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FINAL REPORT - VOLUME I
EARTHQUAKE ANALYSES FOR STRUCTURAL DEFINITION
AND MATERIAL CHARACTERISTICS OF THE MONO CRATERS
AND LONG VALLEY MAGMA SYSTEMS

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EXECUTIVE SUMMARY

This two volume report presents the results of a multi-year effort undertaken by Woodward Clyde Consultants in cooperation with the University of California at Santa Cruz to increase the scientific understanding of the tectonic and magmatic processes occurring in the Long Valley and Mono Craters regions of California. The effort has been fruitful in that it led to six articles submitted to referred journals for publication as well as several unpublished reports. All of these are included in these volumes. The journal articles are listed in the attached table. It is anticipated that several other articles will be submitted for publication in the near future based on these investigations.

The studies performed were of four different types. The first were based on a seismic data collection effort carried out at Long Valley in cooperation with the USGS and several other groups investigating similar problems. Both explosive and earthquake sources were recorded. The data collection effort is summarized in the report for the first year. This data was later analyzed in a search for evidence of the Long Valley magma chamber. Both reflected and screened arrivals were searched for with essentially negative results. Though this was not the desired outcome, it is essentially consistent with the results of other workers. Though some seismic evidence for the existence of a magma chamber has been reported, it is much weaker than most researchers involved in the Long Valley studies anticipated.

The second category of investigations carried out were intensive studies of important large earthquakes that have occurred in the Long Valley region. These include the May 25, 1980 event and a large aftershock (report on year 1,

and year 3), the 1941 sequence (report on year 2), and the Round Valley earthquake of November 23, 1984 (report on year 4). The central scientific issue surrounding these larger events regards their mechanism. Some evidence indicates that, rather than being caused by slip on a fault plane, they were caused by magma injection. Such a difference should change the equivalent moment tensors for the events from double couples to compensated linear vector dipoles (CLVD's). Unfortunately, several common sources of uncertainty could mimic this effect. The overall indication of the studies presented here is that the Long Valley events could be, within error, typical basin and range earthquakes.

The third types of studies involved statistical analyses of seismicity data. The first study (year 1) involved microearthquake modeling to constrain possible magma injection associated with the 1983 Mammoth Lakes sequence. Spatial and temporal patterns were found in this data that were consistent with the existence of a weak quiescent hole in the Long Valley region. The second study (year 2) involved a clustering analysis of the seismicity data. The Long Valley region showed a typical level of clustering up to late in 1976. In the period leading up to the October 1978 event, seismicity decreased by an order of magnitude within Long Valley, and the incidence of clustering decreased throughout the frontal fault system. After 1978, the number of events occurring in clusters increased by an order of magnitude.

The final studies involved the development of some important new theoretical methods for modeling the effects of screening bodies, such as magma bodies, on three dimensional wave fields (year 4). The theory for modeling screening bodies has not been developed as fully as the theory for

reflecting or refracting bodies. The recently developed three dimensional slowness method is shown here to be a very useful tool for treating such problems. A sample calculation of the effects of the Long Valley magma chamber on S waves is presented. It is shown that diffraction of energy around a three dimensional screening body needs to be considered carefully in assessing screening observations. It is also shown that anelasticity alone can account for screening by a magma chamber if Q for shear waves drops to levels between 10 and 100.

LIST OF PUBLICATIONS

1. Wallace, Terry C., A re-examination of the moment tensor solutions of the 1980 Mammoth Lakes earthquakes, J. Geophys. Res., 90, 171-176, 1982.
2. Wallace, Terry C. and J. S. Barker, The 1941 earthquake sequence near Long Valley Caldera, California, Bull. Seism. Soc. Am., (in prep), 1986.
3. Barker, J. S. and T. C. Wallace, A finite fault model for the 1980 Mammoth Lakes, California earthquakes, Bull. Seism. Soc. Am., (submitted), 1985.
4. Barker, J. S., and Terry C. Wallace, A note on the teleseismic body waves from the November 23, 1984 Round Valley, California earthquake, Bull. Seism. Soc. am., (in press), 1985.
5. Burdick, L. J., Screening of S waves by a low Q body, Bull. Seism. Soc. Am., (submitted), 1986.
6. Burdick, L. J. and C. A. Salvado, Modeling body wave amplitude fluctuations using the three dimensional slowness method, J. Geophys. Res., (in press), 1986.

SECTION 1

DATA ACQUISITION FOR VOLCANO-TECTONIC STRUCTURAL ANALYSES

Introduction

A primary emphasis during the first year of research by Woodward-Clyde Consultants was the acquisition of high-quality seismological data sets. The objectives and activities involved in collecting these data sets are described in this section of the report. Analyses of the data are discussed in subsequent sections of this report.

Approach

The detection and interpretation of the presence of subsurface magma using wave propagation techniques requires either the passage of seismic waves through the magma or reflection of seismic waves from the margins of the crustal region occupied by magma. In the absence of detailed knowledge about the location and wave propagation characteristics of a region containing magma, carefully designed experiments and dense instrumental coverage are needed, along with good luck, in order to be able to successfully define an existing magma region. If no evidence for the occurrence of magma is found, the lack of diagnostic data may mean either that the magma is not present or that the position of seismic sources and receivers was not adequate to detect

the presence of magma. Thus care was needed both in planning the field experiments and in interpreting the results.

In the field activities we conducted during August 1982 and January 1983, we used all available information and opinions to plan the deployment of instruments. The strategy behind the data collection was the following:

1. The data collected should be three-component , high-resolution digital data suitable for extensive waveform analysis. The use of three components allows for maximal identification of secondary arrivals of direct or converted P and S waves.
2. The data should be collected in areas not already monitored by other groups. Of particular importance in this regard were the controlled source refraction experiments conducted by the USGS, since the known source location could allow specific testing of various hypotheses about the structure of the crust.
3. Close cooperation should be maintained with other groups in order to efficiently supplement their data collection activities while taking specific advantage of the instrumentation and research objectives of our program. In our field activities, especially close coordination was maintained with the USGS and with Dr. John Rundle of Sandia.
4. Efficient logistical planning should be used to maximize the cost-effectiveness of the data collection.

In the two field deployments discussed in the following subsections, the above strategies were applied to two different but related experiments.

August 1982 Refraction

During August 1982, the USGS set off a series of large underground explosions (on the order of 500 to 1000 lbs of high explosives) accompanied by deployment of refraction of seismographs. Our objective was to take advantage of these seismic sources to look for reflected phases from possible magma bodies in the northern portion of the Long Valley Caldera. Since the shots were primarily to the northwest of the caldera and extending as far south as Casa Diablo, we placed our deployment between the last two shot points to both fill in the USGS refraction line and to collect three-component data from the shots. In light of the above approach, this deployment provided coverage slightly to the east of the shot line both for the Mono Craters area (using the more distant shots) and for the western Resurgent Dome area (using the close in shots). The USGS experiment is discussed in Meador and Hill, 1983 and Hill et al., 1985. The location of the three most southerly shot points and the deployment of instruments is shown in Figure 1.1.

Our field deployment was conducted in cooperation with Dr. John Rundle of Sandia Laboratories. Sandia provided three Sprengnether DR-100 digital event recorders with 1.0 Hz seismometers, Woodward-Clyde provided an additional DR-100 for installation, backup DR-100's used to keep the four primary units operational, and two MEQ-800 recorders used to monitor the

ambient seismicity and to verify the occurrence of the shots. The field sites for these instruments are shown in Figure 1.1. The shots occurring on the nights of August 5 and August 10 were recorded.

Initial examination of the data collected did not reveal strong evidence of the presence of secondary arrivals that were suggestive of the presence of seismological anomalies consistent with magma body interpretations. Due to the problematical nature of the interpretation of such data, we reasoned that secondary arrivals would need to be clearly evident to provide the basis for extensive waveform analysis. Thus, we tentatively interpreted the data to suggest that we did not detect the presence of magma with our data sets in the northwestern caldera area. This interpretation is consistent with the results of the USGS refraction analysis (Hill et al., 1985) and the interpretation of S-wave screening by Sanders, 1984 and Sanders and Ryall, 1983. No further analysis of the data were conducted.

January 1983 Swarm

On January 11, 1983, a significant earthquake sequence began in the South Moat area of the Long Valley Caldera. This sequence culminated in a magnitude 3.1 event on January 13 that was followed by a long-lasting swarm-like sequence of microearthquakes. This sequence was immediately recognized as a significant occurrence of earthquake activity in the eastern Sierras because it took place on the margin of and within the Long Valley Caldera rather than several tens of kilometers to the south of the caldera as had the May 1980 swarm. Woodward-Clyde began to mobilize equipment on the day the sequence

began, and arranged DOE approval of a change in priorities to allow rapid deployment of instrumentation to record the sequence. This field study had two objectives: (1) to operate instruments directly above the sequence in order to provide high-resolution microearthquake locations and (2) to use the larger earthquakes of the sequence as known sources in a further search for wave propagation effects of the presence of magma in the Long Valley region.

The field deployment began early on January 11 using instrumentation provided by both Woodward-Clyde and the University of California at Santa Cruz. UC Santa Cruz provided four SMA-1 strong-motion film recorders and three Sprengnether MEQ-800 drum recorders. Woodward-Clyde provided five MEQ-800's, three DR-100 three-component digital recorders, a complete complement of spares and field supplies. A Woodward-Clyde team installed and operated the instrumentation for more than two weeks, the most active period of the sequence. The MEQ-800 recorders were installed in six locations as shown in Figure 1.2. Each site consisted of one recorder with a 1.0-second vertical seismometer. In addition, MEQ-800 recorders with horizontal seismometers were installed at stations WCM-5 and WCM-6, thus providing horizontal records to use with the vertical records in providing the most accurate identification of S-wave arrivals. The S-P data are used to provide maximum constraint on focal depth. Records were changed every twelve hours during the early part of the recording period in order to provide more accurate timing resolution. The resulting collection of smoked paper records have been analyzed in conjunction with readings from USGS and University of Nevada stations. These analyses and results are discussed in Year 1, Section 2.

The accelerographs were installed at four of the sites (WCM-1, -2, -3, and -4) in case a large event occurred. Due to the small size of most of the events in the swarm, however, during the period of operation of the portable stations no accelerograph triggers were recorded.

Three digital seismographs were installed during the early weeks of the swarm to record data that may reveal the presence of a highly attenuating body or that may contain reflected or converted phases produced by a low-velocity magma body. The locations of the instruments are shown in Figure 1.2. Due to the very cold weather, the instruments were installed in foam-insulated wooden housings. This protection was not adequate, and two of the instruments (WCM-8 and WCM-9) operated erratically. However, WCM-7 operated very well and recorded hundreds of events. Preliminary inspection of these data did not suggest the presence of reflected or converted phases related to possible magma bodies. The data were analyzed in terms of S-wave screening, as discussed in Year 3, Section 2.

Summary

The data acquisition efforts conducted during the 1982-1983 period were successful in producing data sets useful for directly addressing questions of crustal structure and seismicity processes in the Long Valley-Mono Craters area. These data sets in some cases provided negative information (no features related to magmatic processes were observed) and in some cases provided data that led to volcano-tectonic interpretations important to the DOE program objectives. These analyses are discussed in subsequent sections of this report.

References

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Figure Captions

Figure 1.1 Locations of shot points (open circles), digital event recorders (solid triangles) and smoked-drum recorders (solid circles) for the USGS refraction shots in August 1982.

Figure 1.2 Three-component digital event recorders (solid triangles) and smoked-drum recorders (solid circles) operated during the first two weeks of the January 1983 swarm.

Figure 1.1

Figure 1.2

SECTION 2

HIGH RESOLUTION MICROEARTHQUAKE MODELING FOR CONSTRAINTS ON MAGMA INJECTION ASSOCIATED WITH THE JANUARY 1983 MAMMOTH LAKES EARTHQUAKE SEQUENCE

Introduction

A set of digital and analog recorders were mobilized and installed several days after the initiation of the January 1983 earthquake swarm in the area extending east and southeast from Mammoth Lakes (Figure 2.1). This swarm has been suggested as a seismic response to magma intrusion by, for example, Rundle and Whitcomb (1984). We are fortunate to have a unique data set with high-resolution coverage for the seismicity data, due to the deployment of the dense portable seismograph network during this episode. During this year we have been analyzing and reducing these data, integrating relevant readings from permanent stations (Figure 2.2). We are continuing to test and verify the local velocity structure for precise hypocenter locations in order to discriminate anomalous zones that may indicate the presence of magma at depth. Earthquake focal mechanisms aid in mapping the stress orientations as a function of time and space. Since both the depths of events and focal mechanisms are extremely sensitive to the velocity structure and seismograph station travel time adjustments, we emphasize careful testing and consistency in the analysis.

The objectives of this work are to assess mechanistic models, using geometric and dynamic constraints regarding the crustal structure and magma body location and properties. This assessment is performed on the basis of detailed seismicity and fault mechanism patterns, as well as results from earthquake source modeling, wave propagation and attenuation modeling. The emphasis is on high-resolution testing and evaluation of previous interpretations regarding the magmatic environment near Mammoth Lakes for designing a precise drilling experiment.

Our findings to date are summarized here, with a technical discussion following.

1. Detailed analyses reveal that the South Moat region, site of the January 1983 earthquake swarm, is outlined by a complex brittle geometry surrounding a zone of seismic quiescence. The shallow (0-4 km) surface material forms a brittle "roof" over the quiescent "hole" and produces small events, consistent with the presence of weak sedimentary material that yields to movements below. The quiescent "hole" is outlined to depths of about 9.5 km, with seismicity along the WNW and ESE edges of the South Moat region. The width of the "hole" is about 2 km. There is no lower boundary in seismicity for the "hole," which could be connected to non-brittle material at greater depth. An apparent lower boundary of brittle material is actually a small bridge lying approximately 1.5 km behind and inward (into the moat) from the seismically defined "hole." It is defined at depths between 6.5 and 8.5 km.

2. The geometry of the quiescent "hole" is crossed by waves of activity that appear to migrate from deep to shallow and from side to side. This suggests that the material in the inner region is capable of transmitting stress, but not capable of deforming brittlely.

3. Fault mechanisms suggest variations in stress orientations around the quiescent "hole," both in space and in time. Comparison of these mechanisms with a simple stress distribution model for a rigid plate with a weak inclusion in the center and loads at the edges can constrain the material properties of the inner zone.

4. Fault segments appear to splay off, away from the boundaries of the "hole," in three directions: WNW and ESE at the edges of the caldera, and from the south rim of the caldera to the fault system that produced the large events in 1980.

Technical Discussion

Combining our portable field data with data from the permanent stations, and after testing of crustal velocity models, we located all events with the program HYPO71 (Lee and Lahr, 1975). The combined stations are shown in Figure 2.2 and the preliminary locations in Figure 2.3. When the data were viewed in cross-section (Figure 2.4), it was apparent that HYPO71 produced a bias in earthquake depth at about 5 km. In order to refine the data set for high resolution analysis, we turned to relocations using HYPOINVERSE (Klein, 1978). The new results are shown in Figure 2.5. A complex geometric

structure became apparent, with a zone of seismic quiescence surrounded by brittle seismic failure (Figure 2.5). Also this figure reveals a lineation of seismicity connecting the South Moat region to the mapped faults further to the south. This would suggest a small fault that might transmit stress from the larger faults (which produced the large 1980 earthquakes) into the caldera itself, concentrating along its edges. The seismicity shown within the box of Figure 2.5 is projected with depth along cross-section A-A' in Figure 2.6. Here again one can see the zone of seismic quiescence outlined by seismic activity. One interpretation is that the quiescence reflects non-brittle material surrounded by brittle material. Other interpretations are possible, however. For example, it is possible that the quiet region slipped seismically in the largest event of the sequence ($M_L=5.2$) and that the aftershocks simply reflect stress redistribution. The dimensions of the quiet zone are compatible with this interpretation.

The limitation of a 2-dimensional projection (as shown in Figure 2.6) is that a 3-dimensional geometry can be obscured. The subsequent effort was directed toward illuminating the fine-scale 3-D structure. An enlargement of the seismicity map with symbols specifying depths of 0-4, 4-6.5, 6.5-8.5, and greater than 8.5 km is shown in Figure 2.7. The following discussion describes the rationale for these particular depth divisions. Initially maps were constructed to reveal the structure in depth ranges of 0-5, 5-7, and greater than 7 km, shown in Figures 2.8A, 2.8B, and 2.8C. Structural variations with depth were apparent, as suggested by the sketched outlines in these figures. Again it appeared that these divisions were too coarse to reveal the fine 3-D structures needed for modeling constraints. At this point

20 maps were constructed at 0.5 km intervals as shown in Figure 2.6. Each depth interval was overlain in sequence to contour connected 3-D seismic structures. The results are shown in Figures 2.9A-D. Between 0 and 4 km (Figure 2.9A) a shallow seismicity "roof" and interconnecting fault lineation are observed (solid outlines). In Figure 2.9B, between depths of 4.0 and 6.5 km, the "roof" over the quiescent "hole" has disappeared, although the side boundaries (WNW and ESE) are maintained. Splay fault segments are observed at the outer edges to the WNW and ESE (solid outlines) from these boundaries. The interconnecting fault lineation to the SSW is maintained. In Figure 2.9C, the latter features to the ESE and SSW have disappeared between 6.5 and 8.5 km depth. A new feature is observed, specifically a brittle "bridge" about 1.5 km behind the quiescent "hole," and inward toward the moat (solid outlines). Also, the WNW and SSE boundaries at the edges of the "hole" are seen to persevere. In Figure 2.9D, between depths of 8.5 and 10 km, the latter "bridge" has disappeared, and all that remains are the roots of the brittle boundaries as the WNW and SSE edges of the "hole."

We now have the outlines of the 3-D brittle region well defined. These geometric constraints will be used for modeling the material properties relative to their behavior under stress, for example tectonic stress or magma intrusion.

Finally, in Figures 2.10 we show the dynamic characteristics of the region in sequential time periods, both in map and depth views, together with fault mechanism evidence for direction of stress. Envelopes indicate areas of seismic concentration with time. An important result is that these envelopes suggest stress migration across the seismic quiet zone, from bottom to top and

side to side, with time. This suggests that while the inner material may be non-brittle to support seismic failure, it can nevertheless transmit stress under dynamic slip conditions.

References

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Table 2.1

date	origin	lat n	lon w	depth	mag	no	gap	dm	rms	erh	erz
83 111	1746	9.58	37 27.18	119 1.88	3.94	2.54	9 321	19.5	0.14	12.5	15.6
83 111	1845	54.15	37 37.57	118 55.66	3.30	2.08	12 101	1.5	0.09	0.5	1.1
83 111	1849	23.02	37 34.03	118 50.18	5.16	2.77	13 150	2.8	0.06	0.7	1.3
83 111	1935	7.78	37 36.99	118 52.67	7.78	2.36	13 112	3.4	0.08	0.6	1.1
83 111	2122	34.83	37 36.87	118 54.58	6.48	2.10	7 175	1.3	0.02	0.8	1.0
83 111	22 5	31.74	37 37.72	118 56.20	8.14	2.73	14 89	1.0	0.09	0.8	0.9
83 111	2317	48.00	37 37.87	118 55.96	7.31	2.58	15 86	0.8	0.08	0.7	0.5
83 111	2324	48.65	37 38.53	118 55.28	5.50	1.88	7 109	1.4	0.06	1.1	2.1
83 112	031	24.21	37 37.34	118 55.91	4.97	2.28	14 113	1.8	0.10	0.6	1.0
83 112	117	57.46	37 37.30	118 54.81	4.45	2.18	14 75	0.9	0.10	0.6	1.0
83 112	123	9.85	37 37.00	118 52.73	8.57	2.37	15 111	2.4	0.08	0.5	1.0
83 112	251	38.83	37 37.32	118 54.90	2.97	2.14	15 80	1.0	0.09	0.5	0.6
83 112	3 3	5.37	37 37.49	118 55.16	3.76	1.72	15 89	1.4	0.09	0.5	0.9
83 112	322	26.80	37 37.69	118 54.96	7.71	1.56	16 73	1.1	0.07	0.6	0.9
83 112	536	54.76	37 36.53	118 54.94	4.37	1.74	15 143	0.2	0.09	0.6	1.0
83 112	612	52.88	37 35.73	118 55.34	1.69	2.34	13 172	1.8	0.07	0.6	0.6
83 112	619	20.77	37 36.96	118 52.70	7.95	1.67	15 113	2.5	0.07	0.6	0.9
83 112	652	52.34	37 36.72	118 52.21	9.43	2.12	17 120	1.9	0.07	0.6	0.9
83 112	750	5.42	37 37.75	118 55.82	6.87	2.05	17 92	1.1	0.10	0.7	0.4 S
83 112	9 4	51.57	37 38.04	118 55.68	7.50	2.08	16 76	0.8	0.06	0.7	0.9
83 112	944	28.23	37 36.95	118 52.73	7.98	1.93	16 113	2.4	0.07	0.6	0.8
83 112	945	10.93	37 35.79	118 55.32	1.02	2.13	16 169	1.7	0.08	0.5	0.8
83 112	10 1	40.42	37 35.63	118 53.42	11.07	2.29	12 203	2.9	0.13	1.9	2.2
83 112	1223	5.24	37 37.37	118 56.74	7.01	2.32	16 91	0.9	0.08	0.8	0.5
83 112	1325	21.52	37 37.02	118 53.50	4.71	1.67	13 105	1.4	0.07	0.6	1.0
83 112	14 4	58.16	37 37.91	118 55.89	2.96	1.69	16 84	0.8	0.07	0.4	0.5
83 112	1549	35.96	37 36.96	118 53.15	6.89	2.10	14 111	1.9	0.08	0.6	0.8
83 112	1623	44.55	37 37.48	118 54.84	7.57	2.26	14 73	0.9	0.08	0.7	1.1
83 112	1639	52.50	37 37.43	118 55.08	1.87	1.64	9 144	1.3	0.06	0.6	0.5
83 112	1827	47.36	37 36.93	118 52.67	8.19	2.33	14 114	2.5	0.07	0.6	1.0
83 112	21 5	41.64	37 37.26	118 55.90	4.24	1.86	8 184	1.9	0.07	1.8	1.3
83 112	22 3	8.89	37 37.82	118 53.38	7.66	2.03	10 148	1.4	0.06	1.9	1.3 S
83 112	2214	37.06	37 37.62	118 57.36	10.24	2.58	7 298	2.2	0.04	4.3	3.7
83 112	2254	5.65	37 37.30	118 52.56	8.19	2.23	16 102	2.5	0.12	0.7	0.6 S
83 113	124	23.02	37 36.67	118 51.91	1.66	1.63	13 148	1.5	0.10	0.6	0.4
83 113	135	31.87	37 37.36	118 55.73	4.61	2.78	19 113	1.8	0.10	0.6	0.9
83 113	147	18.21	37 37.66	118 54.53	3.65	2.13	18 69	0.6	0.07	0.5	0.7
83 113	231	12.92	37 37.80	118 56.28	4.52	2.49	19 83	0.9	0.09	0.5	0.9
83 113	329	28.97	37 37.21	118 56.74	1.67	1.56	17 137	0.8	0.07	0.6	0.3
83 113	4 3	21.74	37 36.91	118 52.66	4.92	2.00	18 114	1.8	0.05	0.5	0.9
83 113	451	43.44	37 36.80	118 52.43	8.22	1.38	9 147	3.7	0.04	1.0	1.3
83 113	456	12.61	37 37.38	118 54.44	1.84	1.71	15 92	0.3	0.08	0.4	0.3
83 113	731	59.36	37 37.49	118 57.02	6.90	2.51	17 100	0.9	0.08	0.8	0.5
83 113	745	21.13	37 37.86	118 57.14	7.46	2.13	17 90	1.1	0.07	1.2	1.2
83 113	758	42.48	37 38.00	118 54.83	2.13	2.73	15 62	0.9	0.10	0.5	1.0
83 113	8 3	13.66	37 37.87	118 54.80	2.26	1.45	14 63	1.8	0.08	0.4	0.9
83 113	849	50.99	37 36.85	118 50.64	2.12	2.19	16 83	0.5	0.06	0.4	0.6
83 113	850	29.60	37 36.83	118 50.73	2.10	1.54	9 87	0.3	0.06	0.6	0.8
83 113	851	1.26	37 37.49	118 55.54	9.09	2.18	16 103	1.7	0.07	0.7	1.0
83 113	922	33.11	37 36.87	118 50.75	2.60	1.53	11 76	0.4	0.08	0.5	0.7
83 113	10 3	19.60	37 37.53	118 55.35	8.65	1.54	14 95	1.6	0.07	1.2	1.5
83 113	1126	3.42	37 37.79	118 55.99	8.83	2.17	18 91	0.9	0.08	0.8	1.0

83	113	1153	11.67	37	37.70	118	54.69	2.98	1.60	20	63	0.8	0.07	0.4	0.5	S
83	113	1218	50.82	37	37.87	118	57.13	6.38	2.41	18	89	1.1	0.12	0.7	0.8	
83	113	1259	58.72	37	36.88	118	52.92	8.12	2.03	17	114	3.0	0.08	0.6	0.9	
83	113	1959	2.17	37	36.97	118	52.70	6.09	2.03	10	160	2.5	0.05	1.2	2.4	
83	113	2041	5.28	37	36.48	118	52.20	8.89	2.12	17	126	1.9	0.08	0.7	1.0	
83	113	2116	38.26	37	38.48	118	56.08	3.35	2.01	18	56	0.4	0.07	0.4	0.8	
83	113	2249	42.91	37	37.87	118	55.23	5.82	3.10	21	76	1.0	0.09	0.6	0.8	S
83	113	2251	45.93	37	38.07	118	55.17	4.30	2.96	12	68	1.5	0.09	0.6	1.2	
83	113	2256	31.07	37	37.61	118	55.98	6.33	2.28	14	206	1.3	0.10	1.2	0.7	
83	114	013	5.67	37	37.04	118	54.02	2.98	2.77	16	96	0.9	0.09	0.4	0.6	
83	114	156	18.28	37	37.01	118	52.20	4.83	1.56	12	136	2.0	0.06	0.6	1.3	
83	114	548	29.77	37	37.17	118	54.47	5.05	1.79	15	102	0.7	0.09	0.5	1.0	
83	114	619	23.50	37	36.45	118	55.40	3.16	1.90	16	151	0.8	0.10	0.6	0.9	
83	114	624	47.36	37	38.14	118	56.50	3.50	1.93	15	69	0.6	0.08	0.4	1.0	
83	114	640	50.57	37	36.68	118	52.39	5.94	2.44	22	121	2.2	0.09	0.6	0.9	
83	114	733	2.71	37	36.72	118	51.45	10.00	1.54	14	141	0.8	0.13	1.5	2.4	
83	114	924	49.31	37	36.43	118	50.91	7.31	2.01	16	122	0.5	0.09	0.6	0.5	
83	114	1025	7.53	37	38.50	118	55.99	3.60	1.35	13	55	0.5	0.07	0.5	0.9	
83	114	1034	37.23	37	36.72	118	52.36	7.37	2.65	19	120	2.1	0.09	0.6	0.7	
83	114	1036	16.89	37	37.73	118	55.14	1.29	1.33	13	78	1.3	0.09	0.3	0.7	
83	114	1153	36.37	37	36.89	118	54.24	2.60	2.16	13	137	1.1	0.11	0.6	0.9	
83	114	1623	0.49	37	36.74	118	52.83	8.73	2.47	15	119	2.5	0.09	0.6	1.0	
83	114	1651	33.39	37	36.92	118	52.81	9.08	2.27	11	113	2.4	0.06	0.8	1.5	
83	114	1924	54.74	37	37.75	118	54.97	3.13	1.25	10	71	1.2	0.06	0.5	0.9	
83	114	2020	44.70	37	37.25	118	54.73	2.22	1.20	11	82	0.9	0.08	0.5	1.0	
83	114	2118	0.16	37	37.61	118	57.53	8.78	2.50	16	208	1.1	0.08	1.4	1.0	
83	114	23 2	10.17	37	36.70	118	54.56	3.56	1.60	13	153	0.6	0.10	0.7	1.3	
83	114	2313	31.75	37	37.70	118	54.78	3.20	2.04	19	68	0.9	0.09	0.5	0.7	
83	114	2324	28.31	37	37.85	118	54.63	3.06	2.04	18	58	0.9	0.07	0.3	0.4	
83	115	018	9.63	37	37.99	118	56.83	7.02	1.70	15	69	1.0	0.06	0.9	0.9	
83	115	025	16.30	37	37.51	118	56.80	6.85	2.43	19	78	1.0	0.10	0.8	0.5	
83	115	146	3.92	37	38.11	118	56.78	6.53	1.93	19	66	0.9	0.05	0.8	1.2	
83	115	151	55.20	37	38.13	118	56.74	6.59	1.83	19	66	1.0	0.06	0.8	1.2	
83	115	210	19.01	37	37.15	118	53.66	8.87	1.32	15	127	1.1	0.07	0.9	1.5	
83	115	218	9.41	37	36.24	118	50.08	2.29	1.45	16	129	1.5	0.06	0.6	1.1	
83	115	233	36.67	37	37.71	118	54.72	1.85	1.25	14	68	0.9	0.10	0.3	0.3	
83	115	330	59.89	37	37.72	118	53.79	8.02	1.70	15	97	0.8	0.06	0.9	1.4	
83	115	530	8.35	37	36.14	118	55.06	4.86	2.21	16	156	0.9	0.08	0.7	1.0	
83	115	552	25.49	37	37.40	118	53.49	8.30	1.93	16	90	1.1	0.06	0.6	1.1	
83	115	718	39.41	37	36.44	118	55.56	2.63	2.78	22	154	1.0	0.08	0.6	0.7	
83	115	10 6	31.64	37	38.10	118	56.98	5.39	1.85	19	69	1.3	0.06	0.7	1.1	
83	115	1047	27.28	37	38.00	118	56.46	4.51	1.76	19	76	0.5	0.06	0.5	0.9	
83	115	1130	14.67	37	37.96	118	56.45	5.42	1.73	19	78	0.5	0.06	0.6	0.9	
83	115	1235	53.94	37	38.11	118	55.98	5.92	1.83	16	74	1.8	0.05	0.5	1.0	
83	115	1237	17.25	37	37.88	118	55.26	2.34	1.21	13	76	1.1	0.08	0.4	1.1	
83	115	1354	42.35	37	36.59	118	55.27	2.40	1.48	16	145	0.5	0.07	0.5	0.7	
83	115	1429	11.97	37	37.57	118	53.38	5.74	1.60	12	137	1.6	0.07	0.6	1.3	
83	115	1438	38.03	37	37.09	118	53.45	7.37	1.54	13	123	1.4	0.07	0.7	0.7	
83	115	1440	17.31	37	37.31	118	53.49	7.34	2.29	19	93	1.1	0.08	0.6	0.4	
83	115	16 1	39.80	37	36.78	118	51.83	5.14	1.57	16	118	1.4	0.07	0.6	1.0	
83	115	1718	59.68	37	37.20	118	51.92	2.26	1.93	13	127	1.8	0.07	0.6	1.5	
83	115	1734	29.16	37	36.87	118	52.91	7.39	1.95	6	204	2.3	0.04	2.7	1.9	
83	115	1755	42.58	37	37.10	118	53.27	2.41	1.22	12	134	1.6	0.08	0.6	1.1	

83 115	1811	10.33	37	37.62	118	55.39	2.87	0.95	9	90	1.7	0.08	0.5	0.8
83 115	1952	53.50	37	37.75	118	56.82	7.37	2.90	20	76	0.9	0.07	0.8	0.5
83 115	2056	14.96	37	38.24	118	55.17	7.50	1.87	16	63	0.6	0.05	0.7	1.0
83 115	2059	53.78	37	37.40	118	52.87	5.28	1.96	13	140	2.0	0.06	0.6	1.2
83 115	2226	57.86	37	36.88	118	51.76	3.71	1.50	13	137	3.6	0.05	0.6	1.4
83 115	2237	46.08	37	37.17	118	53.24	8.72	2.73	18	102	1.6	0.08	0.6	0.9
83 115	23 0	6.29	37	37.76	118	54.36	7.77	1.91	14	51	0.6	0.06	0.8	1.3
83 115	2316	2.31	37	38.08	118	56.52	5.93	2.44	20	70	0.7	0.06	0.6	1.0
83 116	0 8	51.20	37	37.93	118	56.04	8.86	2.47	24	82	0.3	0.09	0.7	0.8
83 116	030	25.36	37	37.60	118	55.07	2.45	1.41	14	80	1.3	0.08	0.5	0.9
83 116	3 9	20.35	37	37.29	118	51.99	2.45	1.40	14	123	1.9	0.06	0.5	1.1
83 116	331	50.02	37	37.60	118	56.39	6.64	2.42	15	89	1.6	0.12	0.7	0.7
83 116	647	51.13	37	36.89	118	51.35	5.07	1.84	14	133	0.7	0.07	0.6	1.2
83 116	754	20.03	37	37.50	118	53.02	5.62	1.55	14	115	1.8	0.07	0.6	1.2
83 116	813	35.86	37	37.72	118	56.31	7.42	1.97	14	86	1.9	0.07	0.8	1.1
83 116	845	14.22	37	37.30	118	53.26	2.84	1.73	15	96	1.5	0.08	0.5	0.8
83 116	854	48.95	37	37.75	118	54.31	7.91	1.52	14	51	0.6	0.06	0.8	1.3
83 116	1010	40.48	37	37.26	118	52.89	6.73	2.06	13	127	2.0	0.08	0.7	1.5
83 116	1322	51.77	37	37.51	118	54.17	2.86	1.38	14	97	0.1	0.08	0.4	0.7
83 116	1744	51.49	37	37.21	118	52.86	6.66	1.94	14	128	2.0	0.07	0.7	1.4
83 116	1751	5.57	37	36.99	118	52.89	7.28	1.67	15	111	2.2	0.07	0.6	0.5
83 116	1827	7.49	37	37.94	118	55.21	4.61	2.06	15	73	1.0	0.08	0.5	0.9
83 116	1934	0.62	37	36.02	118	55.10	1.91	1.71	14	205	1.2	0.11	1.0	0.7
83 116	1943	20.51	37	35.62	118	55.26	2.12	0.00	13	173	2.0	0.08	0.8	1.3
83 116	1955	47.70	37	37.94	118	55.41	3.24	1.44	15	76	1.2	0.07	0.5	0.8
83 116	20 9	47.80	37	38.02	118	56.19	1.86	1.61	14	95	2.2	0.08	0.4	0.4
83 117	2024	33.14	37	37.89	118	54.58	7.85	1.97	14	56	0.9	0.05	0.8	1.3
83 117	2028	46.57	37	37.49	118	53.51	3.41	1.61	13	112	1.1	0.08	0.5	0.9
83 117	18 8	12.27	37	37.15	118	53.71	3.45	2.95	16	97	1.0	0.09	0.5	0.8
83 117	1833	48.03	37	37.09	118	53.79	4.55	3.05	14	98	0.9	0.06	0.5	0.9
83 117	21 7	30.69	37	37.09	118	52.01	5.85	1.98	13	131	1.8	0.06	0.8	1.6
83 117	2149	58.68	37	38.34	118	56.17	5.00	1.76	13	56	0.2	0.07	0.7	1.3
83 117	2314	5.47	37	32.94	118	48.73	11.95	2.57	17	151	4.8	0.07	0.8	1.5
83 118	1 1	43.11	37	37.46	118	52.96	5.81	1.71	15	118	1.9	0.07	0.6	1.2
83 118	120	7.99	37	37.17	118	53.00	7.55	2.32	22	104	1.6	0.07	0.6	0.7
83 118	432	18.98	37	37.47	118	53.39	2.06	2.29	22	113	0.9	0.08	0.4	0.7
83 118	754	56.74	37	37.13	118	53.47	0.83	2.80	20	131	1.3	0.11	0.3	0.3
83 118	850	12.04	37	36.40	118	51.19	6.18	1.76	14	127	0.7	0.08	0.7	1.0
83 118	930	23.23	37	36.72	118	52.77	9.19	1.94	15	120	2.5	0.07	0.9	1.1
83 118	13 5	57.61	37	38.29	118	56.21	6.17	1.97	15	66	0.1	0.08	0.7	1.3
83 118	1458	3.85	37	37.55	118	53.47	3.45	1.98	15	110	1.1	0.08	0.5	0.9
83 118	1520	44.24	37	38.89	118	56.27	3.54	1.95	17	65	1.1	0.08	0.4	0.8
83 118	1532	18.69	37	37.00	118	54.01	2.95	2.12	15	99	0.9	0.07	0.5	0.6
83 118	17 2	54.44	37	32.16	118	48.02	2.19	2.40	15	152	6.5	0.09	0.7	1.5
83 118	1756	47.29	37	31.41	118	48.68	3.79	3.02	16	163	7.6	0.10	0.8	5.5
83 118	1757	22.87	37	31.57	118	48.87	6.61	0.00	15	163	7.2	0.09	0.8	1.4
83 118	1759	8.82	37	30.95	118	48.39	5.36	1.94	12	295	8.4	0.08	5.8	3.2
83 118	2050	34.01	37	37.75	118	56.32	2.17	1.96	13	93	1.0	0.06	0.5	1.1
83 118	2056	0.80	37	37.77	118	56.27	2.03	1.75	16	85	0.9	0.07	0.4	0.9
83 118	23 3	22.22	37	37.83	118	54.37	7.85	2.75	17	80	1.2	0.06	0.8	1.0
83 118	2314	56.82	37	37.21	118	52.69	3.95	2.02	11	129	2.6	0.07	0.6	1.4
83 119	022	7.14	37	38.08	118	56.31	5.90	2.48	14	74	0.4	0.05	0.7	1.2
83 119	054	25.61	37	37.02	118	52.28	8.31	2.71	18	135	1.4	0.08	0.9	1.1
83 119	139	43.24	37	37.16	118	52.97	2.86	2.30	15	131	2.5	0.06	0.5	0.7

83 119	155	11.48	37	37.43	118	53.09	4.86	1.91	12	118	2.0	0.06	0.6	1.2
83 119	6 1	10.63	37	37.85	118	54.33	8.03	2.07	15	81	1.2	0.06	0.8	1.2
83 119	1156	7.78	37	36.41	118	55.06	2.35	1.70	12	189	0.5	0.08	0.6	0.9
83 119	1211	16.88	37	34.97	118	50.22	3.59	2.00	11	239	1.4	0.05	2.1	2.6
83 119	1258	9.32	37	37.95	118	56.04	5.32	2.33	10	85	2.0	0.05	0.7	1.3
83 119	1331	24.40	37	37.10	118	52.44	3.75	2.51	14	133	2.4	0.06	0.7	1.3
83 119	1354	27.54	37	34.72	118	49.10	5.71	2.90	16	224	1.5	0.07	1.3	0.9
83 119	14 3	18.09	37	37.44	118	53.16	1.66	2.40	13	117	1.9	0.08	0.4	0.5
83 119	1436	18.01	37	38.07	118	55.34	3.61	1.98	12	71	0.9	0.04	0.6	0.9
83 119	1441	32.78	37	37.33	118	52.82	8.91	2.96	13	123	2.3	0.06	0.8	1.4
83 119	1442	8.22	37	37.17	118	52.63	8.90	0.00	11	145	2.8	0.04	1.3	1.7
83 119	1919	29.86	37	37.35	118	52.84	4.82	2.26	12	123	2.3	0.07	0.7	1.3
83 120	11 6	17.33	37	38.45	118	56.26	3.69	2.18	11	108	0.3	0.06	0.6	1.1
83 120	1158	11.54	37	37.99	118	56.86	6.43	2.24	18	94	1.0	0.10	0.7	0.7
83 120	1332	0.48	37	37.67	118	52.50	5.53	2.73	15	130	0.9	0.07	0.7	1.2
83 120	1511	9.30	37	38.00	118	54.82	7.36	2.12	11	98	0.7	0.08	1.0	1.0
83 120	2317	25.00	37	37.90	118	56.74	6.16	2.43	13	66	1.7	0.09	0.6	0.8
83 120	029	49.42	37	37.53	118	53.56	4.51	1.87	10	109	1.6	0.07	0.7	1.5
83 120	042	13.33	37	37.88	118	55.16	7.94	2.71	18	73	0.9	0.07	0.6	0.9
83 120	225	24.24	37	36.20	118	54.79	4.00	2.81	18	152	0.9	0.09	0.6	1.1
83 120	327	59.58	37	36.45	118	51.60	5.92	2.54	13	125	3.7	0.09	0.7	1.4
83 120	655	53.76	37	38.20	118	56.17	5.10	2.07	11	97	0.2	0.08	0.8	1.4
83 120	7 1	19.10	37	38.14	118	55.23	7.46	1.70	11	82	0.8	0.08	1.0	1.4
83 120	1927	30.74	37	38.14	118	56.30	4.76	2.04	12	96	2.2	0.07	0.6	1.1
83 120	20 1	16.87	37	37.75	118	53.70	7.48	1.91	11	98	1.1	0.09	0.9	1.4
83 120	1632	50.81	37	38.07	118	54.22	6.91	1.70	10	116	0.9	0.10	1.0	1.6
83 121	114	3.00	37	36.37	118	54.85	3.48	2.41	14	188	0.6	0.08	0.7	1.0
83 121	252	25.22	37	37.47	118	53.92	0.44	1.67	10	110	1.6	0.09	0.4	1.6
83 121	429	26.24	37	37.02	118	56.53	2.07	1.99	13	168	1.1	0.08	0.7	1.3
83 121	6 8	22.00	37	37.95	118	56.41	7.50	3.19	18	74	0.4	0.09	0.7	0.8
83 121	610	2.63	37	38.44	118	58.25	4.68	0.00	9	199	3.1	0.13	1.6	1.1
83 121	616	54.89	37	37.81	118	55.88	7.48	2.53	17	90	0.5	0.08	0.7	0.9
83 121	741	22.36	37	36.95	118	53.16	6.82	2.76	17	111	2.3	0.07	0.6	0.8
83 121	945	47.03	37	37.78	118	55.04	4.58	2.30	14	73	1.1	0.08	0.6	1.0
83 121	1025	56.27	37	37.67	118	55.36	4.06	2.69	15	87	1.3	0.10	0.6	1.1
83 121	1654	28.11	37	37.28	118	53.57	4.80	0.00	10	119	2.0	0.09	0.9	1.3
83 121	1830	1.59	37	35.68	118	55.06	3.64	1.97	13	168	1.8	0.09	0.7	1.3
83 121	1840	48.45	37	37.24	118	55.77	4.40	2.21	14	118	1.6	0.09	0.6	1.0
83 122	151	39.52	37	37.75	118	55.24	7.42	2.61	15	81	1.2	0.07	0.6	0.8
83 122	216	34.33	37	35.70	118	53.94	6.90	3.05	15	155	2.3	0.07	0.7	0.7
83 122	725	58.01	37	37.85	118	56.19	7.07	2.15	15	84	0.8	0.06	0.6	0.6
83 122	831	23.22	37	36.08	118	56.43	0.60	1.83	12	231	2.2	0.09	1.1	0.9
83 122	1211	50.01	37	37.58	118	56.78	7.06	2.24	15	76	1.2	0.08	0.7	0.6
83 122	18 6	5.95	37	37.74	118	55.76	7.86	3.03	17	92	1.1	0.08	0.7	0.9
83 122	19 7	50.76	37	37.46	118	51.55	6.17	2.55	14	102	2.7	0.09	0.6	1.1
83 122	2027	57.48	37	37.72	118	56.44	7.04	2.34	14	82	1.1	0.08	0.7	0.6
83 123	0 5	44.71	37	38.01	118	54.99	6.89	2.37	8	105	1.9	0.04	0.9	1.6
83 123	557	8.57	37	37.30	118	53.04	4.70	2.50	9	179	2.2	0.05	0.8	1.7
83 123	627	18.32	37	37.89	118	54.61	2.78	2.20	10	108	1.6	0.05	0.5	0.8

WCM-7 ▲

JANUARY 1983
SWARM AREA

● WCM-5

● WCM-4

● WCM-1

● WCM-6

● WCM-2

● WCM-3

MAMMOTH LAKES SEISMIC STATION

DEPTHS

- + 0.0+
- 5.0+
- ◇ 13.0+
- △ 20.0+

MAGNITUDE

- 0.0+
- ◻ 1.0+
- ◻ 2.0+
- ◻ 3.0+
- ◻ 4.0+
- ◻ 5.0+
- ◻ 6.0+

MAMMOTH LAKES SEISMICITY JANUARY 1983

MAMMOTH LAKES SEISMICITY JANUARY 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 13.0+

△ 20.0+

MAGNITUDE

• 0.0+

◦ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

MAMMOTH LAKES SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES

3M SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

◻ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

MAMMOTH LAKES SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES, DEPTH 0-5 KM
SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES, DEPTH 5-7 KM
 SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES, DEPTH 7-DEEPER KM SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES

SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES

SWARM SEISMICITY JAN/11 TO JAN/23 1983

MAMMOTH LAKES SWARM SEISMICITY JAN/11 TO JAN/23 1983

H LAKES, PLOT ONE 83/01/11-12

RM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+	0.0+
□	5.0+
◇	7.0+
△	20.0+

MAGNITUDE

•	0.0+
◦	1.0+
◻	2.0+
◻	3.0+
◻	4.0+
◻	5.0+
◻	6.0+

MAMMOTH LAKES, PLOT ONE 83/01/11-12
 SWARM SEISMICITY JAN/11 TO JAN/23 1983

3TH LAKES, PLOT TWO 83/01/12 3M SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

◻ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

MAMMOTH LAKES, PLOT TWO 83/01/12
 SWARM SEISMICITY JAN/11 TO JAN/23 1983

TH LAKES, PLOT THREE 83/01/12
 RM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

◻ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

MAMMOTH LAKES, PLOT THREE 83/01/12
 SWARM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

Δ 20.0+

MAGNITUDE

• 0.0+

◻ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

4 LAKES, PLOT FOUR 83/01/12-13 RM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

□ 1.0+

□ 2.0+

□ 3.0+

□ 4.0+

□ 5.0+

□ 6.0+

MAMMOTH LAKES, PLOT FOUR 83/01/12-13
 SWARM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS	
+	0.0+
□	5.0+
◇	7.0+
△	20.0+
MAGNITUDE	
•	0.0+
◦	1.0+
□	2.0+
□	3.0+
□	4.0+
□	5.0+
□	6.0+

4 LAKES, PLOT FIVE 83.01/13-14 AM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+	0.0+
□	5.0+
◇	7.0+
△	20.0+

MAGNITUDE

•	0.0+
◦	1.0+
□	2.0+
□	3.0+
□	4.0+
□	5.0+
□	6.0+

MAMMOTH LAKES, PLOT FIVE 83.01/13-14

SWARM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

- + 0.0+
- 5.0+
- ◇ 7.0+
- △ 20.0+

MAGNITUDE

- 0.0+
- 1.0+
- 2.0+
- 3.0+
- 4.0+
- 5.0+
- 6.0+

3TH LAKES, PLOT SIX 83/01/15 3M SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS	
+	0.0+
□	5.0+
◇	7.0+
△	20.0+
MAGNITUDE	
•	0.0+
◻	1.0+
◻	2.0+
◻	3.0+
◻	4.0+
◻	5.0+
◻	6.0+

MAMMOTH LAKES, PLOT SIX 83/01/15

SWARM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

◻ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

I LAKES, PLOT SEVEN 83/01/15-16

RM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

◻ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

MAMMOTH LAKES, PLOT SEVEN 83/01/15-16

SWARM SEISMICITY JAN/11 TO JAN/23 1983

AKES, PLOT EIGHT 85/01/16-17-18-20
 RM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

◦ 1.0+

□ 2.0+

□ 3.0+

□ 4.0+

□ 5.0+

□ 6.0+

MAMMOTH LAKES, PLOT EIGHT 85/01/16-17-18-20
 SWARM SEISMICITY JAN/11 TO JAN/23 1983

AKES, PLOT NINE 83/01/20-21-22-23
 RM SEISMICITY JAN/11 TO JAN/23 1983

DEPTHS

+ 0.0+

□ 5.0+

◇ 7.0+

△ 20.0+

MAGNITUDE

• 0.0+

◦ 1.0+

◻ 2.0+

◻ 3.0+

◻ 4.0+

◻ 5.0+

◻ 6.0+

MAMMOTH LAKES, PLOT NINE 83/01/20-21-22-23
 SWARM SEISMICITY JAN/11 TO JAN/23 1983

SECTION 1

THE 1941 EARTHQUAKE SEQUENCE NEAR LONG VALLEY CALDERA,

CALIFORNIA

Introduction

The nature of the recent seismicity in the Long Valley Caldera region has been a source of considerable scientific controversy. For many of the larger earthquakes there is a discrepancy between the long- and short-period P-wave polarities, and the moment tensor inversions of the teleseismic waveforms yield substantial minor double couples. Further, the epicenters do not appear to correlate with surface Holocene faulting features. This has lead some investigators (Julian, 1983; Aki, 1984) to suggest that the seismicity is directly related to the movement of magma within the Caldera. The fact that there was a broad domal uplift in the western portion of the Caldera between 1978 and 1980 (Savage and Clark, 1982) has been cited a supporting evidence for this hypothesis. Other investigators (Wallace, 1985; Ekstrom, 1983; Barker and Wallace, 1984, summarized in the previous section) prefer a less causal relationship to the magmatic activity, and suggest complexity in the faulting process to account for the non-double-couple moment tensor. In an attempt to differentiate between these two models for the recent seismicity we have studied the historic record to determine if it is substantitally different than the recent activity. The 1941 earthquake sequence is similar

in size and extent to the 1980 sequence so it provides a very good comparison.

Since the mid 1960s there have been three major episodes of seismicity near Long Valley (exclusive of the November 1984 Round Valley event). Between 1961 and 1978, the Long Valley region was remarkably quiet; there were no events with magnitudes as large as 5. The October 4, 1978 Wheeler Crest earthquake ($M_L = 5.7$) marked the return of seismicity to the area (Figure 1.1 shows the epicenter and an outline of the first two days' aftershocks). The May 1980 Mammoth Lake sequence was a major seismic strain release episode. There were four events with $M \geq 6$ which occurred during a 48 hour period (Figure 1.1 shows the extent of aftershocks for the week May 25 - 31, 1980). Activity continued in the 1980 aftershock zone for well over a year: there was a $M_L = 5.4$ event on August 1, 1980, a $M_L = 5.5$ on September 31, 1980, and finally a $M_L = 5.8$ on September 7, 1981. A very intense swarm of earthquakes began in early January of 1983 that can be separated from the 1980 sequence of aftershocks on the basis of spatial and temporal characteristics. The January swarm hypocenters define an east-west plane in the western moat of the caldera (see Figure 1.1). The largest event in the swarm was only $M_L = 5.3$, but there were thousands of small events tightly clustered along the east-west plane. Almost all the events were shallow (less than 5 km). Unlike the 1978 and 1980 sequences, the 1983 events show no "frequency dependence" of fault plane solutions. The swarm is dominated by right-lateral motion along the east-west plane.

The three modern earthquakes swarms are summarized in Table 1.1. Certain systematics are apparent: (1) it is difficult to identify the main shock on the basis of magnitude alone, and (2) aftershock activity of significant size occurs over an unusually protracted length of time. A survey of the Townley and Allen (1939) and the Caltech catalogues indicates there were 5 earthquakes ($M_L > 5.5$) between 1889 and 1960 in the Long Valley region (1889, 1910, 1912, 1927, and 1941). The 1941 sequence is fairly well recorded by the Caltech and Berkeley networks and appears very similar to the 1980 sequence (the 1941 sequence is summarized in Table 1.1); there are three events with $M_L > 5.5$ during a two hour period, and aftershocks occurred nearly a year later. On the other hand, there was no significant uplift in Long Valley Caldera or other evidence of magmatic activity preceding the 1941 sequence. In an attempt to compare the 1980 and 1941 sequences, we relocated the 1941 events and determined their focal mechanisms.

Relocation of the 1941 Sequence

Richter (1958) gives the location of the main shock in the 1941 sequence as 37.6° N, 118.7° W, or near Tom's Place at the southeastern end of Lake Crowley (Figure 1.1 shows Richter's location). We relocated the 1941 event using several of the modern earthquakes as master events. Unfortunately, we could find only three stations which were operational in 1941 and still operational in the late 1970's: (1) Tinemaha, less than 100 km away, southeast of the source region, (2) Mt. Hamilton, 250 km due west of the

source region, and (3) Pasadena, 370 km south of Mammoth Lakes. Since the azimuthal distribution of stations is so wide, there is good control on the epicenter location. Using each master event location we took the difference in the P-wave arrival time of the master event and the 1941 event to define loci, or a surface of relocation. The difference in arrival times between stations is used to get a apparent velocity, so we do not need an earth structure (an approximation made possible by the small distances between relocations compared to the distances to the stations). As a test of this relocation procedure we used each of the master events to relocate, in turn, the other master events. Figure 1.2 shows the locations of master events. Using event C we could relocate B to less than 1 km; event A could locate C and B to within 2.5 km.

The relocation of the 1941 mainshock is shown in Figure 1.2. The location moved south by about 20 km, and is within the Sierra block removed from the caldera. It appears to be in line with the three largest events in the 1980 sequence. This relocation is the average of those from the three master events. The error bars shown define a rectangular box which contains all three relocations. Using this new location for the 1941 event, we relocated the largest aftershocks which occurred within two days of the mainshock. In this case, we have many more stations (7) available for this relocation procedure. Figure 1.3 shows the mainshock and the relocated aftershocks, which define a pronounced north-south trend 7-8 km long (very similar to the 1978 Wheeler Crest event).

Figure 1.4 summarizes the locations and aftershocks for the different seismic episodes. There are two apparent trends. Earthquake sequences which occur within the Sierra block, away from the caldera, have north-south distributions. On the other hand, the 1983 swarm in the southwest moat appears to have an east-west alignment. The 1980 sequence has an "L-shaped" distribution, indicating both types of activity.

Focal Mechanisms of the 1941 Sequence

In 1941 a broad band seismograph (1-90) was operational at Pasadena, and remains so today. This facilitates a comparison between the faulting mechanisms of the modern events and the 1941 mainshock. Figure 1.5 shows a comparison of the P waveforms for the three earthquakes used as master events in the relocation procedure and the 1941 event. It is immediately obvious that the 1941 event is very similar to the 1980 and 1978 events - but very different from the 1983 swarm event. The focal mechanisms shown in Figure 1.5 were determined by constrained long-period waveform modeling; the 1978 and 1980 events are oblique slip while the swarm event is pure strike slip.

It is possible to determine a relative mechanism for the 1941 event by using Green's functions derived from the modern events. We assumed the long-period mechanism for each of the modern events and then adjusted the structure Green's function to achieve a perfect synthetic seismogram fit to a given master event. This means that the Green's functions are, in a sense, arbitrary since they are different for each event. However, since three different sets

are used, the average orientation for the 1941 event should be well determined. Once the Green's functions are determined for a given master event a suite of synthetics for different faulting orientations are generated and compared to the 1941 waveform with an error function based on the cross correlation of synthetics and data (Wallace, et al., 1981). Each of the faulting parameters (strike, dip and rake) is iterated and the error function is contoured. It is simplest to think of this as a three-dimensional graph with strike, dip and rake as the axes and the error function as the dependent variable. The sharpness of the minimum defines the uniqueness of the fault--plane solution.

The results are shown in Figure 1.6. The master event mechanisms are given in the left hand column, and the relative mechanism is given on the right hand side. Both the 1978 and 1980 events give very similar results for the 1941 event: oblique slip on moderately dipping planes. It is difficult to find a good solution using the 1983 swarm as a master event (note the large error). This is expected since this event is so close to pure strike slip and contains very little information about the vertical dip-slip and 45° dip-slip fundamental faults. It is reasonable to assume that the 1941 sequence was oblique slip.

Discussion

The faulting mechanism of the 1941 sequence appears to be very similar to the 1978 and 1980 sequences. The general trends of the aftershock zones further support the fact that these seismic episodes under the Sierras are very similar. We find oblique slip on a plane trending north-south, with a tension axis at about N65°E plunging at less than 20°. Within the caldera the fault motion changes to predominantly east-west strike-slip motion. It is fairly clear that the 1941 sequence is not related to magmatic activity. Therefore it is tempting to suggest that the 1978 and 1980 events are slip episodes controlled by the regional tectonic environment, while the 1983 swarm could be related to magmatic activity.

Figure 1.7 summarizes the historic seismic activity. On November 23, 1984 a $M_L = 5.5$ event occurred just north of the relocated 1941 epicenter. The aftershocks appear to trend NE-SW, and show oblique slip similar to that suggested for the 1941 sequence. Careful analysis of the 1984 sequence will help finalize our interpretation of the 1941 sequence.

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Figure Captions

Figure 1.1 Locations of three major seismic episodes in the Long Valley Caldera region. Stars give the epicenters, and outlines are the aftershock zones. The 1941 location is from Richter (1958).

Figure 1.2 Relocation of the 1941 mainshock. Master events are shown with stars. The error bars give the extent of the three relocations.

Figure 1.3 Aftershocks of the 1941 sequence.

Figure 1.4 Summary of aftershock zones for major seismic episodes near Long Valley Caldera.

Figure 1.5 A comparison of P waveforms for Long Valley events recorded on the Pasadena (PAS) 1-90 instrument. The mechanisms shown are determined from constrained long-period modeling.

Figure 1.6 Relative mechanisms determined for the 1941 mainshock (right). The master event mechanisms are shown on the left. The errors are based on cross-correlation.

Figure 1.7 A summary of the earthquake activity around Long Valley Caldera.

Table 1.1

LONG VALLEY AREA EARTHQUAKES

Oct. 4, 1978				Sept. 14, 1941				May 25, 1980				Jan. 7, 1983			
MO	DA	TIME	MAG	MO	DA	TIME	MAG	MO	DA	TIME	MAG	MO	DA	TIME	MAG
10	6	16:42	5.8	9	14	16:43	5.8	5	25	16:33	6.4	1	7	1:31	4.1
		16:59	4.5			16:54	4.5			16:49	5.8			1:38	5.2
		17:39	5.3			18:21	5.5			17:06	4.9			3:24	5.3
		18:22	4.3			18:39	6.0			19:44	6.5			3:30	4.3
10	5	1:17	4.4			21:16	5.0			20:35	5.5			5:11	3.6
		6:41	4.4	10	23	20:44	4.5			20:59	4.9			6:38	3.9
1	19	18:10	4.3	12	31	6:48	5.4	5	26	12:24	5.2			7:14	3.4
1	24	21:14	4.4			18:05	4.5			18:57	4.9			8:45	3.4
				1	1	3:41	4.5	5	27	14:50	6.3			13:12	3.5
				2	4	3:32	4.5			19:01	5.0	1	9	11:57	3.4
				7	6	21:11	4.5	5	31	15:16	4.9	1	17	22:28	3.3
								6	11	4:41	5.0				
								8	1	16:38	5.4				
								9/81	7	4:37	5.7

Figure 1.1

Figure 1.2

Figure 1.3

Figure 1.4

Figure 1.5

MASTER EVENT MECHANISM

Figure 1.6

Figure 1.7

SECTION 2

STATISTICAL ANALYSIS TO IDENTIFY REGIONS OF TECTONIC AND VOLCANIC SEISMICITY

The seismicity signature of the 1980 Mammoth Lakes earthquake is highly complex and surely reflects a superposition of responses and processes. We separate and quantify the first order seismicity characteristics by statistical analyses and by referencing activity in the Long Valley region against a nearby 300-km section of the Eastern Sierran Frontal fault system. Large clusters containing many earthquakes are conspicuous in the Long Valley region during the 21 months prior to the 1980 mainshocks. Another important change in seismicity is that nearly two-thirds of the "independent" earthquakes trigger one or more subsequent events, as compared with only one-fifth during the 1970-1976 period. This triggering may indicate increased levels of stress prior to failure in the mainshocks.

The data base used is the University of Nevada at Reno earthquake catalog, containing earthquakes of magnitude M_L 2.5 and larger. Three time periods are compared, using numerical measures of clustering that are normalized to one year and 100 km² unit area.

1970-1976: The earthquake time series fits a generalized Poisson distribution of independent events and superposed clustering, as measured by the Poisson dispersion coefficient and chi-squared

tests. 46% of events in the Long Valley region and 56% of events in the entire Eastern Sierra front are within clusters. However, the normalized number of clusters is 2.4 times greater in the Long Valley region (3.1) than along the frontal system (1.3).

1977-8/1978: The total number of earthquakes in the Long Valley region decreases by an order of magnitude compared to the earlier period. None of the events in the Long Valley region and only 17% of the events along the Sierran front are within clusters.

9/1978-5/24/1980: 93% of the events in the Long Valley region and 52% of Sierran Front events are within clusters. Although there are a few large clusters in the Long Valley region (e. g., clusters with 82, 21, and 46 events), a dramatic change is that the normalized number of clusters increases by nearly an order of magnitude relative to the first period (from 3.1 to 26.8). This change is not explained by a Poisson rate change.

An important result bearing on the possible presence of magma in the south moat region is that the seismic patterns indicate stress transfer from the Hilton Creek fault system into the South Moat area. Anomalous seismic decay patterns are found that correlate with laboratory simulations. Also, high stress and high fluid pressure conditions are indicated.

The accompanying preliminary figures and captions further illustrate the results obtained.

Figure Captions

Figure 5.1 Background seismicity from January 1970 through December 1976. All events, independent events (the catalog with triggered events removed), and first events of a cluster. Horizontal lines at 37°45' and 38°00' delimit the three sub-catalogs: Long Valley region (LVR), Mono, and Eastern Sierran Frontal fault system (FF).

Figure 5.2 Precursory seismicity from September 1978 to 25 May 1980.

Figure 5.3 Seismicity from mainshocks to end of catalog (25 May 1980 through February 1983).

Figure 5.4 Seismicity in the LVR from 1970-1983 for M 2.5 and greater. Independent events have no preceding trigger and include the first event in a cluster. Cluster occurrence rate is plotted as cumulative number. Significant times in LVR are shown by three vertical lines. There are no apparent seismicity changes in the FF during the entire time.

Figure 5.5 Seismicity in the FFZ from 1970-1983 for M 2.5 and greater. For comparison the cumulative plots for FFZ (dashed lines) are shown. From this reference we choose a time for the seismicity rate change as indicated by arrows in 1979.

Figure 5.6 Seismicity in the Mono region from 1970-1983 for M 2.5 and greater. Our estimated time of seismicity rate change in LVR is shown by the arrows in 1979. For comparison the cumulative plots for LVR (dotted line) and FFZ (dashed line) are shown.

Figure 5.7 Cumulative strain release (square root of energy) for LVR from 1970-1983. Strain for 5 categories of events is plotted. Our estimated time of seismicity rate change in LVR is shown by the arrows in 1979. For comparison the cumulative plots for FFZ (dashed line) are shown. The increase in strain release in 1979 can be attributed to events in clusters, and not at all to isolated clusters.

Figure 5.8 Cumulative strain release (square root of energy) for Mono region from 1970-1983. Strain for 5 categories of events is plotted. The increase in strain release in 1979 can be attributed to events in clusters, and not at all to isolated events.

Figure 5.9 Dispersion coefficient curves for all events from 1970-1976 at magnitude cutoffs of 2.5, 3.0, and 3.5. The curve for 3.5 represents a nearly random data set, indicating that virtually all clustering in this time is due to smaller earthquakes.

Figure 5.10 Poisson dispersion coefficient curves for declustering time of 1440, 1800, 2160, 2520, 2880, 3240, 3600, 3960, and 4320 minutes (one day to three days in six-hour increments). Each curve tests the degree of remaining clustering within time intervals as indicated on the x-axis. A random time series would fluctuate about $y=1$. 3240 minutes was chosen for the best fit to a random time series.

Figure 5.11 LVR events that initiate clusters with DCL=3240 minutes.

Figure 5.12 Dispersion coefficient curves for catalogs of only cluster initiators in the LVR for DCL=3240 minutes (2.25 days). An increase of cluster occurrence rate by almost 10 times in 1978 hinders the identification of triggered (non-random) events and the catalog from 1970-1983 appears to be non-random. When broken up into three time periods, each time period is found to be random.

Figure 5.13 Selected clusters with activity decay plots: (a) map, (b) Omori decay plot (rate for fixed number of earthquakes), (c) average rate decay plot (rate since beginning of cluster). The average rate plots (c) are more stable for small sequences.

Figure 5.14 Selected clusters with activity decay plots: (a) map, (b) Omori decay plot (rate for fixed number of earthquakes), (c) average rate decay plot (rate since beginning of cluster). The average rate plots (c) are more stable for small sequences.

SNGBZ Earthquakes ($M \geq 2.5$)

1970 thru Dec. 1976

Figure 5.1

SNGBZ Earthquakes ($M \geq 2.5$)
1978 Sept. to 25 May 1980

Figure 5.2

SNGBZ Earthquakes ($M \geq 2.5$)

25 May 1980 thru 1983 Feb.

All Events

Independent Events

Cluster Initiators

Figure 5.3

FFZ (NORTH OF 38.33 DEG)
LOCAL.OPL 4-APR-25 21:35:06

Figure 5.4

LVR (SOUTH OF 37.75 DEG)

LCCAL.OPL

4-APR-85 21:36:43

Mammoth Mainshocks

Figure 5.5

MONO (37.75 DEG TO 38.33 DEG)
LOCAL.OPL 4-APR-85 21:37:33

Figure 5.6

Figure 5.7

MONO (37.75 DEG TO 38.33 DEG)
 LOCAL.OPL 4-APR-85 22:53:06

Figure 5.8

M=2.5. DCL= 0.. FILE=PREPRE. RSL

Figure 5.9

M=2.5. DCL=1440.. FILE=PREPRE.RSL

Figure 5.10

Figure 5.11

M=2.5, DCL= 0. FILE=MAMMCLU.RSL

Figure 5.12

LVR CLUSTERS
1982/ 5/ 7 12:14 TO 1982/ 5/13 17:27
GAP: 1.0PL G-AP: 25 15:16:51

1982/ 5/ 7 12:14

To: 1982/ 5/13 17:27

16 events in 6.2 days

Rate of Earthquakes (2 per interval)

Average Rate of Earthquakes

Average $M = 3.0$

LVR CLUSTERS
1978/10/ 4 16:39 TO 1978/10/10 2:11
GAP: 1.0PL G-AP: 25 14:43:47

From: 1978/10/ 4 16:39

To: 1978/10/10 2:11

22 events in 5.4 days

Rate of Earthquakes (3 per interval)

Average Rate of Earthquakes

Average $M = 3.6$

LVR CLUSTERS
1983/ 1/ 7 1:28 TO 1983/ 1/13 8: 1
GAP: 1.0PL G-AP: 25 15:20:28

From: 1983/ 1/ 7 1:28

To: 1983/ 1/13 8: 1

74 events in 6.3 days

Rate of Earthquakes (6 per interval)

Average Rate of Earthquakes

Average $M = 3.1$

Figure 5.13

LVR CLUSTERS
1980/ 5/12 6: 4 TO 1980/ 5/22 13: 6
00001.0PL 00001.0SL 0-001-05 14:54:10

To: 1980/ 5/22 13: 6
40 events in 10.3 days

Rate of Earthquakes (4 per interval)

Average Rate of Earthquakes

Average M = 2.9

LVR CLUSTERS
1979/11/ 5 23: 7 TO 1979/11/26 17:29
00001.0PL 00001.0SL 0-001-05 14:55:00

From: 1979/11/ 5 23: 7

To: 1979/11/26 17:29

73 events in 20.8 days

Rate of Earthquakes (6 per interval)

Average Rate of Earthquakes

Average M = 3.0

MONO CLUSTERS
1980/ 9/ 4 13:36 TO 1980/ 9/23 18:37
00001.0PL 00001.0SL 01-001-05 10:17:01

From: 1980/ 9/ 4 13:36

To: 1980/ 9/23 18:37

115 events in 19.2 days

Rate of Earthquakes (5 per interval)

Average Rate of Earthquakes

Average M = 3.2

Figure 5.14