

# Earthquake Occurrence in the Reno-Carson City Urban Corridor

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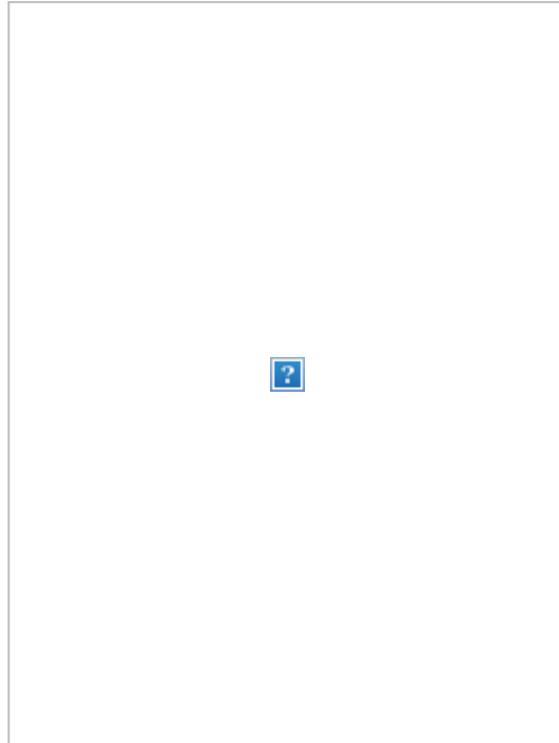
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published in the

[Seismological Research Letters](#), Volume 68, May/June, 1997, pages 401-412.

## Introduction

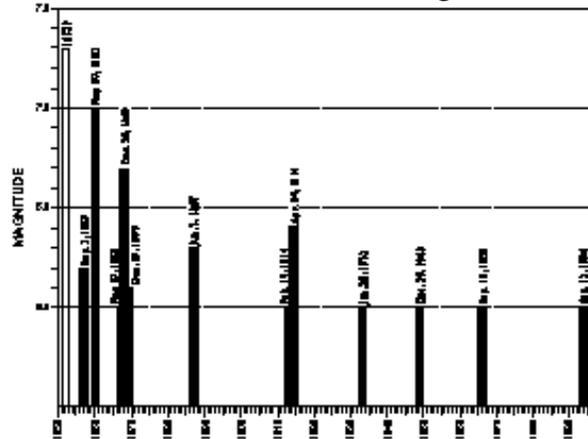
The Reno-Carson City urban corridor is the second most populated region in Nevada, and lies in one of the most seismically active parts of the State. This has prompted the development of an earthquake scenario (dePolo et al., 1996) to assist with earthquake preparedness and emergency response planning within the corridor's communities. As part of this effort, we have estimated probabilities of a potentially damaging earthquake affecting the scenario area (Figure 1) over a 50-year time period. This paper briefly describes local historical earthquakes of magnitude  $\geq 6$  and compares their occurrence rates with b-value curve extrapolations from the instrumental time period and preliminary estimates based on local fault activity rates.



**Figure 1:** Major historical earthquakes in the Reno-Carson City urban corridor (population ~400,000), western Nevada, based on published and ongoing research. All earthquake locations, except the 1966 and the 1994 earthquakes, are only approximately known. Magnitudes used are from Rogers et al. (1991).  
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## Historical Earthquakes

Thirteen earthquakes of magnitude 6 or greater have occurred in the scenario region since 1850 (see Figure 1 and [Table 1](#)). These events are briefly described in the [Appendix](#). For many of the earlier events, only newspaper accounts are available and the locations are uncertain. Two of the earliest events on record in western Nevada (1852? and 1857) are not shown on Figure 1 because their locations are highly uncertain at this time. Although their location within the scenario area is equivocal, these two events did appear to occur in western Nevada (see [Appendix](#) for discussion). Further research, including a review of local diaries, is planned for these and other, earlier events to aid in understanding their locations and sizes.



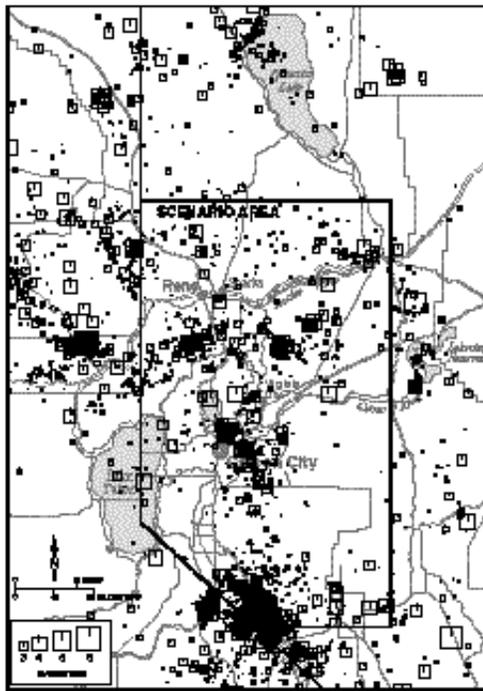
**Figure 2:** Time line of major earthquakes in western Nevada. Magnitudes are from Rogers et al. (1991) and the University of California, Berkeley.

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Earthquake magnitudes used in this paper are from Rogers and others (1991) and from the University of California, Berkeley. Many of these magnitudes are uncertain and other magnitudes are reported (see [Appendix](#)). Variations in magnitude estimates are larger for the earlier events (0.2 to 0.7 magnitude units), whereas events within the last few decades have been determined within about 0.1 magnitude unit.

A time line of the larger earthquakes occurring in the scenario area (see Figure 2) clearly shows that the mid to late 1800s was the most active period in the area's history. No earthquakes of magnitude  $\geq 6.5$  have occurred in the scenario area since 1869, but earthquakes with magnitudes 6 to 6.4 have continued, with intervals between earthquakes ranging from 65 days to 28 years.

The 1868-1869 sequence and the 1914 earthquakes were both temporally clustered, although the 1914 earthquakes were apparently spatially separated. Although of smaller magnitudes, the 1868-1869 sequence bears resemblance to the famous 1954 Rainbow Mountain-Stillwater-Fairview Peak-Dixie Valley earthquakes east of the scenario area, which included two magnitude 6 earthquakes and three events of magnitude 6.8 or larger (the largest was magnitude 7.2) over a time period of six months (Slemmons, 1957). This temporal clustering of earthquakes has an important risk implication. Buildings weakened by the initial event may suffer further damage or collapse from subsequent events, as occurred in Fallon in 1954 from the July 6 and August 23 earthquakes (Steinbrugge and Moran, 1956).



**Figure 3:** Seismicity in western Nevada from 1960 to 1995. Data are from the University of Nevada, Reno Seismological Laboratory.

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## Probabilistic Estimates of Earthquake Activity

The probability of a magnitude  $\geq 6$  earthquake occurring in the scenario area is estimated from historical earthquakes, instrumental seismicity, and geological estimates. We use two methods to estimate rates of magnitude  $\geq 6$  earthquakes, three methods for magnitude  $\geq 6.6$  earthquakes, and four methods for magnitude  $\geq 7$  earthquakes ([Table 2](#)). The historical earthquake method simply counts the number of earthquakes of a given magnitude or larger within a region. The historical time period is then divided by the number of events to get the average recurrence interval. The inverse of this average recurrence interval is the earthquake occurrence rate (number of a given magnitude event or larger per year). The probability of an earthquake in  $T$  years is estimated using (in Fortran notation):

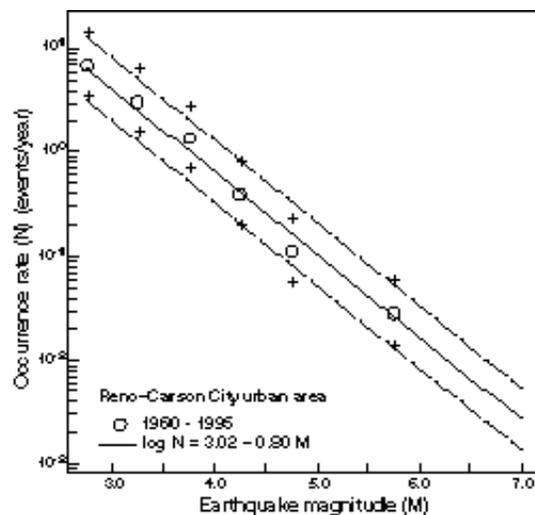
$$p = 1 - \exp(-N*T),$$

where  $p$  is the probability of one or more events occurring of a given magnitude or larger,  $N$  is the number of events per year, and  $T$  is the time period of interest (in this case, we use 50 years). This equation assumes earthquake occurrence can be described by a Poisson process, hence, earthquakes are considered to occur randomly through time. Considering uncertainties in magnitudes and locations of historical earthquakes, there were 9 to 12 events in 145 years (~1851 to 1995) with magnitudes of 6 or larger, 1 to 3 events of magnitude 6.6 or larger, and 1 to 2 events of magnitude 7 or larger that have occurred within the scenario boundaries.

The instrumental seismicity method uses earthquakes recorded in the scenario area between 1960 and 1995. This 36-year period roughly represents the installation of local instrumentation and, consequentially, a relatively complete earthquake catalog. The number of events per year of a given magnitude or larger are modeled by the standard Gutenberg-Richter b-value formula (Gutenberg and Richter, 1954; here in Fortran notation):

$$N = 10^{*(a - b*M)},$$

where  $N$  is the number of events per year with magnitude  $M$  or larger,  $a$  is the productivity (an overall earthquake activity coefficient), and  $b$  is a coefficient that describes the relative number of small earthquakes versus large earthquakes (the slope of the relationship). These coefficients are determined by fitting a line through the instrumentally recorded occurrence rates. These rates are derived after testing the completeness of different magnitude bins ( $\pm 0.5$  magnitude units wide) centered on even magnitude values by using techniques after Stepp (1972). The instrumental seismicity from the University of Nevada, Reno Seismological Laboratory catalog includes 5773 events (Figure 3) and confirms the active seismicity of the area. The seismicity within the scenario boundaries and a band 5 km wide outside of the boundaries are used to derive the b-value line shown in Figure 4. The b-value formula is then used to extrapolate to magnitude  $\geq 6$ , magnitude  $\geq 6.6$ , and magnitude  $\geq 7$  occurrence rates to give the instrumental seismicity rate estimates (Table 2). To evaluate the potential uncertainty in the instrumental method, we removed the 1994 Double Spring Flat earthquake and its associated earthquake sequence by limiting the time frame to events occurring prior to 1994. Occurrence rates were significantly affected, with the largest difference being about a factor of 2. We thus assumed that the uncertainty in the instrumental method could be represented by varying the occurrence rate by a factor of  $\pm 2$ , which corresponds to a variation of  $\pm 0.3$  in the  $a$  coefficient (Figure 4).



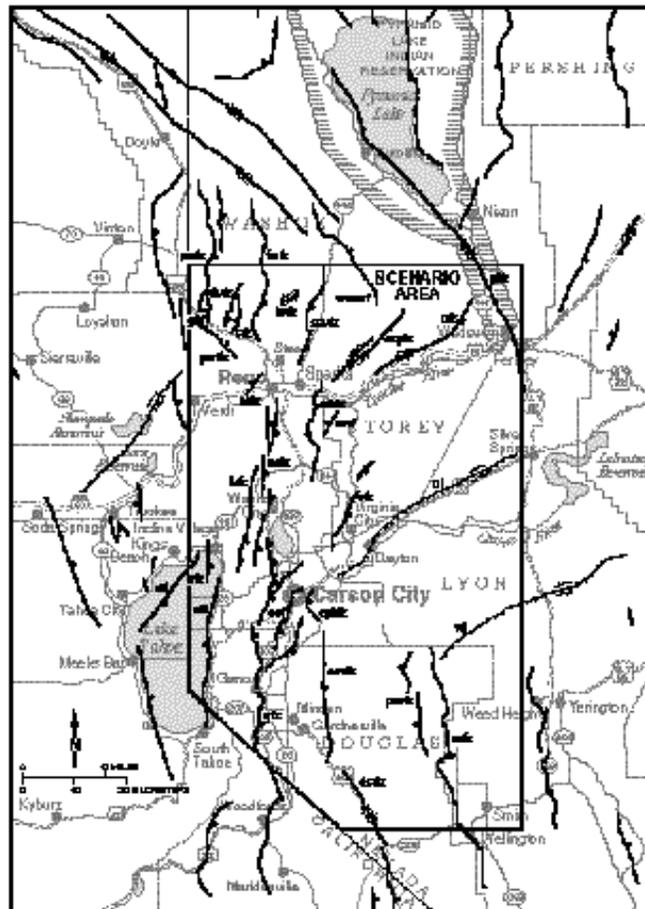
**Figure 4:** Average number of events per year, including aftershocks, for the years 1960 through 1995, in the western Nevada scenario area (octagons). The crosses are these activity rates multiplied by  $\pm 2$  to represent uncertainty. The b-value curve is determined from a visual fit to the points shown in the plot.  $N$  is the number of events with magnitude  $M$  or larger. The dashed lines represent the estimated uncertainty of the relationship using  $\pm 0.3$  times the  $a$  value.

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The b-value derived here ( $b=0.8$ ) is also used in the "modified historical" method to extrapolate from the historical rate of 9 to 12 events with magnitude  $\geq 6$  to estimate the number events with magnitude  $\geq 7$ . This provides an independent estimate of large earthquake rates, since the magnitudes of the early events are uncertain.

The geological method uses the local Quaternary or suspected Quaternary faults that are either partly, or entirely, within the scenario area. Expected earthquake magnitudes (mean-value magnitudes) are estimated using speculative earthquake segment lengths and maximum surface displacements from faults. These parameters are then used in empirically derived formulas to estimate surface-wave magnitude. The empirical relations used include Basin and Range province data (dePolo et al., 1990) and data from extensional environments (Mason, 1992, 1996). These regressions are for all senses of displacement (Table 3). The average of all values characterized for a fault are used for the expected magnitude. In most cases, this is limited to segment length because maximum surface displacements have not been reported or measured. Although detailed segmentation studies have in general not been conducted for these faults, the defined

segment lengths are comparable to historical Basin and Range province ground-rupturing events. Further, the logarithmic scale of length used in magnitude versus length relations makes size estimates relatively insensitive to moderate errors in length estimates. Earthquake size estimates based on length are assumed to be accurate to within  $\pm 0.3$  magnitude units. Since most earthquakes of magnitude 6 to 6.5 in the Great Basin are not associated with significant primary surface rupture (dePolo, 1994), the minimum magnitude associated with faults having surface expression is magnitude 6.6. Fault slip rates were estimated using reported rates, offset Quaternary surfaces, geologic offsets, or based on a fault's geomorphic expression (dePolo, in prep.). A paleoseismic surface displacement or a displacement empirically correlated with the expected earthquake magnitude is divided by maximum and minimum fault slip rates to get the minimum and maximum average earthquake recurrence intervals. Displacements correlated with magnitude are maximum surface values and are halved to represent average displacement for the calculation of the average earthquake recurrence interval. Thus, each fault is associated with an earthquake magnitude and an average earthquake recurrence interval, or occurrence rate. Occurrence rates for faults associated with a given magnitude or larger are added together for use in determining the probabilities of earthquake occurrence.



**Figure 5:** Principal Quaternary and suspected Quaternary faults in western Nevada. Faults are shown schematically, with balls on the downthrown side and arrows indicating strike-slip motion. The lines with dots are seismogenic lineaments. Fault acronyms correspond to [Table 4](#).  
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The 30 faults considered in this study ([Table 4](#) and Figure 5) include only the larger or more prominent Quaternary and suspected Quaternary faults. It is likely that there are more faults in the scenario area yet to be identified. Also included in this data set are two "seismogenic lineaments". These are structural trends that have discontinuous Quaternary fault scarps and/or associated seismicity. The importance of these lineaments is underscored by the location of two magnitude 6 earthquakes that occurred in 1948 (Verdi earthquake) and in 1966 (Boca Valley earthquake) along or proximal to the Dog Valley lineament, which

lies immediately west of the scenario area. Although fault scarps and seismicity indicate these lineaments are seismogenic, they lack the through-going character of the other identified faults. Consequentially, the weak and discontinuous geomorphic expressions are assumed to indicate a limit to their potential earthquake magnitudes. For example, they are considered unlikely to rupture over their entire lengths during single events.

The earthquake occurrence rates estimated using the different methods are presented in three magnitude groups, magnitude  $\geq 6$ ,  $\geq 6.6$ ,  $\geq 7$  ([Table 2](#)), which were chosen for the following reasons. A magnitude 6 earthquake is a large enough event to be expected to cause damage over part of the scenario area. A magnitude of 6.6 is based on the minimum magnitude value associated with primary tectonic surface faulting, and hence, the minimum magnitude value assigned to faults having surface expression. An event of this size could cause damage over much of the scenario area, with locally severe damage. A magnitude 7 or larger earthquake would be expected to cause severe damage over large portions of the urban area (dePolo et al., 1996).

## Discussion

A clear observation from Figure 2 and the differences in the historical and instrumental methods ([Table 2](#)) is that the past 36 years have been seismically quiet relative to the first 100 years of the region's history. This good fortune cannot be relied upon to continue. However, although a longer time interval is considered to give a more reliable estimate of seismicity rates, the possibility that the first 100 years of our historical record were unusually active cannot be ruled out. This is supported by the geologic estimates, which are similar to the lower instrumental rates, but the geological estimates must be considered to have very large uncertainties at this time, both in fault identification and in earthquake occurrence rate estimation. More Quaternary faults are suspected to exist, some within ranges and others buried by recent alluvium within basins. Further, the estimated slip rates generally only consider faults with normal slip, although suspicious lineaments and a predominance of strike-slip focal mechanisms from local earthquakes (Martinelli, 1989) indicate unrecognized strike-slip faulting. Thus, we suspect that future research will tend to increase these rates and, consequently, to increase the geologic probability estimates of having an earthquake. Other assumptions that potentially underestimate the geologic probability are the size of the maximum background earthquake and the percentage of maximum surface displacement that represents the average displacement. If a smaller maximum background earthquake is assumed, smaller sized events that occur more frequently would be estimated for some faults. If average displacement is a smaller percentage of maximum displacement, earthquake occurrence would also increase. In this light, the similarity of geological rates and instrumental rates may be coincidental, with a longer term average somewhere between the instrumental and historical estimates.

As mentioned earlier, several earthquakes in the Great Basin have occurred as sequences of strong earthquakes, rather than as individual events. If the communities within the scenario area face multiple magnitude  $\geq 6$  earthquakes over a short time period, serious mitigation efforts and prudent engineering and construction practices will likely have more than a one-time benefit.

## Conclusions

The probabilities estimated for having earthquakes in the scenario area over a 50-year period are summarized in [Table 5](#). The probability of at least one magnitude  $\geq 6$  event is estimated to be between 34% and 98%, the probability of a magnitude  $\geq 6.6$  event between 9% and 64%, and the probability of a magnitude  $\geq 7$  event between 4% and 50%. Daily probabilities are estimated to range from 0.02% to 0.0002% ([Table 5](#)), with the uncertainty in each magnitude category varying by an order of magnitude. The scenario area could also be affected by earthquakes that are nearby but outside of its boundaries, as in 1966,

further raising the total estimated hazard. Overall, the probabilities of potentially damaging earthquakes within the region are relatively high and are commensurate with many parts of California, a state with a well-recognized high earthquake hazard. Thus, the earthquake hazard and potential in the Reno-Carson City urban corridor should be considered high, and earthquake risk preparedness, planning, and mitigation efforts are well warranted.

## Acknowledgements

This paper benefitted significantly from the review and comments of Alan Ramelli, Diane Doser, John Ebel and Dick Meewig. A special thanks goes to Kris Pizarro of the Nevada Bureau of Mines and Geology for drafting the figures. The Western Nevada Earthquake Scenario Project was jointly funded by the Nevada Bureau of Mines and Geology and a grant from Federal Emergency Management Agency to the Nevada Office of Emergency Support. Data used in this paper were developed with support from the U.S. Geological Survey National Earthquake Hazard Reduction Program; specifically award #1434-95-G-2612 to the Nevada Bureau of Mines and Geology and awards #1434-94-G-2479 and #1434-95-A-01298 to the University of Nevada, Reno Seismological Laboratory. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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## Tables

**Table 1 Earthquakes of Magnitude 6 and Larger in the Scenario Region**

<u>Date</u>	<u>Magnitude</u> <sup>1</sup>	<u>Location</u>
1852?	7.3	Western Nevada
Sept. 3, 1857	6.2	Western Nevada
March 15, 1860	7.0	Pyramid Lake area
May 29, 1868	6.0	Virginia Range
Dec. 26, 1869	6.7	Virginia Range
Dec. 27, 1869	6.1	southern Virginia Range
June 3, 1887	6.3	Carson Valley
Feb. 14, 1914	6.0	Verdi area
Apr. 24, 1914	6.4	northern Virginia Range

June 25, 1933	6.0	northern Singatze Range
Dec. 29, 1948	6.0	Verdi area
Sept. 12, 1966	6.0	Truckee, CA <sup>2</sup>
Sept. 12, 1994	6.0	Double Spring Flat

1. Magnitudes from Rogers *et al.* (1991) and the University of California, Berkeley for the 1994 event.
2. Outside boundary of scenario area.

**Table 2 Estimated Probabilities of Earthquakes within the Scenario Area**

<u>Mag.</u>	<u>Method</u>	<u>Time</u>	<u>Occurrence</u>		
		<u>Interval</u>	<u>Rate</u>	<u>Number</u>	<u>Probability<sup>1</sup></u>
		<u>(Years)</u>	<u>(Events/Year)</u>	<u>per Century</u>	<u>in 50 Years</u>
>=6	Historical	145	0.062-0.083	6.2-8.3	95%-98%
>=6	Instrumental	>=6	0.0083-0.033	0.8-3.3	34%-81%
>=6.6	Historical	145	0.0069-0.021	0.7-2.1	29%-64%
>=6.6	Instrumental	>=6	0.0028-0.011	0.3-1.1	13%-42%
>=6.6	Geological	10 <sup>3</sup> -10 <sup>6</sup>	0.0018-0.011	0.2-1.1	9%-42%
>=7	Historical	145	0.0069-0.014	0.7-1.4	29%-50%
>=7	Md. Historical	145	0.0098-0.013	1.0-1.3	39%-48%
>=7	Instrumental	>=6	0.0013-0.0052	0.1-0.5	6%-23%
>=7	Geological	10 <sup>3</sup> -10 <sup>6</sup>	0.00091-0.0041	0.1-0.4	4%-19%

1. Probability of at least one event of the indicated magnitude or greater.

**Table 3 Empirical Magnitude versus Fault Parameter Regressions**

Magnitude versus fault length

$$M_s = 5.2 + 1.2 (\log L) \text{ dePolo et al. (1990)}$$

$$M_s = 5.27 + 1.06 (\log L) \text{ Mason (1992)}$$

Magnitude versus maximum surface displacement

$$M_s = 6.8 + 0.8 (\log D) \text{ dePolo et al. (1990)}$$

$$M_s = 6.85 + 0.58 (\log D) \text{ Mason (1992)}$$

Magnitude versus fault length times maximum surface displacement

$$M_s = 5.88 + 0.57 (\log LD) \text{ Mason (1996)}$$

## Maximum surface displacement versus magnitude

$$\text{Log } D = 0.97 (M_s) - 6.5 \text{ dePolo (unpublished)}$$

$M_s$  = surface-wave magnitude

$L$  = surface fault length

$D$  = maximum surface displacement

**Table 4 Major Quaternary or Suspected Quaternary Faults in the Scenario Area**

<u>Fault Name</u>	<u>Acronym</u>	<u>Magnitude</u> <sup>1</sup>	Fault	Earthquake
			<u>Slip Rate</u> (m/kyr)*	<u>Occurrence Rate</u> Minimum-Maximum (Events/Year) x 10 <sup>-5</sup> *
Carson City flt.	ccf	6.8	0.05-0.3	8-48
Carson lineament	cl	6.9	0.005-0.05	0.64-6.4
Comstock flt. zn.	cfz	6.6	0.005-0.05	1-13
Double Spring Flat flt. zn.	dsffz	6.7	0.01-0.1	2-20
East Tahoe flt.	etf	7.0	0.1-0.5	10-51
Eastern Carson Valley flt. zn.	ecvfz	6.7	0.05-0.3	4.1-61
Eastern Prison Hill flt. zn.	epfz	6.6	0.05-0.3	13-74
Eastern Reno Basin flt. zn.	erbfz	6.9	0.01-0.1	1.3-13
Freds Mountain flt. zn.	fmfz	7.0	0.05-0.2	5.1-21
Genoa flt. zn.	gfz	7.4	0.3-2.5	6.3-63
Granite Hills flt.	ghf	6.6	0.05-0.3	13-74
Hungry Valley flt.	hvf	6.6	0.001-0.1	0.25-25
Incline Village flt. zn.	ivfz	6.6	0.01-0.1	2.5-60
Little Valley flt. zn.	lvfz	6.9	0.05-0.3	6.4-39
Mount Rose flt. zn.	mrfz	7.1	0.1-0.5	8.2-41
North Tahoe flt.	ntf	7.0	0.05-1	3.3-10
Northern Virginia Range flt.	nvrfl	6.6	0.01-0.1	2.5-25
Northwest Reno fault zone	nrfz	6.6	0.01-0.08	2.5-20
Olinghouse flt. zn.	ofz	7.1	0.05-0.3	4.1-25
Peavine Mountain flt. zn.	pmtfz	7.0	0.05-0.3	2.1-74

Peterson Mountain flt. zn.	pmfz	7.0	0.05-0.3	5.1-31
Pine Nut Valley flt. zn.	pnvfz	6.8	0.01-0.1	1.6-16
Pyramid Lake flt. zn.	plfz	7.3	0.4-1.1	42-56
Smith Valley flt. zn.	svfz	7.2	0.12-0.81	7.9-53
Spanish Springs Peak flt. zn.	sspfz	6.6	0.05-0.3	13-74
Spanish Springs Valley flt. zn.	ssvfz	6.9	0.05-0.3	6.4-39
Stead flt. zn.	sfz	6.6	0.01-0.1	2.5-25
Wabuska lineament	wl	6.9	0.01-0.1	1.3-13
Western Lemmon Valley flt. zn.	wlvfz	6.6	0.01-0.1	2.5-25
Western Warm Springs Valley flt.	wwsvf	6.9	0.005-0.1	0.64-13

1. Estimated values are thought to be representative of these faults, but they are not, in general, the results of detailed studies and should not be used for engineering studies without review. Estimated magnitude values have a general uncertainty of  $\pm 0.3$  magnitude units.

**Table 5 Summary of Probabilities of Earthquakes in the Western Nevada Scenario Area<sup>1</sup>**

<b>Mag.</b>	<b>Number per Century</b>	<b>Probability<sup>2</sup> in 50 Years</b>	<b>Probability<sup>2</sup> in one day</b>
>=6	0.8-8.3	34%-98%	0.003%-0.02%
>=6.6	0.2-2.1	9%-64%	0.0005%-0.006%
>=7	0.1-1.3	4%-50%	0.0002%-0.004%

1. Note that the area can also be affected by damaging motion from earthquakes outside its borders that are not included in these estimates. Thus, these values represent minimum probabilities of damaging earthquakes.

2. Probability of at least one event of the indicated magnitude or greater.

## **Appendix - Major Earthquakes in the Western Nevada Scenario Region**

### **Magnitude Key**

Magnitudes reported in titles are from Rogers et al. (1991). Other Magnitudes:

**M<sup>SL</sup>** Slemmons et al. (1965)

**M<sup>TO</sup>** Topozada et al. (1981)

**M<sup>BM</sup>** Bolt and Miller (1975)

Note that dates and times given are in Pacific Standard Time to increase local relatability and relevance; to

convert to GMT add 8 hours, except for the 1966 and 1994 events, which occurred during daylight savings time, add 7 hours for these events.

### **Western Nevada Earthquake, 1852(?), M7.3**

The 1852(?) western Nevada earthquake is one of the first earthquakes on record in Nevada. Its location appears to have been in the Carson Sink region (possibly near Stillwater). An 1869 account by a Northern Paiute, who was a boy at the time, recalls Paiutes being knocked down by the event, collapsed river banks in the Carson Sink area, broken ground, and the temporary reversal of flow of the river near Stillwater Station (Gold Hill Daily News, 12/30/1869). If the river was temporarily reversed at this location, this is possibly a near-field, tectonic effect. Another potential effect of this event was a large landslide that occurred at Slide Mountain in late November or early December of 1852 (Washoe Weekly Times, 6/10/1865). Reportedly, two men at Genoa distinctly heard and felt the shock associated with the landslide; it is unlikely that the landslide itself caused perceptible ground motion or noise that could be heard as far south as Genoa. It is more likely that they heard and felt the effects of an earthquake that caused the slide. Five people passing along the emigrant trail in the valley below were apparently buried by this slide (Washoe Weekly Times, 6/10/1865). Some corroboration of this account is given by a discussion of Paiute traditions, that a great many years ago, the "whole side" of Slide Mountain came down during an earthquake (Territorial Enterprise, 11/27/1894). The most direct account for placing this earthquake in 1852 comes from an account in 1865 that says that the Northern Paiutes often talk about a "great" earthquake that occurred 13 years before (Daily Reese River Reveille, 10/17/1865). Ryall (1977) suggests this event occurred in 1845; notes by Ryall indicate that this was based on interpreting the 1869 account strictly (the Paiute was "a boy" at the time of the earthquake and was guessed in 1869 to be about 30 years old) and a lack of felt reports in the Sierra Nevada in 1852. There are other accounts of earthquakes in western Nevada in the 1840s as well (e.g., Silver State News, 10/5/1915). Anderson and Hawkins (1984) suggested that a recent break along the Pyramid Lake fault zone, south of Pyramid Lake, may have been caused by a historical event, possibly the 1852(?) event.

### **Western Nevada Earthquake, September 3, 1857, M6.2**

Very little is known about this earthquake, which occurred on September 3, especially about its exact location. The first newspaper in Nevada began in 1858. Topozada et al. (1981) examined the intensity pattern in the Sierra Nevada communities and concluded that the effects were similar to the 1860, 1868, 1869, and 1887 Nevada earthquakes, and that it was likely near the Nevada/California border. [M<sup>TO</sup> 6.0]

### **Pyramid Lake Earthquake, March 15, 1860, M7.0**

This earthquake caused goods to be shaken from shelves and general panic in Carson City, although no damage was reported (Holden, 1898; Topozada et al., 1981). The earthquake was felt as far away as Yreka and San Francisco in California (Topozada et al. 1981). Topozada et al. (1981) suggest that the epicenter of the event was near Pyramid Lake since seven aftershocks were reported the same day (March 15) in the Pyramid Lake area and rock slides were reported between Pyramid Lake and Carson City. This earthquake may have caused the young surface rupture near Derby noted by a prospector in the 1860s; if so, the Olinghouse fault may have been the source of the event (see discussion under 1869 Virginia Range earthquakes). Anderson and Hawkins (1984) also mention the 1869 event as a possible cause of the recent break along the Pyramid Lake fault zone. [M<sup>SL</sup> 7.-, M<sup>TO</sup> 6.3]

### **Virginia Range Earthquake, May 29, 1868, M6.0**

This earthquake was strongly felt at Virginia City, where brick buildings were cracked, some bricks shaken down, and plaster fell in nearly all brick buildings (Topozada et al. 1981). Two foreshocks were reported in Virginia City, 14 and 5 minutes before the main event (The Daily Tresspass, 5/30/1868). Topozada et al. (1981) comment that the intensity distribution for this event resembles that of the 12/27/1869 earthquake. This event may have been a foreshock to the 1869 earthquakes. [ $M^{SL}$  6.-,  $M^{TO}$  5.8]

### **Virginia Range Earthquakes, December 26 and 27, 1869, M6.7 and M6.1**

The December 26, 1869 Virginia Range earthquake strongly shook western Nevada and eastern California. This event seriously damaged masonry walls in Virginia City and Washoe City, and caused some damage in communities of the Sierra Nevada foothills of California. A second large earthquake (perhaps the largest aftershock) occurred eight hours later and strongly shook Carson City, but reportedly did little damage. Slemmons (1969) reports that Dr. Gianella of Mackay School of Mines interviewed a prospector from the WadsworthOlinghouse area who reported that during the 1860s surface faulting appeared in the Derby Dam area of the Truckee River Canyon. In Slemmons' judgement, the largest event in the 1860s was in 1869. Thus, Slemmons felt it was likely that this surface rupture (which he found) was from this earthquake and that this suggests the location of the event. This surface rupture along the Olinghouse fault was mapped by Sanders and Slemmons (1979), who found left-lateral offsets as large as 3.7 m (12 ft). Topozada et al. (1981) suggest that an epicenter near Steamboat Springs (south of the Olinghouse location) would better fit the damage distribution and the second earthquake as an aftershock; this second event appears to have occurred in the southern Virginia Range. It is also noted that Steamboat Springs spouted most furiously to a height of 3 to 4.5 m (10 to 15 ft) after the earthquake (Gold Hill Daily News, 12/27/1869). A magnitude 6.7 or larger was estimated by Sanders and Slemmons (1979) using earthquake intensity area. [ $M^{TO}$  6.1 and 5.9]

### **Carson Valley Earthquake, June 3, 1887, M6.3**

This earthquake caused very strong shaking in Carson Valley. At Genoa, houses were shifted off their foundations and bricks were thrown down (Territorial Enterprise, 6/4/1887). At Carson City, chimneys were damaged, brick and stone walls were damaged, and plaster fell. At the State Capitol, the west wall was cracked and plaster fell in several rooms (Territorial Enterprise, 6/4/1887). Some people who were in the streets of Carson City that morning (the earthquake occurred at ~2:45 a.m.) were apparently thrown to the ground by the shock (Territorial Enterprise, 6/4/1887). At Mound House, a hotel and wayside resort was totally destroyed by a fire on the day following the earthquake; the earthquake had separated several joints in the stove pipe and when the stove was lit the morning of the 4th, fire leapt out of the break in the pipe and ignited the wood backing (Carson Daily Index, 6/5/1887). Near Cradlebaugh's Bridge, south of Carson City, a fissure 15 m (50 ft) long opened up and mud and hot water spouted for a half an hour without abating (Reno Gazette-Journal, 10/28/1979). Springs all around Carson City either increased in flow or went suddenly dry. General alarm occurred in Virginia City and Reno, but there was little damage. The earthquake appears to have occurred in Carson Valley. [ $M^{TO}$  6.3]

### **Verdi Earthquake, February 18, 1914, M6.0**

In 1914 a pair of strong earthquakes shook the Reno region; these events occurred on February 18 and April 24 (discussed in next section). The first event had a magnitude of about 6 (Slemmons and others, 1965). Damage in Reno was limited to bricks falling from a chimney at the University of Nevada, broken windows and cracked plaster (Reno Evening Gazette, 2/18/14; A. Jones, unpublished notes). The event occurred at 10:19 a.m. (PST) and schools and buildings were evacuated immediately. At the University of Nevada, "the students and professors vied with one another in an attempt to be the first outside" (Reno Evening Gazette,

2/18/14). Because the strongest intensity of this event was to the west of Reno, it appears that this event occurred in the Verdi area (Priestley, 1981).

### **Northern Virginia Range Earthquake, April 24, 1914, M6.4**

The second event occurred on April 24 and had a magnitude of 6.4 (Slemmons et al., 1965). This event brought down four chimneys at the University of Nevada and caused considerable glass breakage in the chemistry laboratory. Broken china and other nonstructural damage occurred in Reno. It is suggested that at least the second event occurred to the east of Reno (Priestley, 1981), which is consistent with strong shaking at Hazen. In a 1934 correspondence to a Californian, Gianella (a professor at the University of Nevada) judged that the event, "was located along the Virginia Range probably near Fernley or Wadsworth." Gianella mentions that this is only a guess, however, since information is incomplete. Several residents said that the earthquake was preceded by a smaller event by about five minutes (Nevada State Journal, 4/25/14).

### **Wabuska Earthquake, June 25, 1933, M6.0**

The Wabuska earthquake was strongly felt in western Nevada. The earthquake was very severe in Virginia City with several chimneys knocked down and the Catholic Church badly damaged (Reno Evening Gazette, 6/26/33). Chimneys were thrown down in Carson City as well, and plaster fell from the assembly chamber in the State Capitol building. Numerous rockfalls occurred around Lake Tahoe, covering the highways. Reno was mostly spared from this event, experiencing only Modified Mercalli Intensity V. This event was part of a remarkably active earthquake period in western and central Nevada from about 1932 to 1934, which includes the 1932 Cedar Mountain earthquake (M7.2) near Gabbs. [M<sup>SL</sup> 6, M<sup>BM</sup> 6.1]

### **Verdi Earthquake, December 29, 1948, M6.0**

On December 29, 1948, a magnitude 6.0 earthquake near Verdi caused Intensity VII damage to that community. The main event was preceded by several foreshocks. On December 27, notable foreshocks occurred at 5:15, 6:24, 8:21, 8:24, 9:24, and 10:04 p.m. (PST). The event at 9:24 p.m. is described as "a prolonged jolt beneath the city [Reno] for perhaps 30 seconds." On December 28, numerous earthquakes were felt, and at Verdi there were almost continuous vibrations. Following a lull of nearly 36 hours, almost everyone in a radius of 80 km (50 mi) was awakened by the mainshock at 5:53 AM on December 29th. Nearly every building in Verdi had some sort of damage. Brick parapets on the east and west sides of the Verdi school building were sheared and thrown off. A wall of a grocery store fell down. Several chimneys came down in Verdi and Floriston, and bricks fell from many others. A chimney was also broken in Dog Valley. Windows were broken as far away as Reno. A water main between Reno and Sparks was sheared. In Verdi, stoves were knocked out of line and in some cases went sliding into walls. Large boulders up to 1.5 m (5 ft) came down in the Truckee River Canyon along U.S. Highway 40 south of Verdi, knocking out both power and telephone lines. Telephone service in Reno was out for one to two days.

The earthquake is thought to have originated in Dog Valley and to have possibly occurred along the Verdi fault (which is northerly striking as is the orientation of the most severe damage) or the Dog Valley lineament. In addition to foreshocks, "mysterious rumbles" or subterranean roars were heard in the Verdi-Reno region for about a year before the Verdi earthquake (Bell et al., 1982). [M<sup>SL</sup> 6, M<sup>BM</sup> 6.0]

### **Boca Valley (Truckee) Earthquake, September 12, 1966, M6.0**

The 1966 Boca Valley earthquake, just northeast of Truckee, California, caused damage to two local dams, highways, railroads and water flumes, and some minor structural damage to buildings. Damage to highways

included cracked bridge abutments, settlement of engineered fill at abutments, slumping and fissuring of the highway (commonly at cut and fill contacts), and slides, slumps, and rockfalls between Boca and the Nevada/California border (Kachadoorian et al., 1967). Rockfalls and horizontal and vertical settlement necessitated repeated realignment and regrading of the Southern Pacific Railroad line (Kachadoorian et al., 1967). Rockfalls from this event also punctured and crushed the wooden flume in the Truckee Canyon, and one 20ton boulder punched a hole in the masonry wall of the Farad powerhouse (Kachadoorian et al., 1967). Building damage consisted mostly of toppled chimneys, but two buildings were racked badly. In Reno and Carson City, plaster fell and loose objects were knocked from shelves.

The 1966 earthquake appears to have been a left-lateral strike-slip event that occurred along the northeast-trending Dog Valley lineament (Kachadoorian et al., 1967; Greensfelder, 1968). Aftershocks extended for 10 to 16 km (6 - 10 mi) along a northeast trend with a vertical dip (Kachadoorian et al., 1967; Greensfelder, 1968). The location of these aftershocks was also coincident with a zone of discontinuous, secondary or non-tectonic fracturing (Kachadoorian et al., 1967). [M<sup>BM</sup> 6]

### **Double Spring Flat Earthquake, September 12, 1994, M6.0**

This earthquake occurred south of Carson Valley near Double Spring Flat. This is the mildest earthquake, in terms of its effects, in the RenoCarson City urban corridor discussed in this paper. Due to its moderate magnitude, the sparseness of population in the epicentral area, and the time of day, the earthquake did only minor damage and caused no reported injuries. One chimney was toppled and there was minor nonstructural damage in Minden, a foundation was damaged in Double Spring Flat, and several rockfalls occurred along roadways. Ground cracking was noted in the epicentral area, but appears to be secondary in nature. The 1994 earthquake was a normal-left oblique-slip event occurring along a northeast-striking fault that dips steeply to the southeast (Ramelli, 1994; dePolo et al., 1995). Aftershocks extended over a distance of about 12 km (7.4 mi). Several small foreshocks occurred over a 12day period leading up to the mainshock and background seismicity notably occurred in the area over the year or two before the event. [M<sub>w</sub> 5.9-6.1, M<sub>L</sub> 6.0]

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