Maximum Earthquake Magnitudes in the Basin and Range: A Geologic Perspective

David P. Schwartz
US Geological Survey
Menlo Park, CA
dschwartz@usgs.gov

One of the issues surrounding the potential for extreme ground motions at Yucca Mountain is the magnitude of the largest earthquake that can possibly occur on a fault in the Basin and Range at a probability of 10^{-8}/yr. With a short historical record and the occurrence of only seven surface-faulting events with magnitudes higher than 6.5 (range Mw 6.6 to Mw 7.3) the argument can certainly be made that larger events are possible. But how large? And is there a physical basis for placing an upper bound on this magnitude? A potential answer comes not from the historical occurrence of earthquakes but from the past earthquake history of the region, namely the paleoseismic record.

One of the first concepts a geology student is exposed to is "the present is the key to the past". Understanding the nature and variability of present-day processes, whether sediment deposition in deltas, the morphology of active landslide deposits, or the geomorphic expression of surface rupture from a historical event provides a basis for more accurate interpretation of similar features preserved in the geologic record. Seismic hazard analysis requires that we estimate what is likely to occur—whether it is the magnitude of a future earthquake, the amount of future displacement at a point on a fault, or ground motions. For those of us working with seismic hazards arena there is also a second basic concept, which is "the past is the key to the future". Knowledge of what has or has not happened over a range of time intervals is critical for forecasting what can occur in the future. To develop a better understanding of the magnitude of future earthquakes in the Basin and Range we can turn to past behavior of the region's active faults.

Locations of Past and Future Slip—The Fault Inventory

Figure 1 shows the locations of faults that have ruptured in the Basin and Range during intervals extending from historical time through the entire Quaternary. The historical record is short and contains few earthquakes. During the past 15 ka faulting has been more widespread, with multiple rupture of some sources, but is unrepresentative of the region as a whole. Faulting during the past 130 ka is broadly distributed and this distribution is not significantly different from the 750 ka interval. The lower map in Figure 1 shows the locations of faults that have slipped during Quaternary time. This series of maps provides an inventory of earthquake sources during the past approximately 2 million years. Future events will almost invariably occur along these existing faults. As such this fault inventory contains the information, in the form of displacement per event and timing, on the size of past earthquakes.

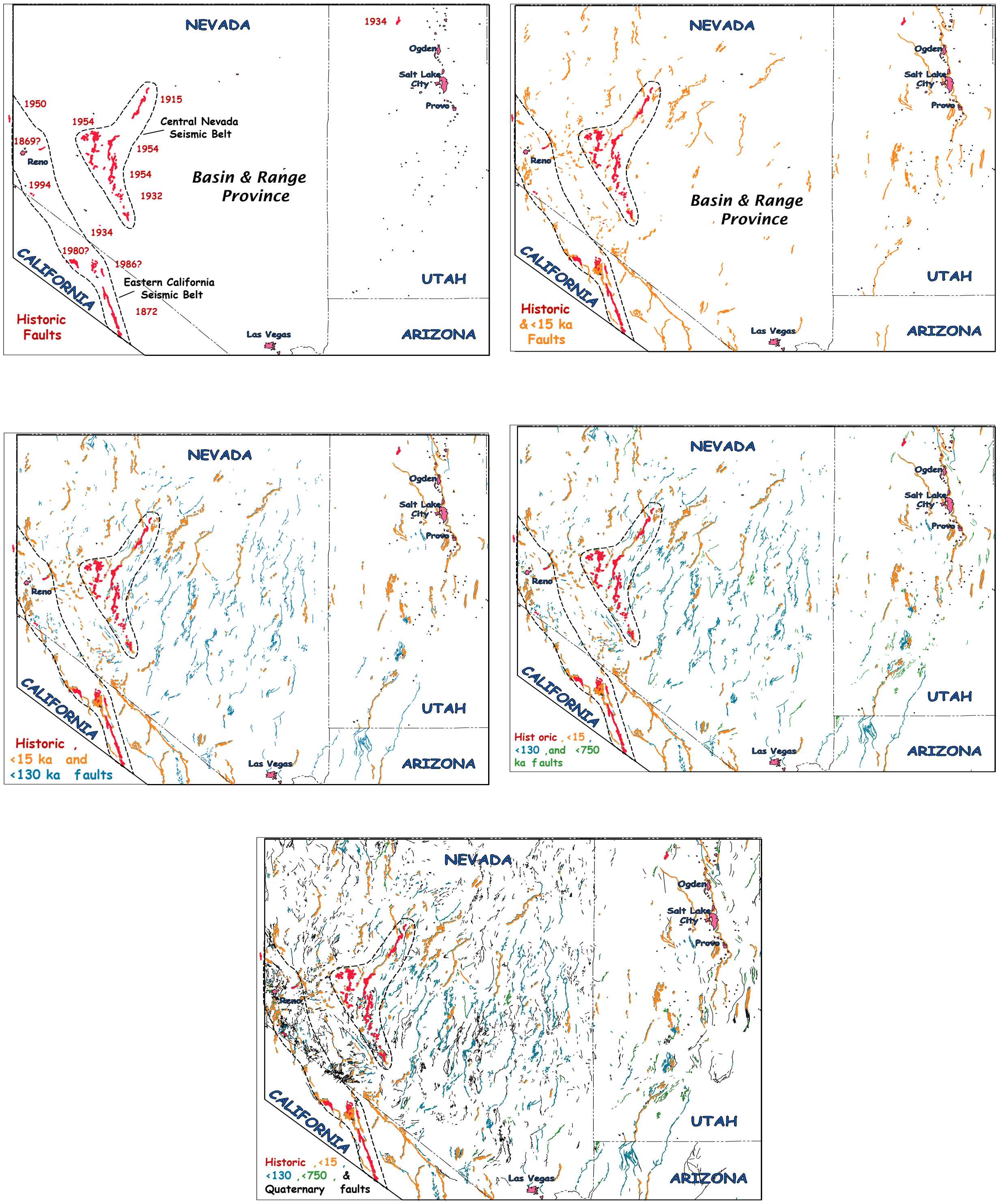

Figure 1. The distribution of faulting during different intervals in the Quaternary (developed by M. Machette from the US Quaternary Faults and Fold Database)

Earthquake Magnitudes

The seismic moment of an earthquake is the product of the fault rupture area (rupture length and rupture width), the average slip, and the shear modulus. This can be converted to moment magnitude by the relation Mw= 2/3logMo-10.7 (Hanks and Kanamori, 1979). Investigations of historical earthquakes show that surface rupture length and the average measured surface offset, along with a fault width derived from the average depth distribution of aftershocks or regional seismcity (thickness of seismogenic crust) provide estimates of magnitude comparable to the seismologic magnitude. In a recent example the magnitude of the 2002 Denali fault Alaska earthquake is calculated as Mw7.8 using surface fault observations, essentially the same as the seismologic magnitude of M7.9 (Haeussler et al, 2004).

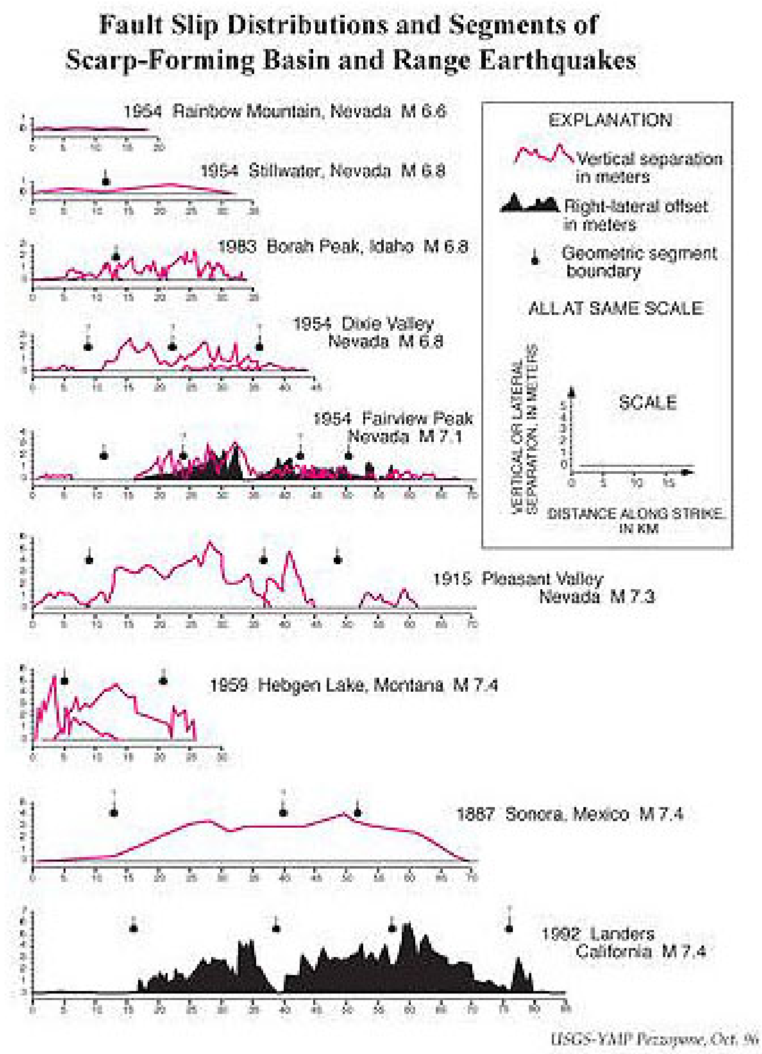

Figure 2. Historica

Trenching and scarp morphologic studies provide data on the amount of surface slip during individual paleoearthquakes. Rupture length can be developed from information on the timing (similarities/differences) of events along the length of a fault, which allows individual rupture segments to be identified. An important uncertainty in calculating paleo rupture lengths is the potential for multi-segment ruptures (see, for example, Chang and Smith, 2002). Just how far can a normal fault rupture propagate? Figure 2 shows the surface rupture lengths and slip distributions from historical Basin and Range earthquakes. Rupture lengths have ranged from 18 km to 70 km. The maximum observed historical surface slip approaches 6 m. In general the average and maximum surface displacement increase as rupture length increases along range bounding faults. However, the largest average historical slip occurred during the 1959 Hebgen Lake earthquake where the Hebgen and Red Canyon faults ruptured for a combined length of only 27 km. These faults lie within a range, and perhaps there is a difference between range front and within-range faults with regard to average slip per event and stress drop.

Fault width is defined by the dip of the fault and its down-dip extent. Figure 3 shows current thinking and a working model for normal-faulting earthquakes. In the Basin and Range the average thickness of the seismogenic crust is about 15 km. This may vary locally (thinner or thicker) but appears to be quite representative of normal fault nucleation depths both here and worldwide. There is also uncertainty in estimating the dip of faults that have not had historical ruptures; there may be those with shallower dips that could result in somewhat larger magnitude earthquakes.

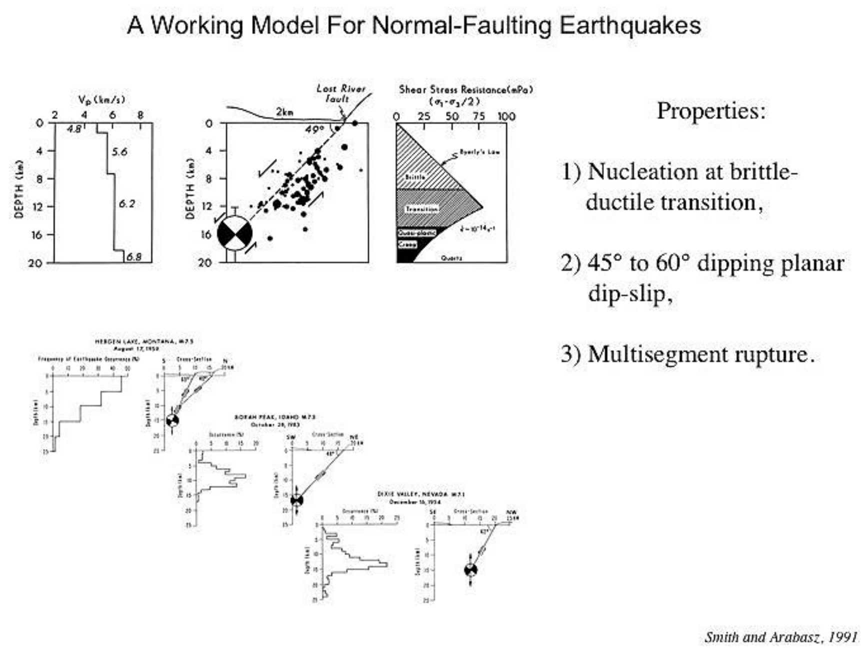

Figure 3. A model of nucleation depths and dips for normal-faulting earthquakes (from Smith and Arabasz, 1991).

Bounding the Magnitude of the Largest Basin and Range Earthquakes—Looking Back to Look Ahead

It is not unreasonable to assert that the historical record is too short to have shown us the largest earthquake that can occur in the Basin and Range. But how large can this earthquake be? The geologic record of faulting in the Quaternary y provides an inventory of earthquake sources containing information on past magnitudes (slip and length) across the entire region. At present much of this is has not been sampled paleoseismically. But where studies have been done, primarily on faults that have ruptured during the past 130 ka, there is no indication of a “planet buster”—that is, an event with slip that is many factors larger than anything already observed. To date the maximum net coseismic surface slip observed both historically and paleoseismically is 5-6m, and even these slip values have occurred only along limited sections of a rupture. In general, repeated net surface displacement observed at individual points along Basin and Range faults is 1-3m.The maximum rupture length that has occurred historically is 70 km. Large earthquakes require sources with dimensions that can produce them. The Wasatch fault is currently the longest continuous active normal fault in the Basin and Range with a total length of 350 km. It is divided into six rupture segments (Machette et al, 1992), each considered a source of future earthquakes. If a scenario is used in which all six segments rupture with an average slip of 4 m (slip of about 2m/event is what is actually observed in trenches along each segment) and an average dip of 40 degrees through a 15 km thick seismogenic crust, the resulting Mw would be 7.85. Increasing the average slip to 8m would increase the magnitude to 8.15

In extending probabilities to 10^{-8}/yr one is placed in a position where is it essentially impossible to never say never. However, our present understanding of fault behavior and crustal rheology combined with expanded observations of faulting (especially paleoseismic slip per event) can provide the basis for a rational and physically realistic upper bound on the magnitude of the maximum earthquake that can be expected to occur on a fault in the Basin and Range.

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Quaternary Faults and Fold Database of the United States http://Qfaults.cr.usgs.gov/