 May 1980	Mammoth Lakes, CA (16)	20	M_L 6.0	U.C. Berkeley Seis. Stat. (1989), Clark *et al.* (1982)
25 May 1980	Mammoth Lakes, CA (16)	20	M_L 6.1	U.C. Berkeley Seis. Stat. (1989), Clark *et al.* (1982)
27 May 1980	Mammoth Lakes, CA (16)	20	M_L 6.2	U.C. Berkeley Seis. Stat. (1989), Clark *et al.* (1982)
21 July 1986	Chalfant Valley, CA† (17)	11	M_L 6.5	U.C. Berkeley Seis. Stat. (1989), dePolo and Ramelli (1987), Lienkaemper *et al.* (1987)

*Numbers in location column correspond to locations in Figure 1.
†Indicates possible minor primary surface rupture.

Table 3
Earthquakes $M \leqq 7$ in the Basin and Range Province Since 1920 with Significant Primary Surface Rupture.*

Date	Location	Magnitude	Maximum Surface Offset (cm)	References
14 Dec. 1950	Fort Sage, CA (18)	M 5.6	60	Gianella (1951, 1957), Bonilla *et al.* (1984)
6 July 1954	Rainbow Mtn., NV (19)	M_s 6.3	30	Tocher (1956), Bonilla *et al.* (1984)
24 Aug. 1954	Stillwater, NV (20)	M_s 7	76	Tocher (1956), Bonilla *et al.* (1984), Bell (1984)
16 Dec. 1954	Dixie Valley, NV (7)	M_s 6.8+	270	Slemmons (1957), Bonilla *et al.* (1984)

*Numbers in location column correspond to locations in Figure 1.

describe scattered seismicity that is not associated with a specific fault. Use of the term "floating earthquake" is somewhat confusing, however, because it implies a lack of understanding of, or relationship to, seismotectonics. Seismologist colleagues have mused that a floating earthquake must be a bad location iteration with a negative depth or a sonic boom. The term "random earthquake" suggests a statistical behavior that may not necessarily apply to these events, especially during swarming or clustering activity. The term "background seismicity" is also commonly used, but it implies a broader range of earthquake sizes (especially lower magnitudes) than is considered here. For this study, the latter term is modified slightly to "maximum background earthquake" (MBE) to describe the largest earthquakes not associated with significant primary surface rupture (dePolo *et al.*, 1990). The MBE includes nonsurface rupture events, as well as earthquakes associated with small secondary and sympathetic surface breaks.

The MBE can be considered the upper bound for background seismicity studies. Such a magnitude distribution or single event is commonly used in probabilistic studies as having a random occurrence over an area, using the number of historical background earthquakes from the area over various magnitude ranges. A deterministic way to input the MBE is to consider it occurring a set, or statistically determined, distance away from the site being analyzed.

The MBE can also be considered the lower-bound magnitude for various magnitude-fault parameter regression equations developed or used in the Basin and Range province. Such regressions are commonly used for scaling the size of potential earthquakes that can occur along a fault. Estimations below the MBE magnitude are likely based on incompletely expressed or secondary ruptures.

Background Earthquakes from the Basin and Range Province

The earthquake data set is limited to the Basin and Range province, which exhibits an extensional tectonic stress regime throughout its area. Previous studies in the eastern Basin and Range province have noted several earthquakes with magnitudes up to $6^3/_4$ which apparently occurred on structures having no surface expression (Doser, 1985; U.S. Bureau of Reclamation, 1986). Arabasz *et al.* (1992) also discuss MBE's from the Intermountain seismic belt. They conclude that the MBE's range from magnitude 6 to 6.5, they adopt M_L 6.3 ± 0.2 as an estimate for Utah, and similarly conclude that events up to this size can occur anywhere, even in areas with no geologic evidence of Quaternary surface faulting.

In this study, two types of background earthquakes ($M \geqq 6$) are compiled: those lacking surface rupture (Table 1), and those having secondary or sympathetic surface rupture without or with only minor primary tectonic surface rupture (Table 2). Also compiled are earthquakes with significant primary rupture that have magnitudes that are $\leqq 7$ (Table 3). All events of magnitude 7 and greater have had significant primary surface rupture. At least 22 background events with magnitudes $\geqq 6$ have occurred since 1920. Five other historical earthquakes were immediate aftershocks of primary surface-rupture earthquakes; four of these events were associated with the 1959 Hebgen Lake, Montana earthquake (*M* 6.5, 6, 6.5, and 6) and one with the 6 July 1954 Rainbow Mountain, Nevada earthquake (*M* 6). These aftershocks are not considered in this study. Although many historical earthquakes of magnitude 6 or greater with no reported surface rupture occurred within the Basin and Range province, earthquakes occurring prior to 1920 are poorly documented and thus were not used.

Fourteen earthquakes ($M \geqq 6$) lacking reported surface rupture have occurred in the Basin and Range province since 1920 (Table 1). Most of these earthquakes are in the magnitude range of 6 to 6.3. The largest event in this category was on 28 June 1925 in Clarkston, Montana. It had a magnitude of M_w 6.6 (M $6^3/_4$), and is considered a reliable event to include because it was specifically studied for evidence of surface deformation and earthquake size (Pardee, 1926; Doser, 1989a).

Eight earthquakes ranging in magnitude from 6 to 6.6 had secondary or minor primary surface rupture (Table 2). Surface breaks associated with these events were commonly distributed and exaggerated in size. Three events may have had some minor primary surface rupture: the 1934 Excelsior Mountains, the 1934 Hansel Valley, and the 1986 Chalfant Valley earthquakes. Displacements were on the order of 13 cm vertical for the Excelsior Mountains event and 11 cm or less right-lateral for the Chalfant Valley event; the Hansel Valley earthquake caused up to 50 cm of vertical surface displacement, but most if not all of this was probably due to liquefaction (McCalpin, personal comm.). Most of the surface ruptures associated with the events in Table 2 were so minor (mostly less than 5 cm) that they were quickly obscured or eroded, and are not generally preserved in the geologic record.

Figure 2 is a histogram showing the number of non-surface-rupture, secondary, and other breaks, and primary surface-rupture events that have occurred since 1920 over the magnitude range of 6 to 7. This figure shows a range of magnitudes (~M 6.3 to 6.6) forming a transition between non-surface-rupture and primary surface-rupture events.

Theoretical Considerations

Another method of assessing the MBE is to evaluate the simple physics of an earthquake that does not rupture the surface in the Basin and Range province and check if the results are consistent with the MBE estimated from

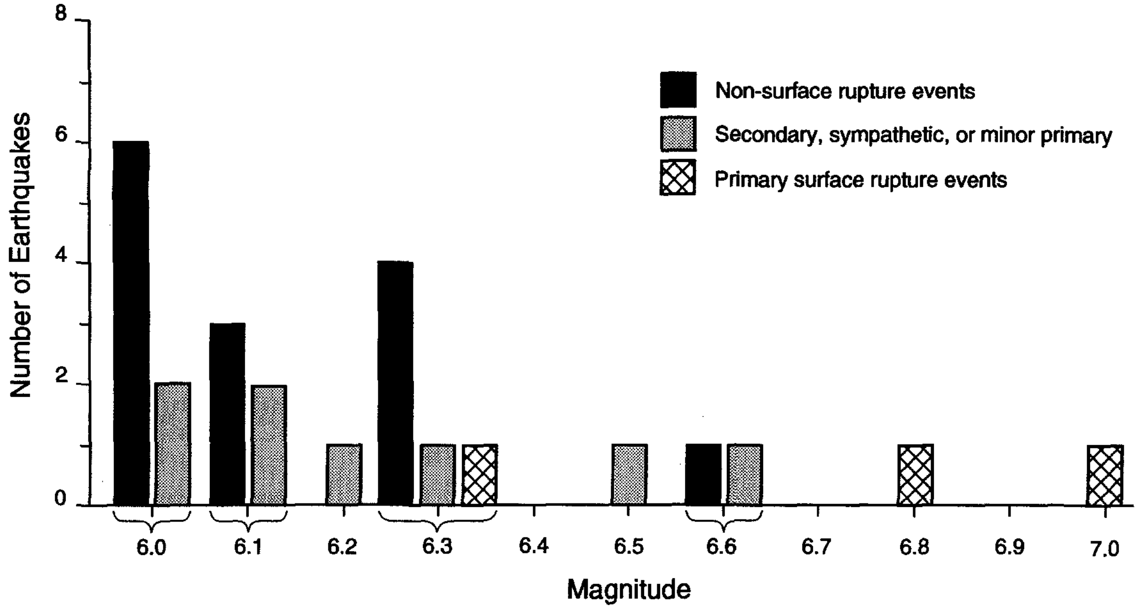

Figure 2. Histogram showing the number of non-surface-rupture, secondary, and other minor surface breaks, and primary surface ruptures occurring over the magnitude range 6 to 7.

historical earthquakes. A circular rupture that is tangential to the ground surface and to the base of the seismogenic zone is considered to be a reasonable model for an earthquake in the intermediate category with regard to causing secondary surface ruptures. Since most of the faults in the Basin and Range province appear to have a dip somewhat shallower than vertical and we are discussing a maximum estimate (MBE), a commonly encountered, 60° dip is used. Perhaps the most uncertain parameter in this model is the stress drop; however, a stress drop of at least 1 bar and as high as 100 bars seems to be a reasonable range for earthquakes (Kanamori and Anderson, 1975; Hanks, 1977). Seismic moments (M_0, dyne-cm) were estimated using this range and the equation developed by Brune (1970, 1971) for circular ruptures,

$$M_0 = \left(\frac{16}{7}\right)(r^3)(\Delta\sigma).$$

In this equation r is the radius (in centimeters) and $\Delta\sigma$ is the average stress drop (in dyne/cm^2). These moments were converted to moment magnitudes for comparison to the historical earthquakes using Hanks and Kanamori's (1979) relation:

$$M_w = \left(\frac{2}{3}\log M_0\right) - 10.7.$$

Values from these calculations are presented in Table 4 for several different values of stress drop and two different estimates of seismogenic depths, 12 and 15 km (seismogenic widths of 13.8 and 17.4 km, respectively). From Table 4, the magnitudes predicted for $\Delta\sigma > 30$ bars are mostly smaller than most events that have caused primary surface rupture, but larger than most of the events without reported surface rupture (Fig. 2). Since these are reasonable stress-drop values for Basin and Range province earthquakes, it is concluded that the MBE estimated from historical earthquakes is consistent with this simple physical model of earthquakes.

Table 4
Theoretical Moment Magnitudes for Earthquakes that Do Not Rupture the Surface

Stress Drop (bars)	M_w (r = 6.9 km)	M_w (r = 8.7 km)
1	5.2	5.4
10	5.9	6.1
20	6.1	6.3
30	6.2	6.4
40	6.4	6.6
50	6.4	6.6
90	6.5	6.7
100	6.6	6.8

Discussion

The tabulation of historical earthquakes without reported surface rupture (Table 1) suggests that the MBE for the Basin and Range province is at least magnitude

6.3 and may be as high as magnitude 6.6. Only two events less than magnitude 6.6 apparently had significant primary surface rupture: the 1950 Fort Sage earthquake (M_L 5.6) and the July 1954 Rainbow Mountain earthquake (M_s 6.3). Surface rupture during these events may be explained by shallow focal depths or a low stress drop. Contrasting this with the occurrence of 14 events without reported surface rupture and eight events with only minor surface rupture in the magnitude 6 to 6.6 range suggests that most earthquakes of magnitude 6.6 and lower in the Basin and Range province generally do not rupture the surface. Although minor primary-surface faulting has occurred in some events (Table 2), it is unlikely to be preserved in the surficial geologic record or to be usable for scaling the size of the causative event.

Figure 3 shows the magnitude of events from Tables 1, 2, and 3 plotted against the maximum surface displacement. This figure shows that the non-surface-rupture earthquakes and other events with minor surface ruptures (Tables 1 and 2) all have displacements ≦20 cm, except for the 1934 Hansel Valley earthquake, where surface faulting was probably enhanced by liquefaction. Furthermore, these events show no real trend of an increase in maximum surface displacement with magnitude. In contrast, the primary surface-rupture events do show a trend of increasing maximum surface displacement with magnitude. It is thought that these primary displacements are representative of the slip at depth, and are appropriate for developing regression equations for estimating potential earthquake sizes. It is also interesting to note that the intersection of this trend with the zero displacement axis is around magnitude 6.6, consistent with Table 4.

Even though different tectonic rates characterize the Basin and Range province, tectonic rate is not considered to be a determining factor in identifying earthquakes lacking surface rupture or in establishing the size of the MBE. Although the distribution of tectonic rates in the Basin and Range province is not well known, based on tectonic geomorphology and seismicity, a range of strain rates is present (Eddington *et al.*, 1987). While most earthquakes used in this study have occurred in areas with apparent high strain rates, significant earthquakes, such as the 1925 Clarkston, Montana (M_w 6.6) and 1935 Helena, Montana (*M* 6 and 6.3) earthquakes, have also occurred in areas that apparently have relatively moderate strain rates. The MBE developed here is thought to be valid for the entire Basin and Range seismotectonic province, but the frequency of this event likely varies with changes in regional strain rates.

The MBE for the Basin and Range province is in the magnitude range of 6.3 to 6.6. Because of the lack of precision involved in the magnitude values and uncertainties in the interpretation of events and their associ-

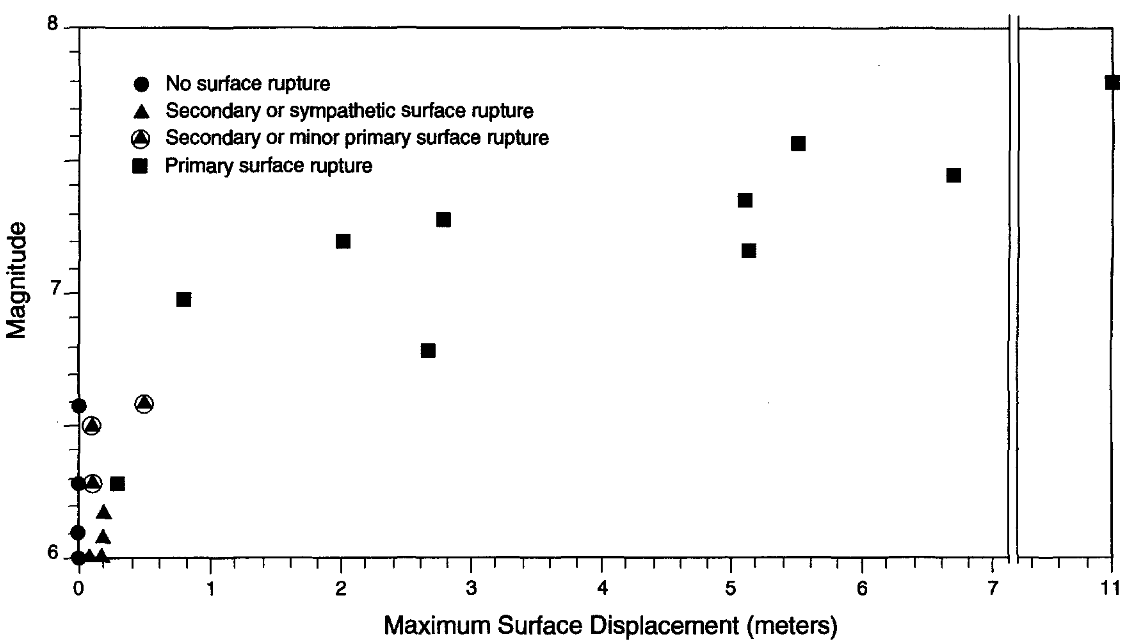

Figure 3. Graph showing magnitude versus maximum surface displacement for non-surface-rupture, secondary, and other minor surface breaks, and primary surface displacements. Note the break in the maximum displacement scale. The additional data used for the larger primary surface-rupture events is compiled in dePolo *et al.* (1991). Uncertainties in the magnitude values are estimated to be on the order of 1/3 of a magnitude unit. Uncertainties in surface-displacement measurements scale with displacement, from a few to 10 cm for the smaller displacements and up to about 1/2 m for the larger displacements.

ated surface displacements or lack thereof, it may be more desirable or reasonable to use magnitude 6.5 as the MBE value.

Conclusions

The term "maximum background earthquake" appears to be an adequate descriptive term for referring to the largest background earthquake. In the Basin and Range province, the number of historical earthquakes in the magnitude range of 6 to 6.6 without significant surface rupture is significantly greater than the number of earthquakes below magnitude 6.6 that have significant primary surface rupture. Based on the historical earthquake record the maximum background earthquake for the Basin and Range province is magnitude 6.6, but given the uncertainties in the magnitude values and other uncertainties, magnitude 6.5 may be more practical for use in seismic hazard studies. These magnitude values are consistent with a simple physical model of earthquake faulting that is tangential to the surface for the Basin and Range province.

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