High Probability of Foreshock Occurrence and Significant Probability of Multiple Events Associated with Magnitude ≥6 Earthquakes in Nevada, U.S.A.

by Craig M. dePolo

INTRODUCTION

Sixty percent of magnitude 5.5 and larger earthquakes in the western Cordillera were preceded by foreshocks (Doser, 1989). Foreshocks also preceded the 2008 Wells (M_w 6.0; Smith *et al.*, 2011) and the 2008 Mogul (M_w 5.0; Smith *et al.*, 2008; dePolo, 2011) earthquakes in Nevada. Understanding foreshocks and their behavior is important because of their potential use for earthquake forecasting and foreshocks felt by communities act as a natural alarm that can motivate people to engage in seismic mitigation. A majority of larger earthquakes in Nevada had foreshocks, and several were multiple earthquakes of magnitude ≥ 6. Multiple major earthquakes can shake a community with damaging ground motion multiple times within a short period of time, such as happened in Christchurch, New Zealand, in 2010 and 2011 (Gledhill *et al.*, 2011; Bradley and Cubrinovski, 2011). Several of Nevada's multiple events occurred within 12 hours of each other, which presents a particular hazard to emergency responders and the general public.

Twenty-three magnitude ≥ 6 historical earthquakes have occurred in Nevada since 1857 (Fig. 1). Earthquake catalogs used in this compilation include Slemmons *et al.* (1965) and Bolt and Miller (1975). Historical research and reanalysis of Nevada earthquakes have been conducted by Slemmons *et al.* (1965), Toppozada *et al.* (1981, 2000), dePolo *et al.* (2003), dePolo and Garside (2006), and dePolo (2012). Research on preinstrumental earthquakes consisted of systematically reviewing available earthquake catalog information and newspaper accounts. Local daily newspapers were found to be the best source of information because of their continuous nature. These records are not necessarily complete but can have important information on earthquake activity. In this study, when a local earthquake occurred beforehand and in the same general area as the event being reviewed, it was considered a foreshock. Pre-event information varied, with less information available for earlier events or events in remote areas. After eliminating two aftershocks (1869 and July 1954) and earthquakes that lacked adequate records (1857, 1860, 1872, and 1903), 17 of the 23 M ≥ 6 Nevada earthquakes were evaluated for foreshock activity (Table 1). Earthquake magnitudes reported are moment magnitudes (M_w) when possible; otherwise they are catalog or historical values (M; dePolo, 2013).

FORESHOCKS PRIOR TO M ≥6 NEVADA EARTHQUAKES

There have been several studies of earthquake foreshocks, including a classic paper on foreshocks along the San Andreas fault system by Jones (1984), which concluded that 35% of M ≥ 5 earthquakes were preceded by an immediate foreshock within one day and 5 km of the mainshock. Considering a two-month time window and a 40 km radius, Doser (1989) studied M ≥ 5.5 earthquakes in the western Cordillera and found that 60% of these events had foreshocks and that 58% of these foreshocks occurred within 24 hours of their mainshock (35% of the total).

An example of foreshock activity from this study is shown in Figure 2, which shows reported foreshock activity prior to the 1948 Verdi, California–Nevada, earthquake (M 6). Local reports indicated that after several isolated earthquakes there was a distinct increase in activity 36 hours before the main event. This earthquake activity was noted as unusual by the local residents and the nearby Reno, Nevada Fire Department, which went into an alert status about 24 hours before the mainshock (dePolo, 2012).

The 17 Nevada earthquakes considered in this foreshock study are listed in Table 1, shown in Figure 1, and described in the Appendix. Most of these earthquakes occurred prior to 1955 and were evaluated based on earthquake catalogs and newspaper accounts. One modern event, the 2008 Wells, Nevada, earthquake, occurred while a regional seismic network was in place (USArray), and the foreshocks were well located (Smith *et al.*, 2011). For most of the rest of the events, only the largest felt foreshocks were reported, and whether microseismicity occurred beforehand is not known.

Several time periods were considered in this study to illustrate and cover different considerations of foreshock activity (Table 2). A year was considered because seismic activity 358 days prior to the 2008 Wells earthquake was located in the epicentral area of the mainshock (Smith *et al.*, 2011),

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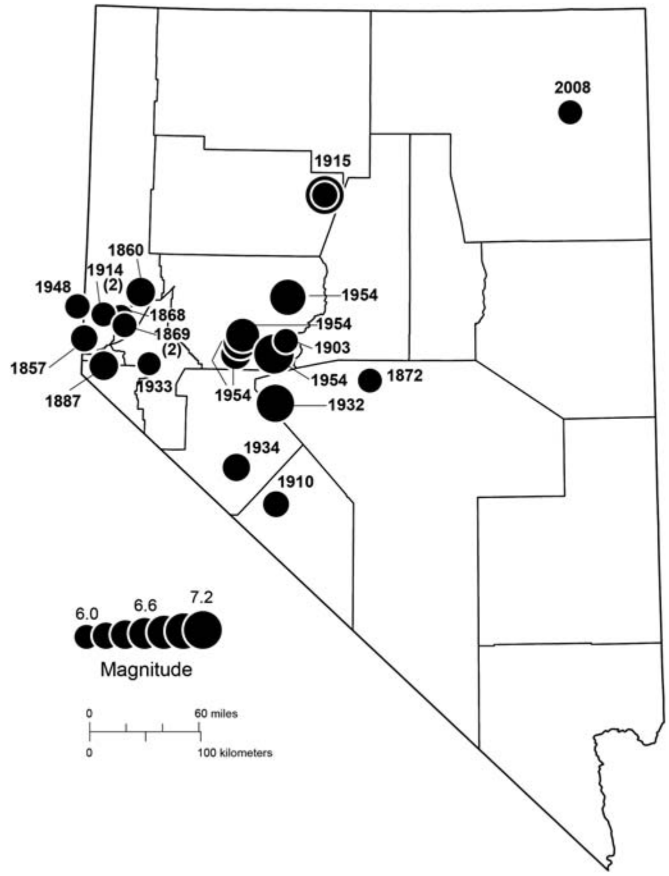


▲ **Figure 1.** The locations of Nevada earthquakes with magnitudes ≥6. The boundaries of Nevada counties are shown for reference.

indicating a strong relationship between these events. Periods of 120 days and 30 days were considered because these timeframes allow the recognition of an earthquake sequence and preparation for earthquakes is most feasible. Shorter time periods of five, three, and one day(s) match those used in foreshock studies and statistical studies on the occurrence of earthquakes the same size or larger, which are commonly given following significant earthquakes (for example Jones, 1984; Jones, 1985; Savage and dePolo, 1993).

A remarkable amount of pre-event activity was found for the 17 earthquakes in Table 1, with 88%–94% of the earthquakes having foreshocks within the 120-day time period. The largest foreshocks were commonly small and moderate events, with a range of M 1.4 to M 6.1. When available, the sense of slip of the major earthquakes is noted in Table 1 for events. The dataset is largely incomplete, but foreshocks occurred before the most common types of earthquakes in Nevada: normal, normal-oblique, and strike-slip earthquakes.

The time of the apparent onset of foreshocks prior to the mainshock is listed in Table 1. In some cases, two times are shown, the onset of the earliest activity and the onset of activity shortly before the main event. Two of the 17 events had foreshocks during the 120- to 365-day window prior to the mainshock, five events had foreshocks during the 30- to 120-day window, and two events had foreshocks during the 6- to 30-day window.

Within the five-day window, 13 of 17 events (76%) had reported foreshock activity. This dropped by one event to 12 of 17 events (71%) for the three-day time window. Four of these 12 events had earlier foreshock activity (49–261 days before) and eight events had reported foreshock activity only within the three-day time period. Six of these latter eight events only had immediate foreshocks within 29 hours (1.2 days) of the mainshock. Eight out of the 17 events in Table 1 (47%) had reported foreshocks within 24 hours of the mainshock.

Eight of the 17 events had foreshock sequences (Table 1), in contrast to only one or two reported foreshocks of other events. Sequences, or swarms of small earthquakes, naturally attract more attention than individual events and may have behavior and characteristics that can one day be used for estimating foreshock probability. Foreshock sequences with an escalating behavior occurred with the 1915 (M_w 7.3), 1934 (M 6.1), and 1948 (M 6) earthquakes. These foreshock sequences generally increased in the rate of events and the magnitude of the largest events with time. Escalating foreshock sequences occurred before other regional earthquakes and smaller magnitude events as well (e.g., 1986 Chalfant, California, earthquake [M_L 6.4], Smith and Priestley [1988]; 1992 Little Skull Mountain, Nevada, earthquake [$M_L \sim 5.6$], Smith *et al.* [2001]; 2008 Mogul, Nevada, earthquake [M_w 5.0], Smith *et al.* [2008]).

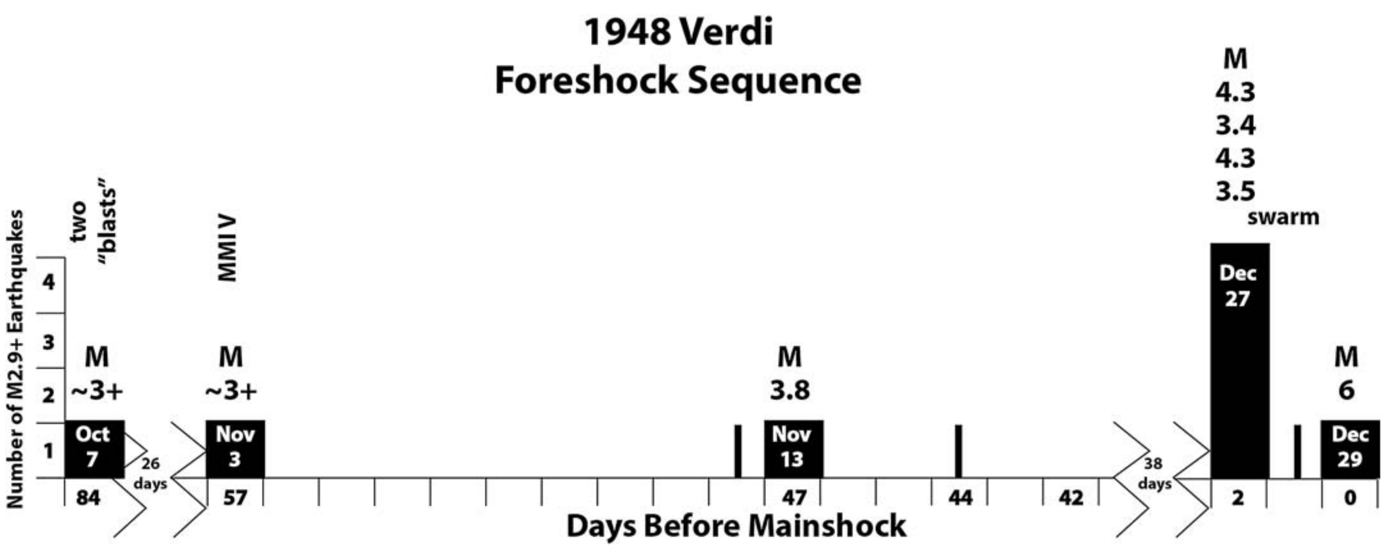
Only one of the M ≥ 6 events studied, the 1887 Carson Valley earthquake (M 6.5), had no convincing foreshocks. A local daily newspaper, *The Carson Daily Index*, was reviewed over the year prior to the mainshock, and no pre-event seismicity was found.

MULTIPLE M ≥ 6 NEVADA EARTHQUAKES

Several of the M ≥ 6 Nevada earthquakes were multiple events that occurred within a few months of each other and the same general area so affected communities multiple times. Some of these additional events occurred during the emergency response of the first earthquake (hours to days) and others occurred during the early recovery period of communities (months). Multiple events can be particularly deadly and damaging because there may be more people in high-risk settings, such as rescuers and construction workers, and buildings may have been weakened from earlier shaking. For example, during the 1935 Helena, Montana, earthquake sequence (M 6¼), a major aftershock of M 6 occurred 21½ days later, which threw two men who were removing a damaged smoke stack to the ground and covered them with falling bricks and mortar (Anderson and Martinson, 1936; Stover and Coffman, 1993). All 23 M ≥ 6 Nevada earthquakes were considered for the percentage of multiple earthquakes. Six pairs of M ≥ 6 earthquakes have occurred during Nevada's recorded history (Table 3). Two of these pairs are part of the 1954 triple major earthquake sequence (July–August 1954). Thus, one event (July 1954) is

Table 1							
Major Historical Nevada Earthquakes Examined for Foreshocks							
Date (GMT; yyyy/mm/dd)	Magnitude	Slip Type*	Foreshock within 120 Days	Foreshock Sequence	Foreshock Magnitude	Time frame (Days)	Reference
1868/5/29	6.0	?	Yes		Small	0.02	dePolo *et al.* (2003); Toppozada *et al.* (2000)
1869/12/27	6.4	?	Yes		Moderate?	8	dePolo *et al.* (2003)
1887/6/3	6.5	?				None	dePolo *et al.* (2003)
1910/11/21	6.1	?	Yes	Yes	Moderate	3	dePolo and Garside (2006)
1914/2/18	6	?	Yes?		Small	Week before	dePolo and Garside (2006)
1914/4/24	6.4	?	Yes	Yes	M 6; small	65; 0.9	dePolo and Garside (2006)
1915/10/3	6.1	N?	Yes	Yes	M 5	0.1	Slemmons *et al.* (1965)
1915/10/3	7.3	N	Yes	Yes	M 6.1	0.2	Slemmons *et al.* (1965)
1932/12/20	7.1	SS	Yes		Moderate	0.03	Gianella and Callaghan (1934)
1933/6/25	6	?	Yes		Moderate	2	Neumann (1935)
1934/1/30	6.1	N	Yes	Yes	M 4.1; M 5.6	261; 1	Callaghan and Gianella (1935)
1948/12/29	6	?	Yes	Yes	M 4.3; Small	84; 1.5	dePolo *et al.* (2008)
1954/7/6	6.2	SS	Yes		M 3	0.04	Bolt and Miller (1975)
1954/8/24	6.8	SS	Yes	Yes	M 6.2; moderate	49; ~1	Slemmons *et al.* (1965)
1954/12/16	7.1	NO	Yes		Small	1.2	Slemmons *et al.* (1965)
1954/12/16	6.9	N	Yes		M 5.9	107	Slemmons *et al.* (1965)
2008/2/21	6.0	N	Yes	Yes	M 3.7; M 1.4	358; 5.4	Smith *et al.* (2011)

*N, normal dip slip; SS, strike slip; NO, normal-oblique slip; ?, unknown.



▲ **Figure 2.** Foreshock sequence for the 1948 Verdi earthquake (M 6). This sequence was reconstructed using local newspaper accounts (dePolo *et al.*, 2008) and Slemmons *et al.* (1965) catalog. The thin bars indicate some earthquake activity occurred on that day. Earthquakes of magnitude 3 or greater are indicated with the thick bars. This record is incomplete below about magnitude 3.

Table 2
Number of the 17 Nevada Events with Reported Foreshocks for Pre-Event Time Periods of 1–365 Days

Time Period (days)	Earthquakes with Foreshocks	Earthquakes with Possible Foreshocks	Earthquakes without Foreshocks	Percentage with Foreshocks (%)
365	15	1	1	88–94
120	15	1	1	88–94
30	14	1	2	82–88
5	13	0	4	76
3	12	0	5	71
1	8	0	9	47

Table 3
Nevada's Multiple M ≥ 6 Earthquakes

Year	First Event	Elapsed Time	Second Event	Location
1869	M 6.4	8 hours	M 6.2	Virginia City
1914	M 6	65 days	M 6.4	Reno
1915	M 6.1	5 hours	M 7.3	Pleasant Valley
1954 July	M 6.2	11 hours	M 6.1	Rainbow Mountain
1954 July	M 6.2	49 days	M 6.8	Stillwater
1954 December	M 7.1	4 min, 20 s	M 6.9	Fairview Park–Dixie Valley

References are given in Table 1.

the same first event for two double events, so five independent earthquakes became multiple events, or 22% of the magnitude ≥ 6 earthquakes in Nevada. Four of these multiple events, or 17% of the M ≥ 6 events, were followed by a second event within 12 hours. For the multiple events where the first event was a foreshock, the second event was between 0.4 and 1.2 magnitude units larger than the first.

DISCUSSION

The chances of an earthquake becoming a foreshock were not calculated in this study, but an idea of what these probabilities are for Nevada can be gained from a study by Savage and dePolo (1993). Savage and dePolo (1993) calculated the probability of an M ≥ 3 earthquake being a foreshock in western Nevada and eastern California using a declustered University of Nevada Seismological Laboratory earthquake catalog. Using the catalog between 1934 and 1991, they found the probability of an M ≥ 3 event being followed by a larger magnitude earthquake that occurs within five days and 10 km is approximately 6%. Using these same parameters, they also found a 1%–2% chance that an event would be followed by an earthquake with an M ≥ 1 unit larger than the foreshock and noted that this is "several orders of magnitude above the low background probability."

Given the findings of this study that a significant number of major earthquakes in Nevada had foreshocks and given the elevated chance following a moderate earthquake for a subsequent larger event noted by Savage and dePolo (1993) and others, it makes sense to use moderate earthquakes as a window of opportunity for earthquake preparedness. Communities can respond in many risk-reducing ways to a reminder that a strong earthquake might occur. Prior to the 26 April 2008 Mogul, Nevada earthquake (M_w 5.0), foreshock activity motivated many citizens to mitigate seismically vulnerable items and saved them from the subsequent strong shaking. The most serious mitigation activity was after two magnitude 4 events occurred 32 hours before the mainshock. Local fire stations kept their fire doors open when the weather allowed prior to the M_w 5 event and during times of aggressive aftershock activity, they parked fire trucks outside of local stations, just in case a larger event occurred. If a moderate earthquake occurs in or near a Nevada community, it is a good time for earthquake-safety actions by that community, such as preparing to respond to an earthquake, securing building contents, and reviewing emergency-response plans. If a strong earthquake does occur, these actions can greatly benefit that community. More than likely a strong earthquake won't occur, but the community would have had a window of opportunity to become more prepared. Communities also need to be aware that earthquakes can occur without any warning and that general preparedness is needed, which is why using seismic activity as a motivation makes sense in the long run. The serious consequences of damaging earthquakes, the need for windows of opportunity for preparedness, and probabilities that are elevated above background levels warrant working with the low probabilities of earthquakes being foreshocks to develop a further understanding of their potential utility.

There is a high enough probability of multiple earthquakes of magnitude ≥ 6 occurring in Nevada that seismic safety after a damaging earthquake must be a rigorous high-priority consideration for the local population and emergency personnel engaged in search-and-rescue and damage-assessment operations. Following a damaging earthquake, emergency and rescue personnel need to realize that there is a distinct possibility of a strong aftershock or additional major earthquake. Safe, careful rescue operations should be favored over faster but more risky approaches. The occurrence of multiple M ≥ 6 earthquakes also implies that earthquake preparedness and risk mitigation in Nevada can have a more than one-time benefit.

CONCLUSIONS

Considering 17 earthquakes in Nevada with magnitude ≥ 6 and adequate records, 88%–94% were preceded by reported foreshock activity within 120 days before the mainshock. Considering a 30-day timeframe, 82%–88% of the events had reported foreshock activity. For a five-day window, 76% of events had reported foreshocks; for three-day window, 71% of events had reported foreshocks; and for a one-day window, 47% of events had reported foreshocks. The foreshocks were commonly small- and moderate-size events, and measured magnitudes ranged from M 1.4 to M 6.1. Eight of these 17 earthquakes had foreshock sequences, and three of these were escalating foreshock sequences. One of the 17 events (1887 Carson Valley earthquake) had no reported foreshocks. The 1887 earthquake is an important reminder that even with the encouragingly high number of events with foreshocks in Nevada, damaging earthquakes will still occur without any apparent foreshock activity. Additionally, four of the 17 events only had reported foreshock activity within the hour before the mainshock; if this was all the foreshock activity for these events, it is a very short lead time.

Twenty-two percent of larger earthquakes in Nevada were multiple events, and 17% were followed by a second M ≥ 6 earthquake within 12 hours. These observations have important emergency response and earthquake-preparedness safety implications.

The response of Nevadans to foreshock activity suggests the broader possibility that moderate events near communities can be used as windows of opportunity for earthquake preparedness. Such preparedness can have great short-term benefits should a strong earthquake occur and long-term benefits for future earthquakes.

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APPENDIX

1868 MAY 30

In 1868, two earthquakes of about the same size occurred within about 10 min (Slemmons *et al.*, 1965). An M 6.0 has been assigned to the first event by Toppozada *et al.* (2000). Two small foreshocks occurred 25 and 12 min before the first major event (dePolo *et al.*, 2003). The earthquakes appear to have originated in the Steamboat Springs area, south of Reno, Nevada (Toppozada *et al.*, 1981).

1869 DECEMBER 27

In 1869, an M 6.4 earthquake was followed eight hours later by an M 6.2 event, both likely originating from the Steamboat Springs area, just northwest of Virginia City (Toppozada *et al.*, 1981). In the Holden (1898) earthquake catalog, an event is listed as occurring in the evening of December 19th that was felt in the mines at Virginia City (eight days before). Townley and Allen (1939) elaborate that these shocks were felt at Mariposa Mill, Virginia City. Earthquake activity also preceded the 1869 earthquakes by 13–19 months (30 May 1868 earthquakes).

1887 JUNE 3

No reported foreshocks of the 1887 earthquake have been found. There was a daily newspaper at the time in Carson City (*The Carson Daily Index*), where the earthquake was located and no local foreshocks were reported in the year preceding the main event (dePolo *et al.*, 2003). There was a pair of small earthquakes just north of the 1887 earthquake area 204 days beforehand (*The Carson Daily Index*, 14 November 1886), but these were not felt in the central part of the earthquake area and do not appear to be foreshocks.

1910 NOVEMBER 21

The 1910 M 6.1 Tonopah Junction earthquake was preceded by three days of small magnitude foreshocks (Slemmons *et al.*, 1965). A lightly damaging event also occurred 14 days before in the region, but it is unclear if this was from the same location as the mainshock (Slemmons *et al.*, 1965).

1914 FEBRUARY 18

The M 6.0 18 February 1914 Reno earthquake may have had a foreshock or two. In the 19 February 1914 *Nevada State Journal* (Reno) it was noted, "According to the seismograph at the Mackay School of Mines at the university the main shock was preceded by a small temblor," but no further information about this event could be found. A newspaper from nearby Virginia City (18 February 1914 *Virginia Chronicle*) noted that "Last week, there was a slight earthquake in this city" (dePolo and Garside, 2006). The location of the later event is unknown. These events are considered as uncertain possible foreshocks.

1914 APRIL 24

On April 24th the largest earthquake (M 6.4) of the 1914 Reno earthquakes occurred. This was a double earthquake sequence and the smaller, February 18th earthquake, 65 days earlier, is considered a foreshock to the April event. There was a more immediate foreshock sequence before the April event as well (dePolo and Garside, 2006). A slight earthquake occurred in Reno 20½ hours before the mainshock and an event that caused much excitement in Reno occurred 16½ hours earlier.

1915 OCTOBER 3 (M 6.1)

This M 6.1 event was part of the foreshock sequence of the Pleasant Valley earthquake (Pancha *et al.*, 2006) and occurred about five hours before the mainshock (Slemmons *et al.*, 1965). A foreshock of magnitude 5 occurred about two hours and 20 minutes before this event, along with numerous smaller foreshocks (Wallace, 1984; Pancha *et al.*, 2006).

1915 OCTOBER 3 (M 7.3)

The M_w 7.3 Pleasant Valley earthquake, Nevada's largest earthquake (dePolo, 2013), had an escalating foreshock sequence for over seven hours before the mainshock that was made up of many events (Wallace, 1994). Major foreshocks occurred seven hours and 20 minutes (M 5) before and about five hours (M 6.1) before the mainshock (Pancha *et al.*, 2006).

1932 DECEMBER 20

The M_w 7.1 Cedar Mountain earthquake was in a remote part of Nevada. Gianella and Callaghan (1934) comment that there was at least one foreshock felt about 40 minutes before the mainshock, reported by a man at Hawthorne (roughly 50 km away) and at about that time, cattlemen within the epicentral area noted the cattle became startled and uneasy.

1933 JUNE 25

The M 6.0 Wabuska earthquake was preceded by two days by a widely felt M 4.1 earthquake that is attributed to the same area (Neumann, 1935; Slemmons *et al.*, 1965).

1934 JANUARY 30

The M 6.1 Excelsior Mountains earthquake was preceded by foreshocks, occurring about 29 hours and 52, 46, and 36 minutes beforehand (Callaghan and Gianella, 1935); the event 52 minutes beforehand was an M 5.6 earthquake (Slemmons *et al.*, 1965). There was also an M 4.1 event in the Excelsior Mountains area on 13 May 1933, 261 days before the mainshock.

There is a suggestion that substantially more earthquake and fault activity preceded the 1934 Excelsior Mountains earthquake in a letter from Vincent Gianella of the University of Nevada to Harry Wood of Carnegie Institute of Washington in Pasadena, dated 15 June 1933. Gianella comments that felt earthquakes have been occurring with considerable frequency in the eastern Excelsior Mountains for the last four years. He notes the events are felt locally and are not felt in Mina, 16 km away. Some of these events are mentioned in Slemmons *et al.* (1965) on 12 May 1933, as "constant light quakes" reported from the Silver Dike Mine (eastern Excelsior Mountains). Gianella also comments in his letter that following the 1932 Cedar Mountain earthquake (M_w 7.1 earthquakes about 40 km away), small displacements occurred on faults in the Silver Dike Mine, as reported by the mine manager and superintendent.

1948 DECEMBER 29

Several foreshocks preceded the 1948 M 6.0 Verdi earthquake beginning 84 days before, including two M 4.3 events 36 hours before the mainshock (Fig. 2; Slemmons *et al.*, 1965; dePolo *et al.*, 2008). Local seismometer coverage was absent, but there was a Weichert seismometer operating in Reno (~20 km east of Verdi) that recorded the larger events.

1954 JULY 6

The M_w 6.2 Rainbow Mountain earthquake was preceded by an M 3 foreshock one hour and four minutes before the mainshock. This foreshock was recorded and located by California Institute of Technology and was reported in Bolt and Miller (1975).

1954 AUGUST 24

The M_w 6.8 Stillwater earthquake occurred along the northern end of the same fault system as the July 6 Rainbow Mountain earthquake. Thus, it is impossible to distinguish an aftershock from the northern end of the July earthquakes from a foreshock of the August earthquake. Nevertheless, the August event appears to have nucleated out of an area that was having earthquakes and there were immediate foreshocks about 13 hours and about 1 hour and six minutes before the mainshock (Slemmons *et al.*, 1965). These foreshocks do not have magnitudes, but 22 and 19 days beforehand two earthquakes, M 5.4 and M 4.7 events, respectively, occurred in the same relative location as the Stillwater earthquake (Slemmons *et al.*, 1965).

1954 DECEMBER 16

The M_w 7.1 Fairview Peak earthquake was preceded by an M 4.0 earthquake 29 hours before that was located in the Fairview Peak area by the Berkeley seismograph stations (Slemmons *et al.*, 1965).

1954 DECEMBER 16

The M_w 6.9 Dixie Valley earthquake occurred four minutes and 20 seconds after the Fairview Peak earthquake and was a triggered event (Caskey and Wesnousky, 1997). The earthquake was preceded three and a half months (107 days) before by an M 5.8 event (31 August 1954) that occurred in Dixie Valley (Slemmons *et al.*, 1965).

2008 JANUARY 21

The 2008 M_w 6.0 Wells earthquake benefitted from the deployment of the USArray that was able to record smaller events in an area that is normally poorly instrumented. Sixty-five earthquakes were located in the Wells area prior to the mainshock (Smith *et al.*, 2011). Almost 40 of these events occurred in an early swarm that started 358 days before the mainshock, was located in the eventual epicenter of the mainshock, and included an event of M 3.7 (Smith *et al.*, 2011). Foreshocks continued as small groups of events and isolated events, including earthquakes between 30 and 120 days prior to the mainshock (Smith *et al.*, 2011). A group of three events occurred within eight days of the event (Smith *et al.*, 2011). These included an M 1.4 earthquake and an M 1.5 event occurring 5.4 and 4.5 days before the mainshock, respectively. No foreshocks appear to have occurred within 24 hours of the Wells earthquake (Smith *et al.*, 2011). Reflecting on this foreshock sequence, Smith *et al.* (2011) suggest that "unusual felt events and continuing activity in rural communities of low seismic hazard could focus monitoring efforts and motivate hazard mitigation efforts."

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