## Title
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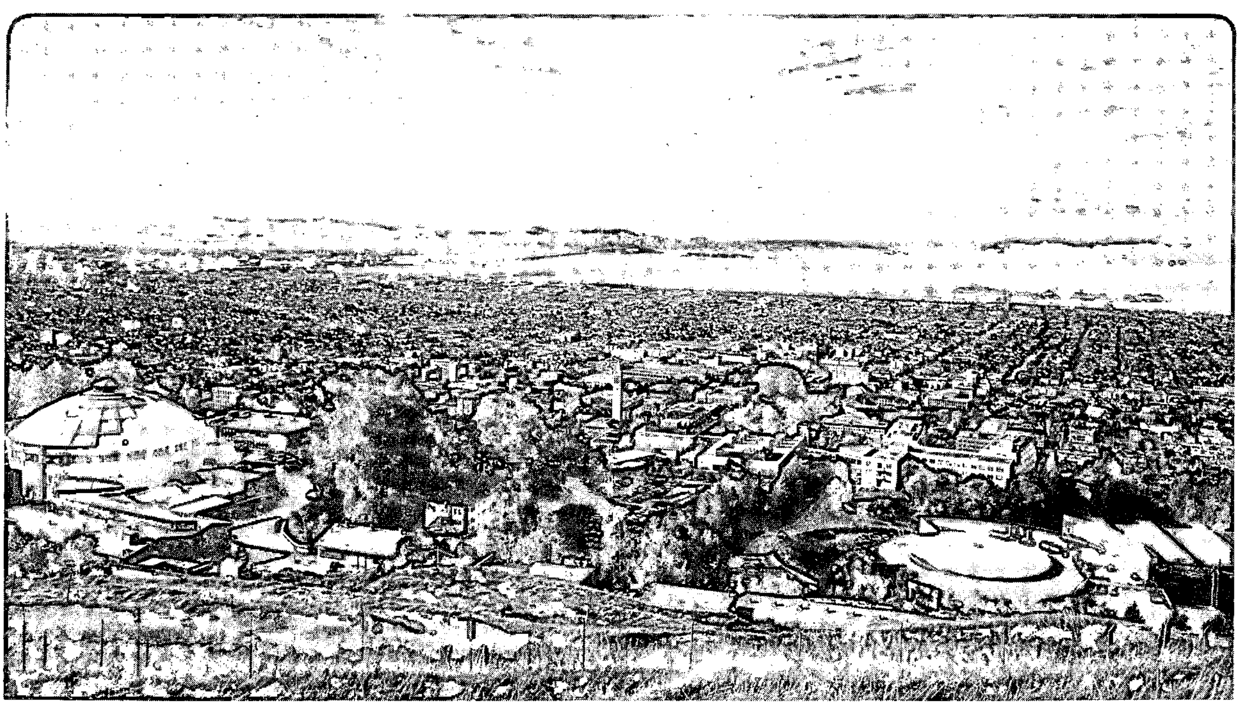



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# Microearthquake Monitoring at the Southeast Geysers Using a High-Resolution Digital Array


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# MICROEARTHQUAKE MONITORING AT THE SOUTHEAST GEYSERS USING A HIGH-RESOLUTION DIGITAL ARRAY

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## ABSTRACT

Microearthquake activity at the Southeast Geysers, California, geothermal field is monitored with a high-resolution digital seismic network. Hypocenters are spatially clustered in both injection and production areas, but also occur in more diffuse patterns, mostly at depths from 1 to 2.8 km. Hypocenters near the injection well DV-11 exhibit a striking correlation with movement of injectate and injectate-derived steam. Preliminary moment tensor results show promise to provide information on the differing source mechanisms resulting from fluid injection and steam extraction.

## INTRODUCTION

Over the last several years, Lawrence Berkeley Laboratory (LBL) has been monitoring microearthquake (MEQ) activity at the Southeast (SE) Geysers, California, using a high-resolution, high-frequency digital array. The original array consisted of eight three-component stations operated by LBL, and five three-component stations operated by Lawrence Livermore National Laboratory (LLNL). A re-configured array of 13 stations telemetered to a central site went on-line in January 1994. From these new data we have been able to determine a three-dimensional (3-D), P- and S-wave velocity model for the SE Geysers, and to utilize this model to obtain high-quality MEQ hypocenters. We have also inverted the data for moment tensors, providing information on event size and source characteristics.

One of the main objectives of the project is to evaluate the utility of high-resolution MEQ monitoring as a geothermal reservoir management tool. Specifically, we wish to determine what kind of hypocentral accuracy can be obtained with this type of network, what kind of analysis can be performed with such hypocentral data, and whether the results of such analysis are of use to reservoir managers. To this end, we report here on the MEQ locations we have obtained in the SE Geysers, and compare them to those determined using the lower-resolution, analog MEQ network operated at the Geysers by the Unocal-NEC-Thermal (U-N-T) partnership. We discuss the seismicity associated with the Unit 18 Cooperative Injection Project, and its relation to the effects of the injection on nearby production wells. We also discuss the seismicity associated with steam extraction in a production well, and compare it with injection-related seismicity.

Another objective of the project is to use the seismic velocity structure obtained from the MEQ data to infer the physical conditions and properties of the reservoir. In this report, however, the velocity structure is discussed only in relation to its use in determining hypocenters.

## NETWORK AND DATA

The LBL array consists of 13 high-frequency (4.5 Hz), digital (480 samples/s), three-component stations deployed on the surface, in portions of the Calpine, U-N-T, and Northern California Power Agency (NCPA) leases. U-N-T has monitored seismicity of portions of the Geysers since 1985 (Stark, 1992). Their network consists of mostly vertical, 4.5-Hz seismometers, with some three-component stations. The data are recorded in analog form, but later digitized at 100 samples/s. Both the LBL and the U-N-T arrays are shown in Figure 1. The U-N-T network covers a larger area and has a larger station spacing.

The LBL network records regional and teleseismic events as well as those from the Geysers area. To avoid processing these extraneous events, U-N-T provides us with a list of events which they have located in the SE Geysers. We use this list to identify and extract the events of interest from our data for processing. Because of the greater sensitivity of the LBL network, this means that many of the smaller events recorded at the SE Geysers by the LBL array,

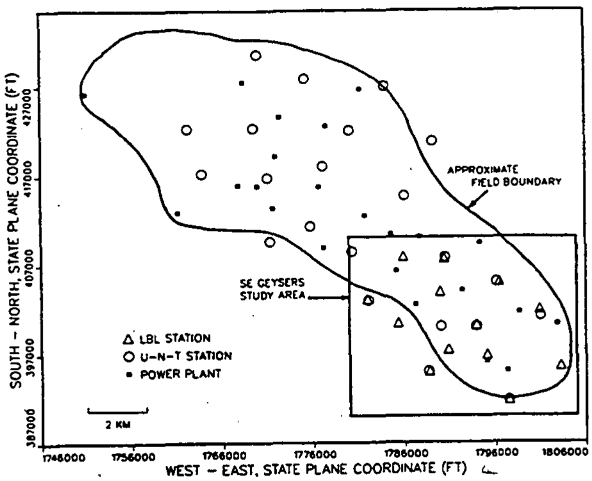



Figure 1. Location of LBL and U-N-T MEQ networks at The Geysers, California.

but not by the U-N-T array, remain unprocessed. Also, because of down-time of the LBL array due to operating problems, some events that were located by U-N-T were not recorded by LBL.

Once the events are identified, the P- and S-wave arrival times for each event at each station are picked manually. The uncertainty in the P arrival time is estimated at 0 to 3 samples, or up to 0.006 s, and the uncertainty in the S arrival time is estimated at 2 to 6 samples, or 0.004 to 0.012 s. These arrival times provide the data set for the velocity model and hypocentral location inversions. The moment tensor inversion models the amplitude (obtained by integration over the pulse width) and polarity of the P-wave pulses.

From January 1994 through July 1994, 930 "U-N-T events" were processed and located using LBL data. In June, we processed all of the LBL data, and located an additional 139 events within the area defined by U-N-T as the SE Geysers (as well as others outside this area that we wished to use in the velocity inversion). Since U-N-T located 225 events in June, it appears that the LBL network is capable of locating some additional 50% of events.

## THREE-DIMENSIONAL SEISMIC VELOCITY INVERSION

In order to determine high-quality hypocenters, an accurate model of the seismic velocity is needed. We chose approximately 300 events from the January to June 1994 time period to use in an inversion for three-dimensional P- and S-wave velocity structure. The events were selected to maximize ray coverage of the imaged volume. The final data set consisted of 2731 P arrival times, and 1578 S arrival times from 295 events.

The joint hypocenter-velocity inversion method of Thurber (1983), as modified by Michelini and McEvilly (1991) was used. Initial velocity values are assigned to nodes on a 3-D grid, and are adjusted in an iterative procedure that minimizes the travel-time residuals using damped least squares. The initial velocity model was an average of the 1-D, P velocity model obtained by O'Connell and Johnson (1991) for the central portion of the Geysers field, and the 1-D P model used by U-N-T (M. A. Stark, pers. comm.), which is based on that obtained by Eberhart-Phillips and Oppenheimer (1984). The initial S model was calculated from the P model using an assumed Vp/Vs of 1.7.

A 7 km by 4 km area bounded by the stations was imaged to a depth of 2.5 km. The horizontal node spacing was 1.0 km and the vertical node spacing was 0.5 km. The inversion resulted in a 52% weighted root mean square residual reduction over the 1-D starting model, and a 59% weighted variance reduction.

## MICROEARTHQUAKE LOCATION RESULTS

The new 3-D, P- and S-wave velocity model was used to relocate the SE Geysers events. The hypocenters for the January to July 1994 time period are shown in Figure 2. They can be compared with the U-N-T hypocenters for the January to June 1994 period shown in Figure 3.

The uncertainty of the hypocenter locations arises primarily from two factors, errors in the arrival times, and inaccuracy of the velocity model. We estimate the uncertainty in locations arising from error in arrival times as less than 30 m. The uncertainties arising from inaccuracy of the velocity model are more difficult to assess. We plane to estimate them by perturbing the velocity values, then relocating the events to see how much the locations change.

Distinct spatial patterns of seismicity are evident on the LBL map (Figure 2). The seismicity on the U-N-T map (Figure 3) appears much more diffuse; the use of the LBL data and the 3-D model results in much tighter clustering of events. Also, absolute locations of many events and clusters differ between the two

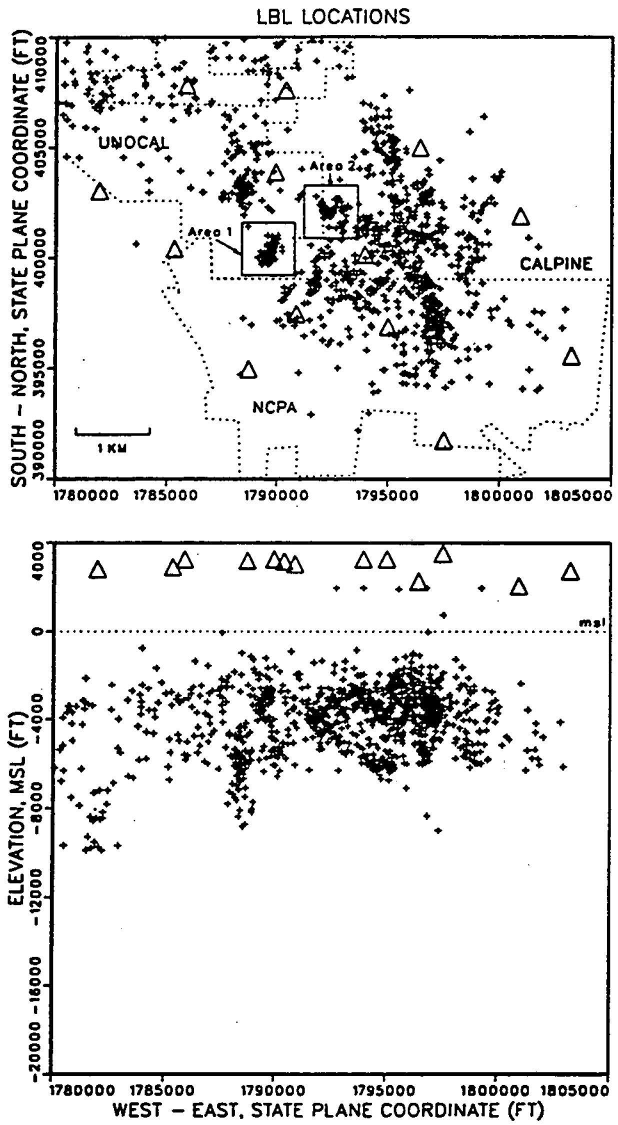



Figure 2. MEQ hypocenters at the SE Geysers for January to July 1994, obtained using the LBL array and a 3-D, P- and S- wave velocity model. Plan view and projection onto east-west plane shown. Areas 1 and 2 are shown in detail in Figures 5 to 8. Triangles represent LBL stations. Note: events north of 407500 and west of 1785000 are from June 1994 only and are additional to the U-N-T events.

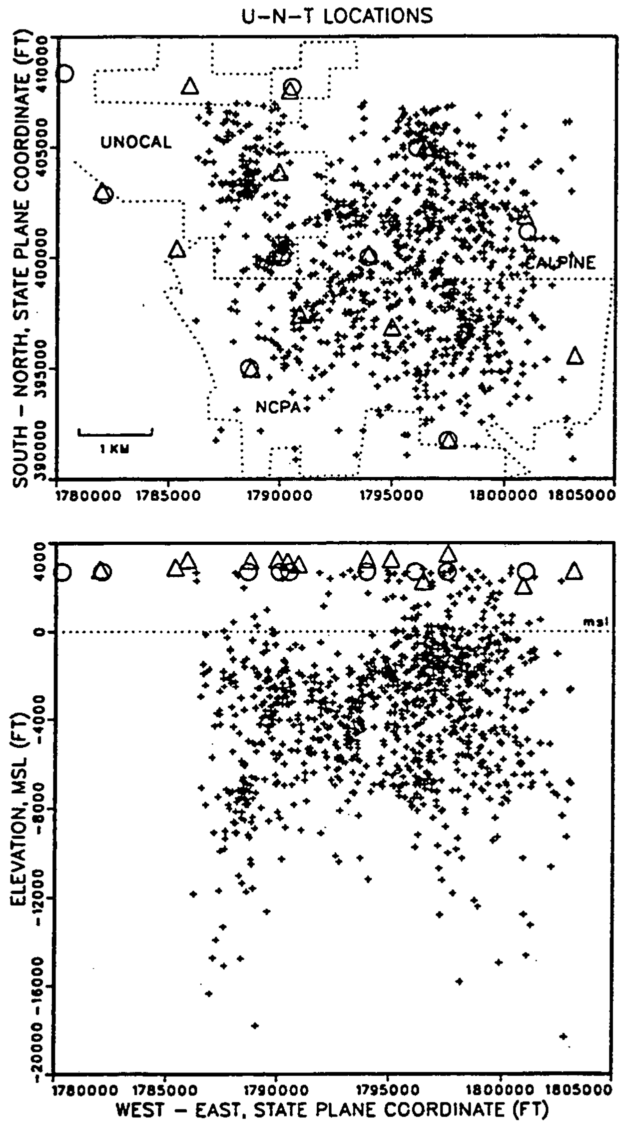



Figure 3. MEQ hypocenters at the SE Geysers from January to June 1994, obtained using the U-N-T array and a 1-D velocity model. Plan view and projection onto east-west plane shown. Circles represent U-N-T stations; LBL stations also shown for reference (triangles). Compare with Figure 2.

figures. Several of the clusters are known to correlate with injection wells, while at least one of the clusters is associated with a production well. Two of these clusters (the boxed areas in Figure 2) are discussed in detail in the following sections. The rest of the seismicity has not yet been studied for detailed correlation with injection and production activities.

The depth distribution of the LBL hypocenters is also less diffuse than the U-N-T hypocenters. The LBL hypocenters locate in a much more limited depth range, between –1000 and –7000 ft msl (–0.3 to –2.1 km msl, or a depth of 1.0 to 2.8 km, using an average surface elevation of 0.7 km msl), with several localized MEQ "stringers" extending below the base of the main zone of seismicity. This result is similar to that found at the NW Geysers by Romero et al. (1994). Using a similar array, they identified a shallow zone of microseismicity between 1 and 3 km in depth, and a more limited zone from 3.5 to 5 km in depth.

The observation that few events occur above –1000 ft (–0.3 km) msl is interesting in that the elevation of the top of the steam reservoir ranges from 1000 ft to –3000 ft (0.3 to –0.9 km) msl in the area that is seismically active (Field Operators, 1992). The top of the steam is above the –1000 ft (–0.3 km) level over approximately one-half of the seismic area. Thus, it appears that the portion of the steam reservoir between 1000 and –1000 ft (0.3 and –0.3 km) msl is relatively aseismic.

More detailed study will be conducted to determine the relation of the base of the seismicity with the bottom of the reservoir. The depths of the deeper events are less well constrained than the shallower events due to poorer resolution of the velocity model with depth. In general, producing wells in this area extend down to elevations of –5000 to –6000 ft (–1.5 to –1.8 km) msl, roughly coincident with the base of the primary zone of seismicity. Clearly, however, some MEQs do occur below the maximum depth that the steam reservoir is currently being exploited.

It would be desirable to know which components of the LBL monitoring process contribute to the differences between the LBL and U-N-T hypocenter results. If, for example, it were determined that the inclusion of S-wave data did not contribute appreciably to improved accuracy, it would be much cheaper to operate a high-resolution network since horizontal components would not be required. Therefore, we conducted several tests to separate the effects of the use of P- and S-wave data vs. the use of P-wave data only, and also the use of a 1-D vs. a 3-D model.

First, the events were relocated using the 3-D, P velocity model, excluding S-wave arrival times. Locations shifted an average of 240 ft (73 m) horizontally, and in a random pattern. The clustered patterns of seismicity were still quite evident, and the depth distribution of events did not differ significantly from the 3-D, P and S case, although depths of many of the individual events shifted appreciably.

Next, the events were relocated using a 1-D, P- and S-wave velocity model. In this case, the clustering of events still occurred, but the locations of the clusters shifted appreciably, up to 1500 ft (0.45 km). The base of the main seismicity zone extended to –9000 ft (–2.7 km) msl. Relocations using a 1-D model without S-waves were also performed. The results are similar to the 1-D, P and S case, although some clusters were not as tight.

We conclude that the high-resolution data and/or the increased density of the LBL array results in more clustered event locations compared to the U-N-T data, and that use of a 3-D velocity model significantly affects the absolute locations of the events and clusters. S-wave data may be of limited usefulness for hypocentral locations of SE Geysers MEQs with this particular array. Because the large amount of energy in the P-wave coda in these seismograms tends to obscure the S-wave arrivals, their arrival times are fewer and less accurate than those of the P waves, and therefore may not contribute appreciably to the inversion. We plan to test the effect of the high-resolution data by adding random noise to the arrival times and relocating the events. This should indicate how much picking error is needed to make the LBL locations as diffuse as the U-N-T locations.

## SEISMICITY ASSOCIATED WITH AN INJECTION WELL

The cluster of seismicity associated with the injection well DV-11 was investigated in detail ("Area 1" in Figure 2). Injection in DV-11 began in late December 1993 as part of The Geysers Unit 18 Cooperative Injection Project, a three-year cooperative program between the U.S. Department of Energy (DOE) and U-N-T, Calpine, NCPA, and Pacific Gas and Electric, to increase the understanding of injection into known productive intervals at The Geysers (Voge et al. 1994).

Analysis of 1993 and 1994 data shows that the DV-11 area was seismically quiescent prior to February 1994. During that month, five MEQs occurred near DV-11. By June 1994, they occurred at a rate of 21 events per month. The injection rate and the seismicity rate are compared in Figure 4. There is a lag time of approximately one month between initiation of continuous injection and the onset of seismicity. A similar lag time is observed between the cessation of injection in late May and the drop in seismicity in July. In contrast, only seven days after the January 7 injection start, enhanced steam production began to occur from the five producing wells on the injection well pad (Voge et al., 1994).

The DV-11 study area and the wells being monitored for physical and chemical parameters during the injection test are shown in Figure 5. Posted next to each well is the nominal flowrate difference in kph (thousand pounds per hour) between 12/1/93 and 4/30/94, four months after injection began (data from Voge et al., 1994). Note that the largest increases in steam production are seen in the wells with steam entries to the west and south of the injector.

The LBL hypocenter locations in the DV-11 injection area are shown in detail in Figure 6. The MEQs are located near and below the bottom of the injection well (from 400 ft above [120 m] to 3500 ft [1070 m] below the well TD), and distances up to 400 ft

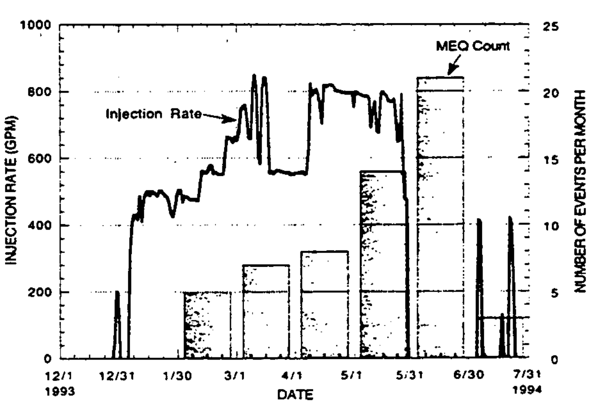



Figure 4. Comparison of DV-11 injection rate and seismicity in the surrounding 2400- × 2400-ft (0.73- × 0.73 km) area. MEQ count is based on U-N-T data, because of some down-time of the LBL network during the period shown.

(120 m) north, 1000 ft (300 m) west, and 1000 ft (300 m) south. This trend in event locations is toward the wells that showed the largest increases in production (wells DV-1, DV-6, DV-15, DV-16, and DV-17; see Figure 5). There are few events to the east of DV-11; likewise, well DV-24-RD, whose steam entries are directly east of DV-11, showed only one-half to one-third the nominal flowrate increase of these other five wells. The maximum depth of the MEQs is similar to the depth of the deepest production wells in this area.

Most of the flowrate increase in DV-6 did not occur until April 1994, while the other increases were seen almost immediately. Voge et al. (1994) suggest that the delayed increase was due to the time necessary for expansion of the boiling front from the injected liquid to reach the deep DV-6 steam entries. This interpretation may be supported by the observation that the deepest MEQs in Figure 6 (those below –4000 ft [–1.2 km] msl) all occurred in June, with the exception of one each in March, April and May. The distribution of the shallower events do not show a temporal pattern.

It has been suggested that MEQs indicate the presence of injectate, but also that conversely, the absence of MEQs cannot be taken to mean its absence. There has been at least one case of injection with no clear increase in seismicity detected (M. A. Stark, pers. comm.), and preliminary correlation of LBL hypocenters with injection wells in the NCPA lease area indicates that seismicity can decrease or even stop around injectors active for long periods of time. Likewise, the absence of MEQs above –2500 ft (–7.6 km) msl in Figure 5 cannot be taken to show that injectate is not leaving the well above that elevation, because the mechanisms by which injection induces MEQs are not known. We have already discussed the existence of a relatively aseismic zone within the reservoir above –1000 ft (–0.3 km) msl over other areas of the SE Geysers.

The top of the felsite intrusion is also shown in Figure 6, and it is seen that the located MEQs occur within the felsite. This observation should be compared with the felsite-dependence of other injection-related MEQs as well as production-related MEQs to evaluate its significance. Much of the Geysers is underlain by this northwest-trending intrusive body, and in the SE Geysers, the productive reservoir is found in both the felsite and the overlying greywacke unit.

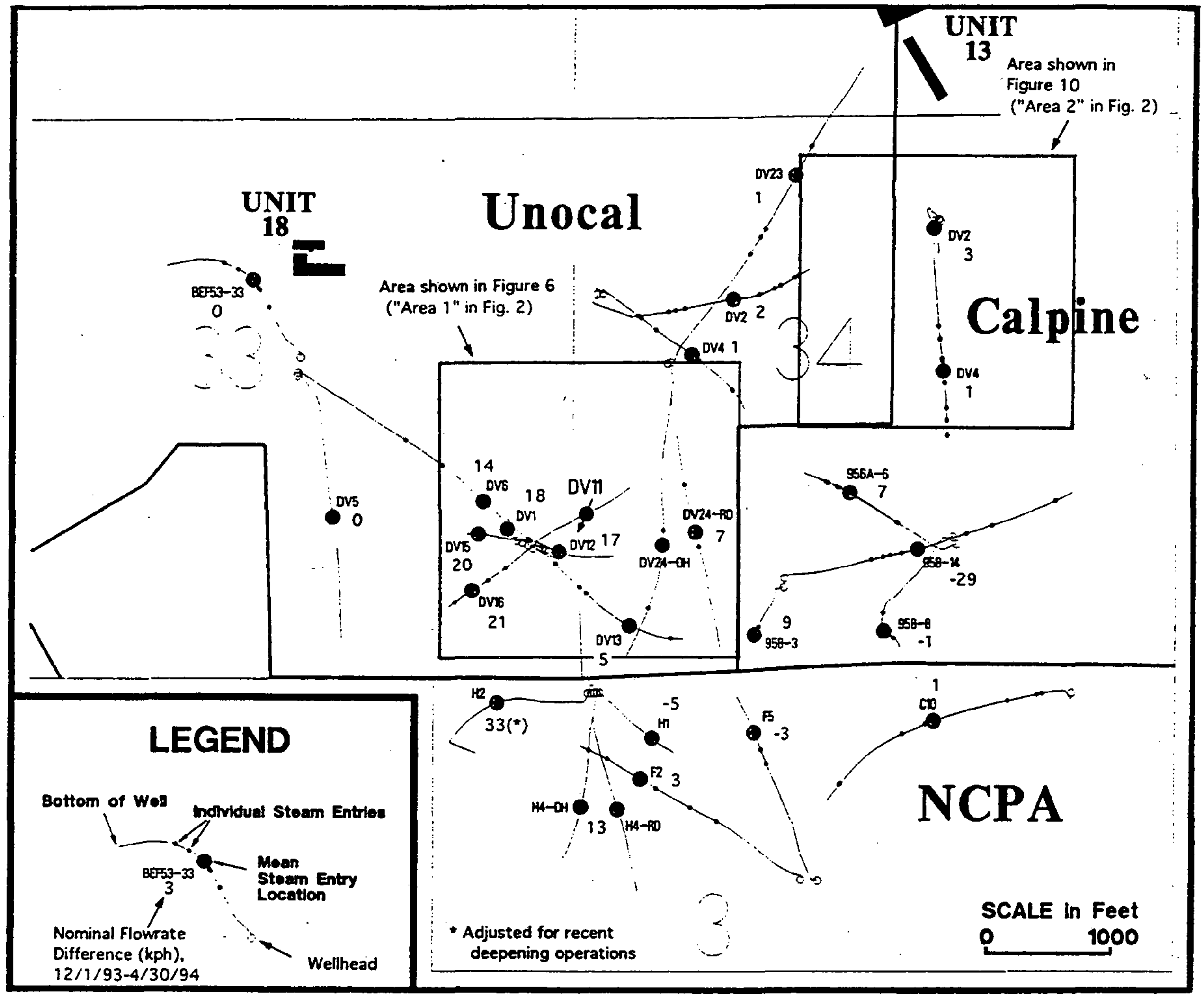



Figure 5. Unit 18 Cooperative Injection Project study area, showing monitored U-N-T, Calpine, and NCPA wells. Base map provided by NCPA.

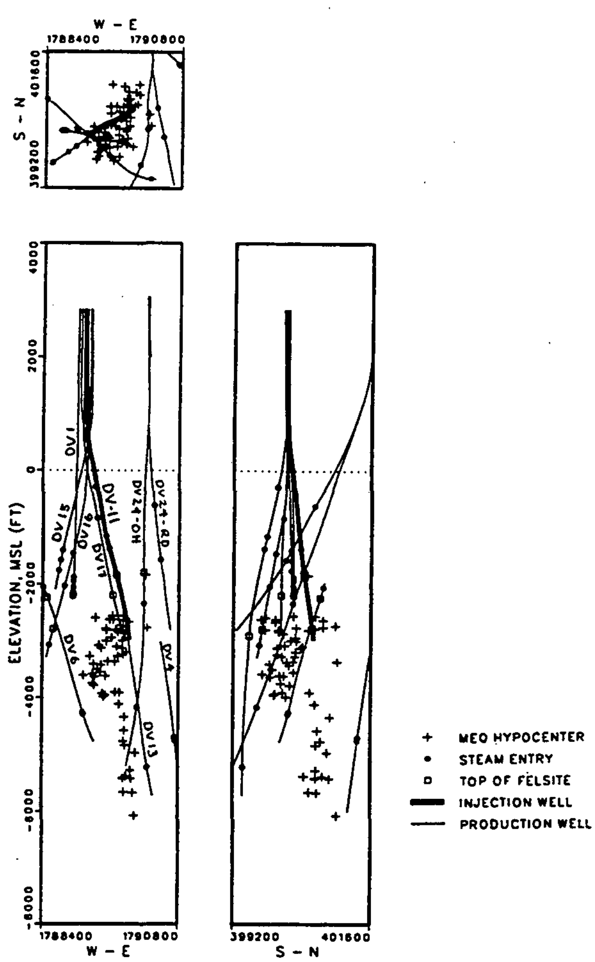



Figure 6. Plan view and east-west and north-south cross sections of seismicity for January to July 1994 near injection well DV-11, obtained using LBL data and 3-D P- and S-wave velocity model. Location of area indicated by boxes on Figures 2 ("Area 1") and 5.

In summary, the data do suggest that the MEQ distribution can be interpreted as a rough indication of the pathway of injectate and/or injection-derived steam, and further, of the existence of fractures or high-permeability pathways. While it is possible that the larger number of wells extracting steam to the west and south of DV-11 influenced preferential fluid movement in that direction and the corresponding seismicity, this would not explain the seismicity to the north of DV-11. If the locations of the hypocenters are accurate, they could indicate the movement of some injectate to the north, and consequently that deep drilling in this area could increase fluid recovery. Voge et al. (1994) estimated for April 1994 a 40.7% near-term recovery of injectate as produced steam in the existing nearby wells, primarily to the south and west.

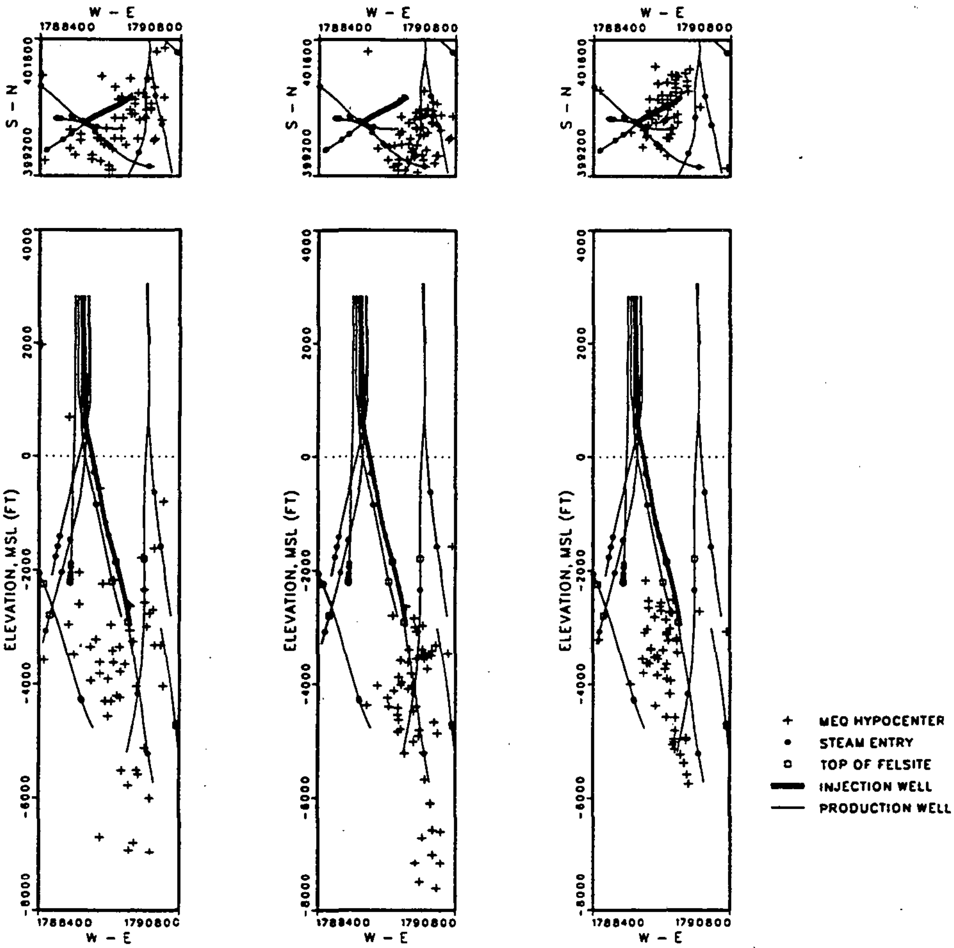
Presented in Figure 7 are plots of the DV-11 seismicity determined using different data and velocity models. They demonstrate that in doing the above type of analysis, confidence is increased by the use of a 3-D model and LBL-type network data, and to a lesser extent, S-wave data. The U-N-T locations (Figure 7a) are more diffuse, both laterally and vertically, than the LBL locations. The trend towards the wells showing increased flowrate is not as defined, and many events locate to the east of DV-11. Events also locate above the felsite, and below the TD of the deepest wells.

Figure 7b shows the hypocenters obtained using LBL data, but with a 1-D model. The events are clustered, but are shifted to the southeast, towards wells that showed low flowrate increases. Some events also locate much deeper than in Figure 6, below the TD of the deepest production wells in this area.

Figure 7c presents the hypocenters obtained with LBL data and a 3-D model, but without using S-wave data. The MEQ distribution is very similar to that in Figure 6, and all of the same conclusions could be drawn from this data. However, elimination of S-wave data has resulted here in more events located to the north of DV-11, making a stronger case for infill well drilling in that area than might be warranted from the 3-D, P- and S-wave results.

## SEISMICITY ASSOCIATED WITH A PRODUCTION WELL

A tight cluster of seismicity occurring around the Calpine production wells DV-2 and DV-4 was also studied in detail ("Area 2" in Figure 2). A detailed plan view and cross-section is shown in Figure 8, and Figure 5 shows the area in relation to the DV-11 injection test. Although Calpine DV-2 and DV-4 are being monitored as part of the DV-11 injection project, we do not believe the seismicity associated with these two wells is related to the DV-11 injection, because the rate of seismicity in this area has not increased appreciably since the injection began. Both LBL and U-N-T data show a cluster of events in this area in 1993. Also, flowrates in Calpine DV-2 and DV-4 have shown almost no response to DV-11 injection, although small amounts of tracers injected into DV-11 have been recovered. They may, however, be influenced by injection in two nearby Calpine wells. One injection wellhead is located just to the east of the area shown, with the well course deviated to the southeast. The other injection




U-N-T LOCATIONS (JAN-JUN 1994)

LBL LOCATIONS, 1-D MODEL, P- AND S-WAVE DATA (JAN-JUL 1994)

LBL LOCATIONS, 3-D MODEL, P-WAVE DATA ONLY (JAN-JUL 1994)

(a) (b) (c)

Figure 7. Plan views and east-west cross sections of seismicity near injection well DV-11, obtained using differing data and velocity models. Compare with Figure 6.

wellhead is on the same pad as 956A-6 and 958-8, shown in Figure 5, and the well course is nearly vertical. Both DV-2 and DV-4 produce at a rate around 70 kph (Voge et al, 1994).

The MEQs occur mostly near and below the bottom of well DV-2, and within the felsite, similar to the seismicity near the injection well DV-11. Again, it appears that the upper portion of the steam reservoir is relatively aseismic here. The events are also displaced laterally from the DV-2 well course, or to its projection downward in the case of those events located below the well's TD. The seismicity nearest to DV-4 is also displaced by about 300 ft (90 m) east. Differences in source characteristics between these events and those near DV-11 are discussed in the next section.

SOURCE MECHANISM STUDIES

In order to obtain information on the size and source characteristics of the MEQs, the LBL data were inverted for moment tensors. The procedure yielded a scalar moment and an orientation of the maximum compressive and tensional stresses (P and T axes) for each event. Because the procedure takes both amplitude and polarity of P waves into account, the results are better constrained than the standard fault plane solutions, which are often ambiguous. High-resolution data is required for this method because

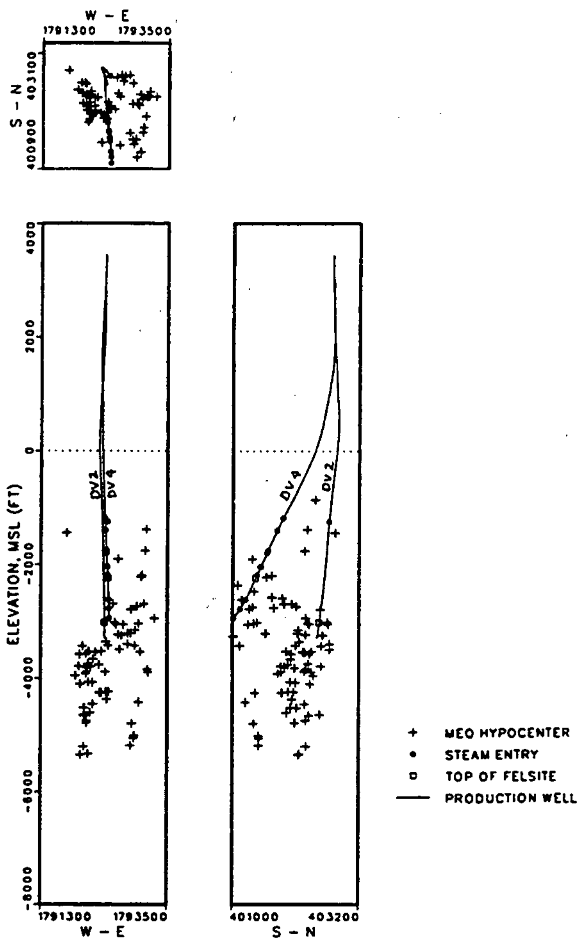



Figure 8. Plan view and east-west and north-south cross sections of seismicity near the Calpine production wells DV-2 and DV-4. Location of area indicated by boxes on Figures 2 ("Area 2") and 5.

the amplitudes are obtained by integration over the pulse width; therefore the uncertainty in arrival time must be small compared to the pulse width. The method is also capable of using S-wave data; however, because of the high uncertainty of the LBL S-wave arrival times, we were not able to do so.

Although the method is still in the development stages, preliminary orientations of the P and T axes of the events in the DV-11 injection area and the Calpine DV-2 and DV-4 production area are shown in Figure 9. While there is a great deal of scatter in the orientations in both areas, it does appear that there are some differences. The axes in the injection area are more randomly oriented while in the production area there is a cluster of P axes oriented in a NE-SW direction, and alignment of many T axes in a NW-SE direction. The production area axes are consistent

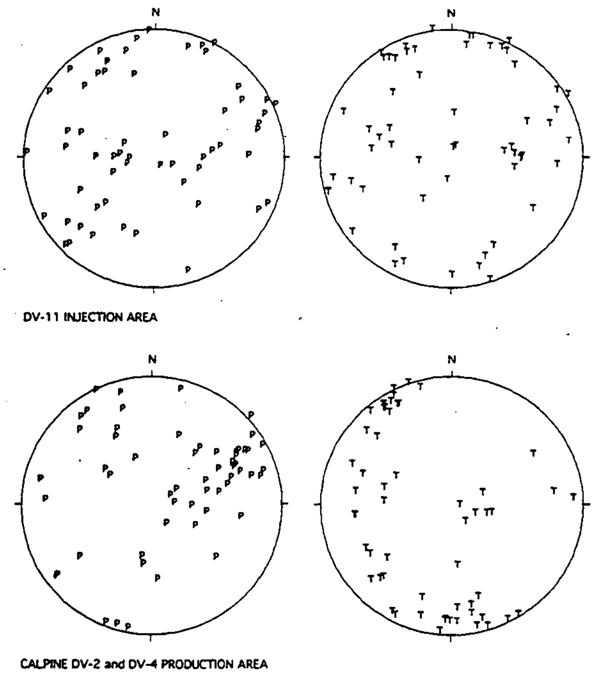



Figure 9. Orientation of P and T axes obtained by moment tensor inversion of the LBL data, for the events for January to August 1994, from the areas shown in Figures 6 and 8. Lower hemisphere equal area projection.

with the orientation of the regional strain field from geodetic measurements, of approximately N79W extension and N11E contraction (Prescott and Yu, 1986), and with many of the P and T axes obtained by Oppenheimer (1986) for The Geysers from fault plane solutions on USGS data.

If this difference in focal mechanisms between one injection and one production area were found for all injection- vs. production-related events at the SE Geysers, it would have important implications for different earthquake-inducing mechanisms. As pointed out by Oppenheimer (1986), agreement between the orientation of the production-related earthquake stress axes with the regional strain rate axes would indicate that the stress perturbations resulting from extraction are small compared to the regional tectonic stress field. On the other hand, the lack of such correlation for the injection-related events would indicate that the local stress perturbations induced by injection dominate.

The scalar moments of the SE Geysers MEQs are shown in a standard "b-value" plot in Figure 10. The

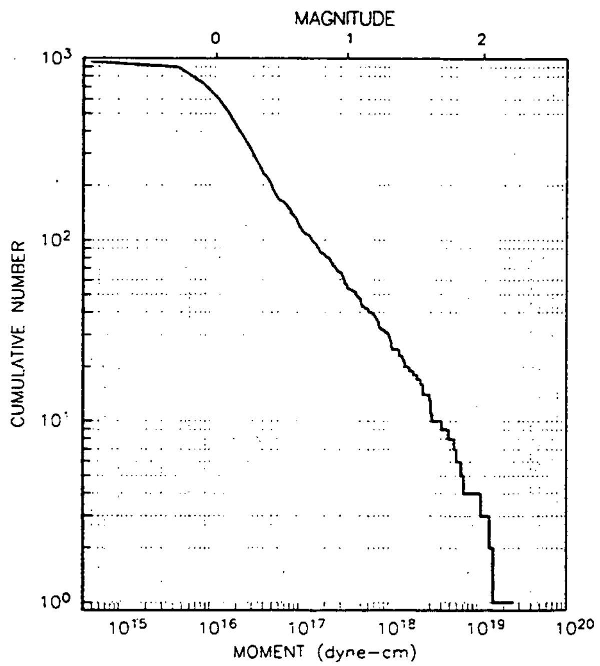



Figure 10. SE Geysers B-value plot, showing cumulative number of events above given moment vs. moment for January to August 1994. Slope of line corresponding to moments less than $3 \times 10^{18}$ is 0.68; slope of line for greater moments is approximately 1.0.

different slope of the line for moments above and below $3 \times 10^{18}$ dyn-cm may indicate differing mechanisms for the events above and below this value. One possible explanation is that the larger events have causes related to tectonic stresses, while the mechanism of the smaller events are related to production, resulting in a different frequency distribution.

The moments ($M_o$) were converted to magnitude ($M_w$) using the relationship

$$M_w = \frac{2}{3} \log M_o - 10.7$$

(Hanks and Kanamori, 1979). The equivalent magnitudes are shown on the upper x axis of the b-value plot. The size of the events at the SE Geysers are quite small. For the time period January to July 1994, the largest event recorded by the LBL array had a moment of $2 \times 10^{19}$ dyn-cm, or a magnitude of about 2.2.

The results presented above indicate that further investigation of moment tensors is warranted and may provide important information regarding the mechanisms inducing MEQs at the SE Geysers. It may also be possible to infer additional source characteristics such as energy release, size of rupture surface, and source duration from the moment tensor results.

## CONCLUSIONS

High-quality MEQ hypocenter locations have been obtained at the SE Geysers using a high-resolution digital array operated by LBL and have been compared with those obtained from the U-N-T array. The use of a 3-D seismic-velocity model is important for obtaining accurate absolute locations, while either the high sample rate or the tight array configuration, or both, is required for accurate relative locations.

Use of the new array reveals that MEQs at the SE Geysers occur in spatial clusters which can be associated with both injection and production activities, as well as in a more diffusely scattered pattern. Elevations of most of the events are between –1000 and –7000 ft msl, or depths of 1 to 2.8 km. The base of this primary seismicity zone is approximately coincident with the maximum depth from which the steam reservoir is currently being produced. The portion of the steam reservoir from 1000 to –1000 ft (0.3 to –0.3 km) msl is relatively aseismic. The seismic moments of the events recorded have been under $2 \times 10^{19}$ dyn-cm, or a magnitude of about 2.2.

MEQs appear to have been induced by injection of water into well DV-11. The LBL data showed that the lateral, vertical, and temporal distribution of seismicity was towards the production wells responding most favorably to the injection, adding credibility to the use of MEQs to track injectate or to infer the location of high-permeability pathways. MEQs also spread north from DV-11 towards an unexploited area of the field, which, using this principle, indicates that recovery of injectate might increase with drilling in this area.

Orientations of P and T axes of moment tensors of events near the injection well DV-11 differ from those of events near the Calpine production wells DV-2 and DV-4. The source mechanism studies are in a preliminary stage, but show promise for providing information on the mechanisms by which water injection and steam extraction induce MEQs. High-resolution data are required for the moment tensor analysis.

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