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Seismicity near the Warm Springs Dam - Lake Sonoma Recorded by the Northern California Seismic Network

by
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Introduction

This report discusses the seismicity recorded by the USGS Northern California Seismic Network (NCSN) in the general vicinity of the US Department of the Army Corps of Engineers (COE) Warm Springs Dam - Lake Sonoma. The construction of Warm Springs Dam was essentially completed in December 1982. Because of the possibility that earthquakes could be induced by reservoir impoundment (e.g., Zoback and Hickman, 1982), the COE funded the USGS to install seismic stations in the region before reservoir impoundment and to provide continuous monitoring of seismicity.

Lake Sonoma is located in the California Coast Ranges and is straddled by two active fault systems. The Maacama-Healdsburg-Rogers Creek fault system is approximately 5 - 10 km to the east, and the San Andreas fault lies about 25 km to the west (Figure 1). The probability of significant earthquake activity between the faults is low in the next 30 years (Working Group on California Earthquake Probabilities, 1990). However, the proximity of Lake Sonoma to these two fault systems suggests that the deviatoric stress levels in the crust are probably sufficient to cause earthquakes.

The crest elevation of the dam is 519 feet (National Geodetic Vertical Datum (NGVD) of 1929), approximately 319 feet above the pre-existing stream bed. The reservoir operation plan calls for the reservoir level to be at conservation pool elevation 451 feet NGVD by the first of May each year. The reservoir level is subsequently reduced by controlled releases during the summer and fall months. The reservoir storage between elevation 451 feet NGVD and the spillway crest elevation 495 feet NGVD is for flood control purposes. Reservoir incursion into the flood storage area is generally of relatively short duration so as to maintain as much flood storage capacity as reasonably possible during the winter and spring months. The reservoir capacity at conservation pool elevation is 245,000 acre-feet, and at spillway crest elevation the capacity is 381,000 acre-feet.

The purpose of this report is to identify any earthquake activity that could be attributed to activities associated with the operation of the reservoir. It documents earthquake activity recorded since 1976, shortly after seismic stations were installed in this region. The information presented in this report should not be interpreted as indicative of the long-term seismic behavior of the region. The monitoring interval (~22 years) is relatively short compared to the seismic cycle (100-1000's of years) of many faults in this region. It is likely that many seismogenic structures in the region have not been illuminated by the recorded earthquake activity during the interval 1976-1998.

Data Acquisition

A review of the earthquake data acquisition systems used by the NCSN is necessary to understand how the data were selected for this report. Earthquake detection and location occurs on two independent data acquisition systems. The NCSN operates a completely automated system called Earthworm (Johnson *et al.*, 1995) and, until 10/1997, operated a predecessor called the RTP (Allen, 1978; Allen, 1982). The RTP and Earthworm systems calculate seismic station arrival times, first motion directions, and shaking (coda) durations. This information is then associated to calculate earthquake origin times, locations, and duration magnitudes. No seismograms are retained by these systems, and most of the earthquake location/magnitude data are not reviewed by seismologists. The NCSN operates a second, independent system called CUSP that processes the same data. However, the CUSP system enables seismologists to examine each digital seismogram and revise the parameters as necessary to properly locate the earthquake. Subsequently the traveltime information from both systems are merged together for archiving, and the digital seismograms and earthquake locations are archived.

Because the number of earthquakes typically varies by a factor of 10 for each unit step in earthquake magnitude, a seismic network will detect more earthquakes with a lower earthquake magnitude detection threshold. The NCSN utilizes the Earthworm/RTP systems to achieve a lower earthquake magnitude detection threshold because there is no additional time required of the seismologist to review and archive the seismograms. The Earthworm/RTP systems typically detect 50% more earthquakes than the CUSP system, and most of these earthquakes have magnitudes (*M*) less than 1.5. In lieu of human review, the NCSN automatically applies quality control filters to all earthquake data produced by the Earthworm/RTP systems. Despite these efforts, some erroneous earthquake information is catalogued.

Location and Magnitude Determination

The Earthworm and CUSP arrival time data for the same seismic event are merged and the hypocenter is then re-located using the earthquake location program Hypoinverse (*Klein*, 1989). In the vicinity of Lake Sonoma, Hypoinverse uses one of three crustal velocity models, whose velocity varies linearly with depth (Table 1; Figure 1). Multiple crustal models partly account for lateral velocity variations within the crust and consequently improve the accuracy of earthquake locations. The compressional/shear velocity ratio (*Vp/Vs*) is equal to 1.78 for all models. Earthquakes occurring between velocity model regions are located with an interpolation between the closest two or three models. The locations of several earthquakes near Lake Sonoma are calculated from an interpolated velocity model (*cf.* Figures 1 and 2). Comparison of these locations with locations computed only from a single velocity model indicate that the maximum epicentral shift is 0.5 km and the maximum shift in depth is less than 2 km. As discussed below, these differences are within the uncertainties of the data.

Table 1. Gradient P-Velocity models[1]

The Geysers (GEY)[2]					
Z (km)	0.00	3.00	8.00	20.00	22.00
V (km/s)	4.10	5.47	5.75	6.02	7.90
North Bay - Coast Ranges (NBY)[2]					
Z (km)	0.00	3.00	8.00	20.00	22.00
V (km/s)	4.10	5.47	5.75	6.02	7.90
Point Arena - Fort Bragg (PTA)					
Z (km)	0.00	2.50	19.80	26.60	
V (km/s)	4.00	5.40	6.40	7.80	

[1]See Oppenheimer et. al. (1993) for associated station traveltime corrections.
[2]Velocity models are identical, but station traveltime corrections differ.

Duration and amplitude magnitudes are calculated using the equations of *Eaton* (1992) which produce magnitudes that are in close agreement with the M_L (Richer) scale utilized by the U.C. Berkeley Seismographic Laboratory. The magnitude calculations utilize station corrections (Oppenheimer *et. al.*, 1993), a distance and depth term, and the time dependent gain history of the seismic station.

A complete description of NCSN operating procedures, station locations, and velocity models are described in Oppenheimer *et. al.* (1993) available at *http://quake.geo.berkeley.edu/ncsn/bulletin.ps*. All data referenced in this report are available via the World Wide Web from the Northern California Earthquake Data Center (NCEDC) at *http://quake.geo.berkeley.edu/ncedc*. Please note that the models given in Table 1 reflect the location procedures at the time this report was written. The catalog periodically undergoes revision to reflect improved velocity models and location procedures.

Data Selection

Approximately 2/3 of the raw earthquake location data from the NCEDC within the area of study were rejected for this report. The raw data obtained from the NCEDC have numerous errors, and a screening process was used to select data that are reliable. The most common error is caused by the Earthworm and RTP systems inability to distinguish earthquakes from short noise bursts introduced by the analog microwave telemetry system. The latter are readily identified in the raw data by a) small numbers of reporting stations, b) nearly coincident arrival times, c) magnitude estimates that are inconsistent with the total number of traveltime readings per event, and d) absence of human review. Examination of the data indicates that requiring each earthquake to be recorded by at least 8 stations eliminates nearly all noise bursts from the data set. We apply additional solution quality criteria to ensure that the earthquake locations are accurate. Finally, we exclude earthquakes occurring before 1976 due to the lack of seismic stations in this region.

Table 2. Selection criteria

Value	Minimum	Maximum	Rejection rate (%)
Solution *RMS* (sec)	0.0	0.3	3
Horizontal Location Uncertainty (km)	0.0	2.5	31
Vertical Location Uncertainty (km)	0.0	5.0	35
Maximum Station Azimuthal Gap (deg)	0.0	180.	34
Number of Stations	8		60
Latitude (deg:min)	38:39	38:51	N/A
Longitude (deg:min)	-123:14	-122:56	
Date (Yr/Mo/Da)	76/01/01	98/08/24	N/A
Magnitude	N/A	N/A	N/A

While the effect of these criteria is to eliminate poorly located earthquakes and noise, it also eliminates some legitimate, low magnitude earthquakes detected by less than 8 stations. The "*b*-value" plot shown in Figure 3 reveals that the magnitude detection threshold above which the seismic network is able to uniformly locate all earthquakes for this region is $M1.3$. Though the data is considerably winnowed by application of the criteria in Table 2, the remaining data shown in Figure 4 still provides reliable information on the occurrence of very small earthquakes.

Seismicity and Fluctuations in Lake Level

The map of earthquakes (Figure 4) in the general vicinity of Lake Sonoma shows that very few earthquakes above *M*1.3 have occurred in this region since 1976 and that most of the seismicity occurs east of the lake. The cause of the latter seismicity is likely tectonic because the earthquakes locate in the vicinity of the Healdsburg fault zone (HFZ) (Figure 1). Excluding the earthquakes on the HFZ, only 26 earthquakes have occurred within the region shown in Figure 4 during the past 22 years, the largest of which is *M*2.7 on Aug 18, 1991. Most earthquakes occur at depths less than 7 km (Figure 4), which is typical of earthquakes in the broader region.

Figure 2a shows that infrequent, small earthquakes occurred in the broad region between the San Andreas and Maacama-Healdsburg-Rodgers Creek fault zones in the 7.8 -year interval before reservoir impoundment. These earthquakes are clearly the result of tectonic forces. Figure 2b shows that minor seismicity occurs in essentially the same region over the next 14.2 years. Thus, the proximity of a few earthquakes to Lake Sonoma is not necessarily indicative of reservoir induced seismicity. The first-motion focal mechanisms (Reasenberg and Oppenheimer, 1985) shown in Figure 4 for these events indicate right-lateral motion on near-vertical, northwest-oriented faults which is consistent with the orientation of tectonic stress this region.

The histogram of earthquakes occurring within the region of Figure 4 as a function of time together with the time history of the lake level (K. Harrington, written communication, March 31, 1998) is shown in Figure 5. Reservoir impoundment began in October 1983; however, significant impoundment did not begin until the fall of 1984. The maximum reservoir level between October 1, 1983 and mid-November 1984 was approximate elevation 319 feet NGVD on December 31, 1983, and it then dropped to elevation 245.3 feet NGVD by November 2, 1984. The reservoir's four highest levels to date occurred on January 16, 1995; March 15, 1995; January 3, 1997; and February 9, 1998 at elevations 483.57 feet, 483.07 feet, 480.74 feet, and 484.06 feet NGVD respectively.

There is no obvious correlation with changes in lake level and changes in the magnitudes or rate of earthquake activity. A minor cluster of 11 earthquakes occurred in the time period June 23 - September 19, 1987 north of Cloverdale in the HFZ (Figures 4, 5c). The largest earthquake in this cluster was *M*1.9. Minor earthquake sequences on active, tectonic faults are not unusual in northern California and not necessarily related to reservoir impoundment. If the earthquakes presumably occurring on the HFZ are removed from the time series comparison (Figure 5b), there is little indication that the earthquake activity near Lake Sonoma is caused by reservoir impoundment.

Conclusions

The seismicity recorded by the NCSN in the vicinity of Lake Sonoma (Figure 4) since 1976 is complete to a magnitude of 1.3. The seismicity that locates in the vicinity of the Healdsburg fault to the east of Lake Sonoma is likely tectonic in origin. In the immediate vicinity of the lake there is a very low level of seismicity. Only 26 events occurred in the interval 1976-1998. The largest recorded event is *M*2.7. Minor earthquakes occur throughout the region between the San Andreas and Rodgers Creek - Maacama fault systems. Many of these earthquakes occurred before reservoir impoundment in October 1983 and are clearly caused by tectonic forces. It is likely that those few earthquakes that have occurred since October 1983 are also due to tectonic forces and were not induced by activities associated with the impoundment of the reservoir.

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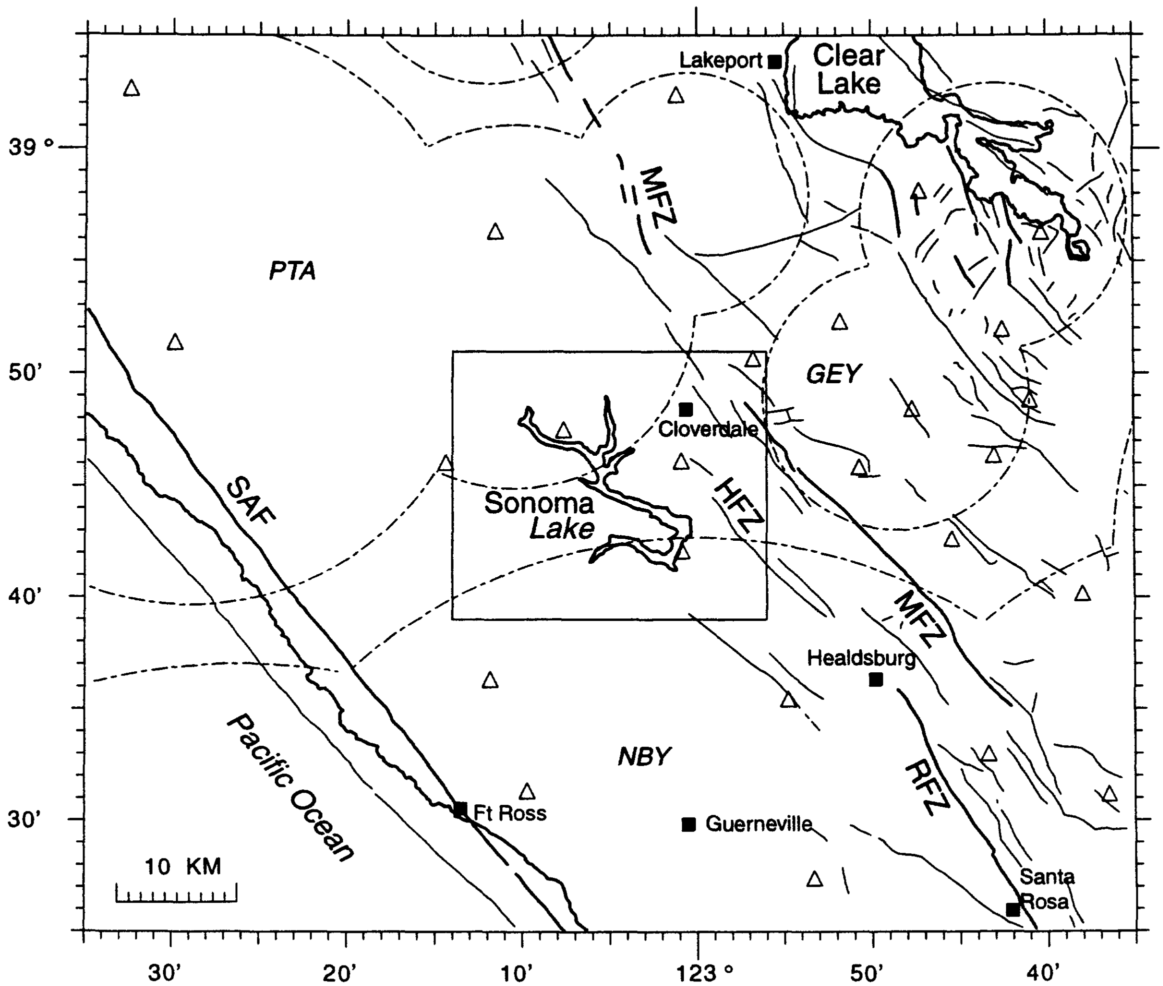

Figure 1. Map of Northern California Seismic Network seismic stations (triangles) operating as of August, 1998. Dashed lines depict boundaries of velocity models. Italicized 3-letter names correspond to models provided in Table 1. Box corresponds to study zone shown in Figure 4. Late Quaternary faults are shown as solid black lines, and those with Holocene activity are shown in bold (Jennings, 1992). HFZ = Healdsburg fault zone, MFZ = Maacama fault zone, RFZ = Rodgers Creek fault zone, SAF = San Andreas fault.

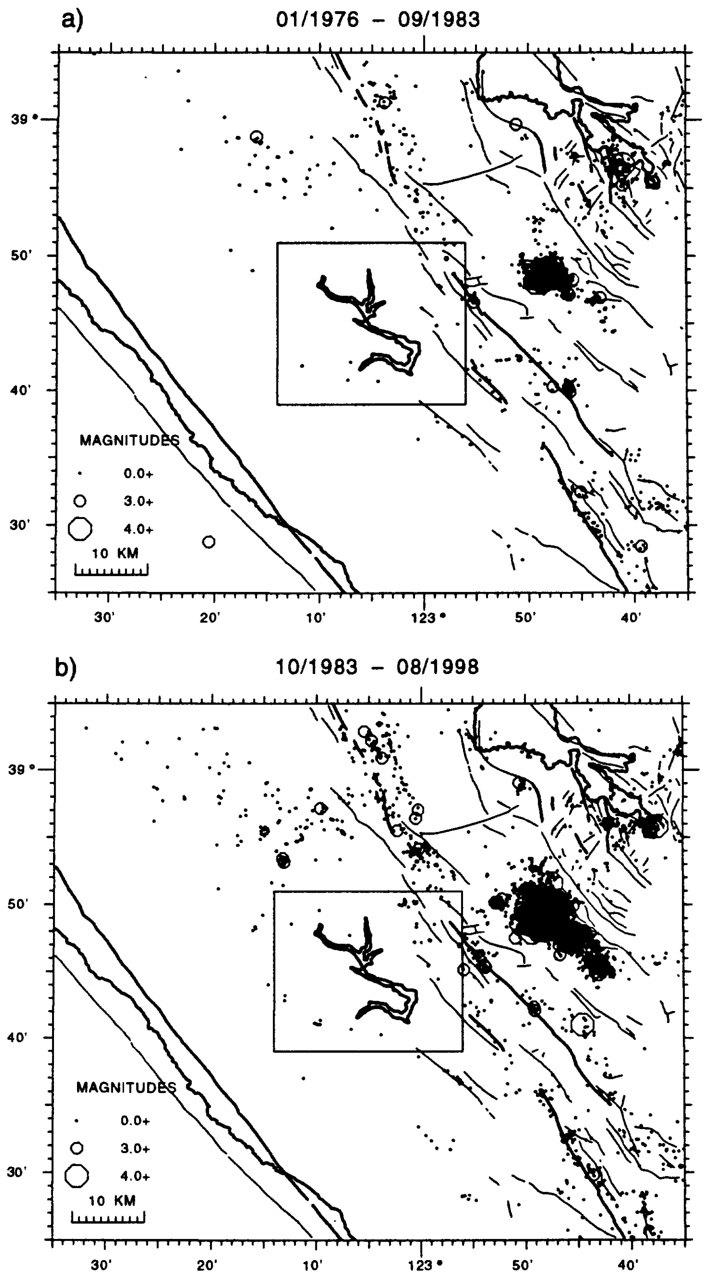

Figure 2. Map of well-located seismicity recorded by the NCSN for the a) 7.8-year period before and b) 14.2-year period after reservoir impoundment. Note occurrence of seismicity in region between the San Andreas and Maacama-Healdsburg-Rodgers Creek fault systems preceding impoundment. The dense cluster of earthquakes at the Geysers geothermal area east of Cloverdale is induced by activities related to steam production and fluid reinjection. Data have been selected with the quality parameters given in Table 2 and with additional criteria that the $M \geq 1.5$. Symbol size is proportional to magnitude. See Figure 1 for explanation of line work.

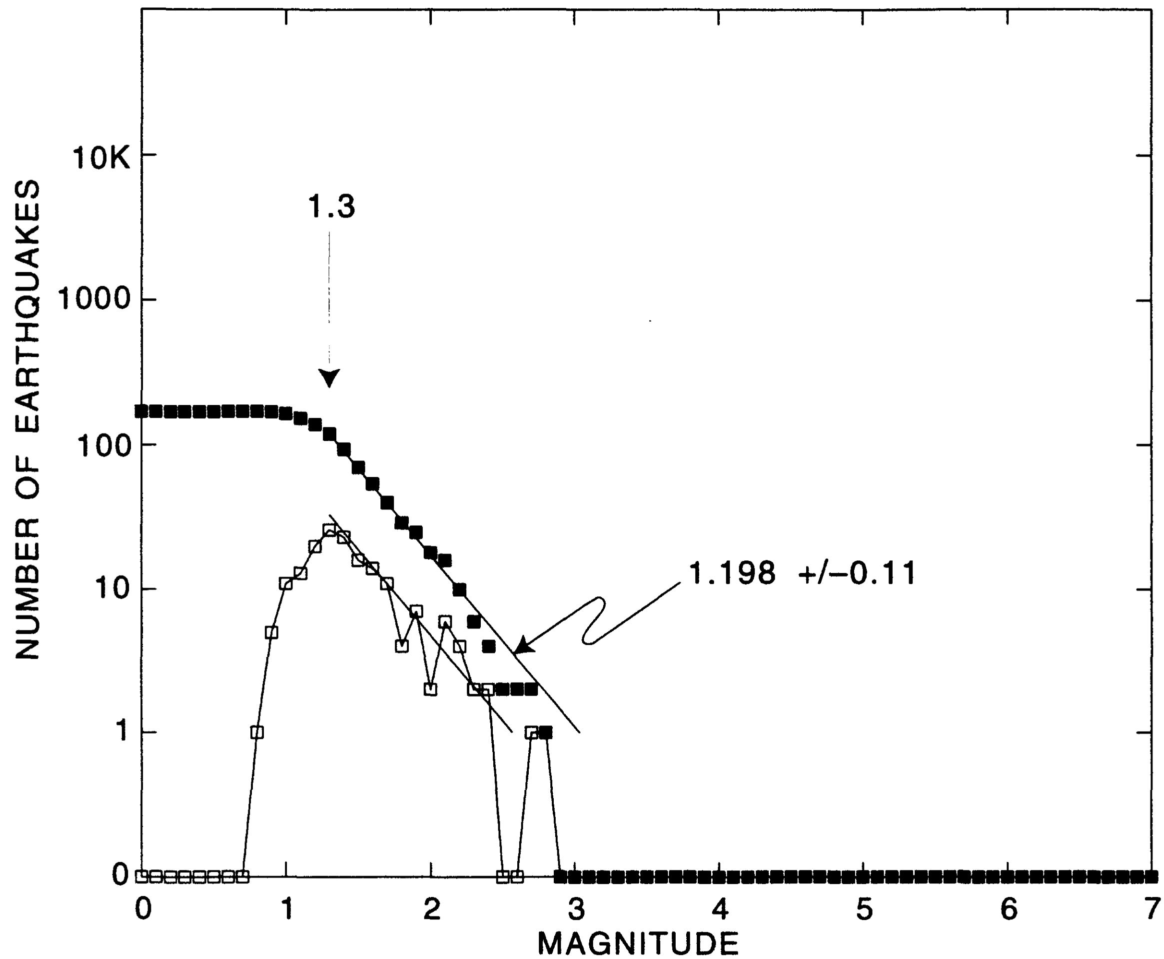

Figure 3. Histograms of the *log(N)*, where *N* = number of earthquakes, as a function of magnitude for area shown in Fig. 4. The (solid) open squares are the (cumulative) number of earthquakes within 0.1 bins of magnitude. The magnitude detection threshold, 1.3, is the magnitude above which the seismic network is able to uniformly locate all earthquakes. It is determined by visual examination of the histogram at the point where the slope of the cumulative number of earthquakes departs from a straight line at smaller magnitudes. The line through the cumulative number of earthquakes is a least-squares estimate of the slope ("b" value) of the data for magnitudes greater than the detection threshold.

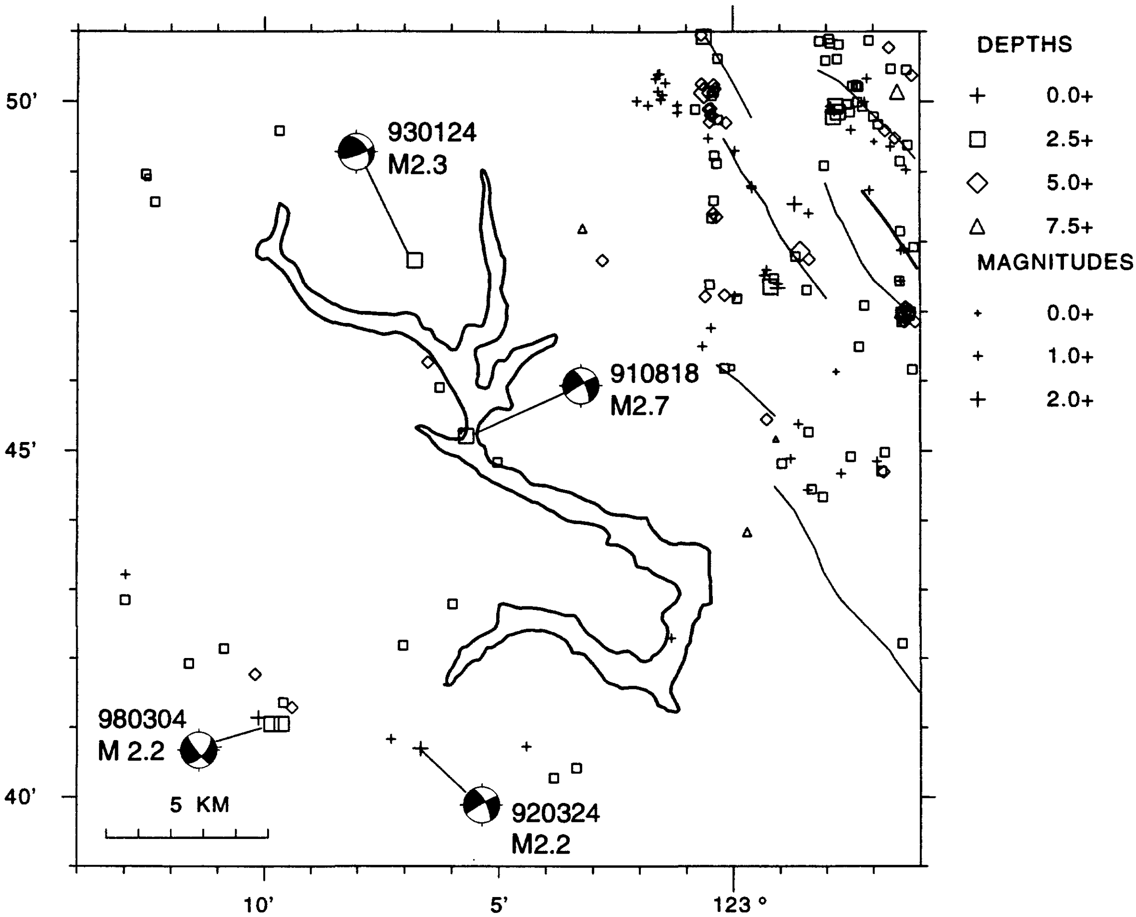

Figure 4. Map of well-located seismicity recorded by the Northern California Seismic Network for the period January 1, 1976 through August 24, 1998 near Lake Sonoma. Data have been selected with the quality parameters given in Table 2. Symbol size is proportional to magnitude. Symbol type is a function of earthquake depth. Well determined first-motion fault plane solutions are shown for 4 earthquakes near Lake Sonoma. The UTC date and magnitude of the event are indicated adjacent to the fault plane solutions. The solutions are shown as lower hemisphere, equal-area projections with the tensional quadrant filled. See Figure 1 for explanation of line work.

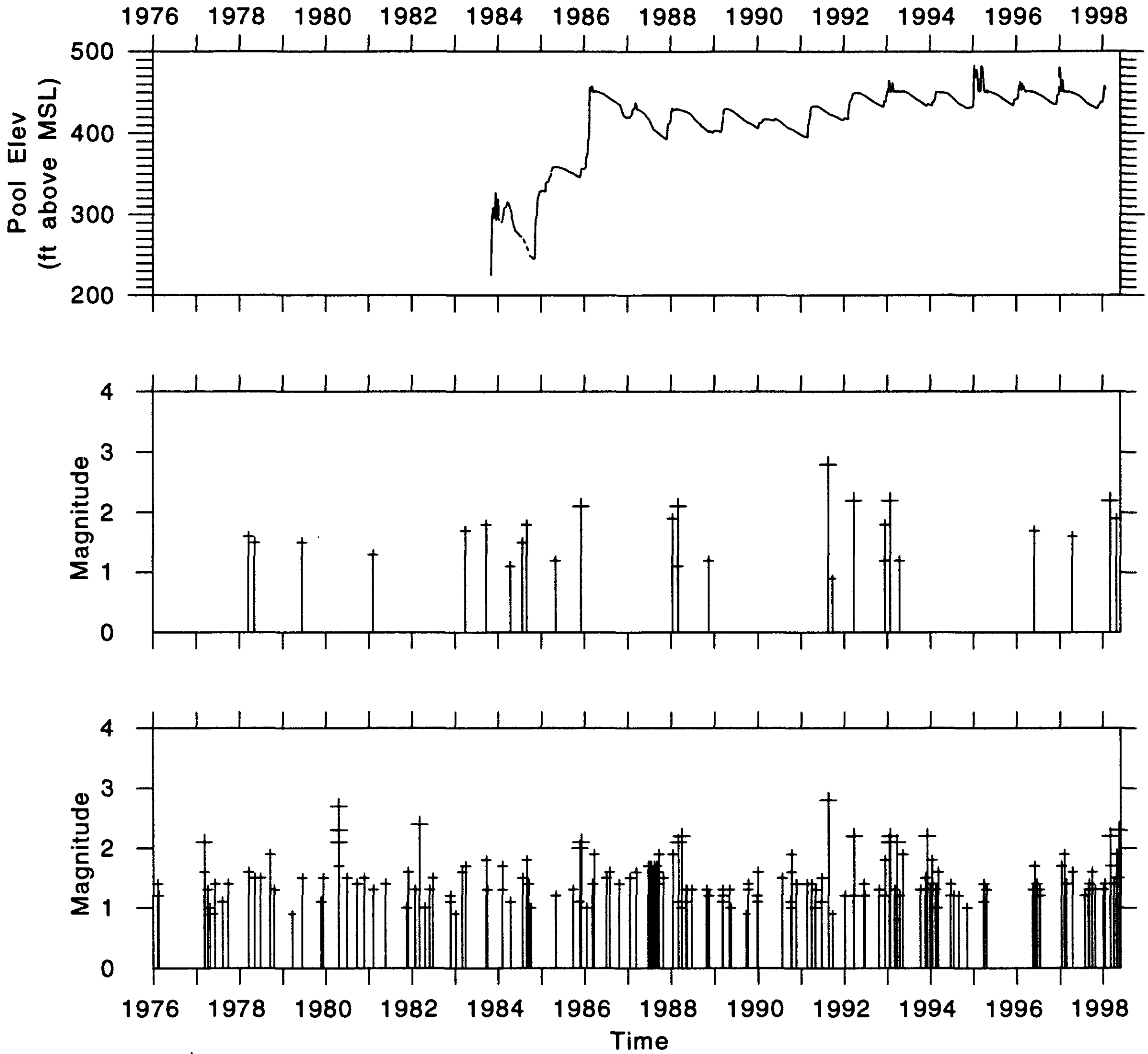

Figure 5. Comparison of time series of a) elevation of Lake Sonoma pool (K. Harrington, written commun., March 31, 1998) with b) magnitudes of earthquakes in Figure 4 west of the Healdsburg fault zone (Figure 1), and c) of magnitudes of all earthquakes shown in Figure 4.