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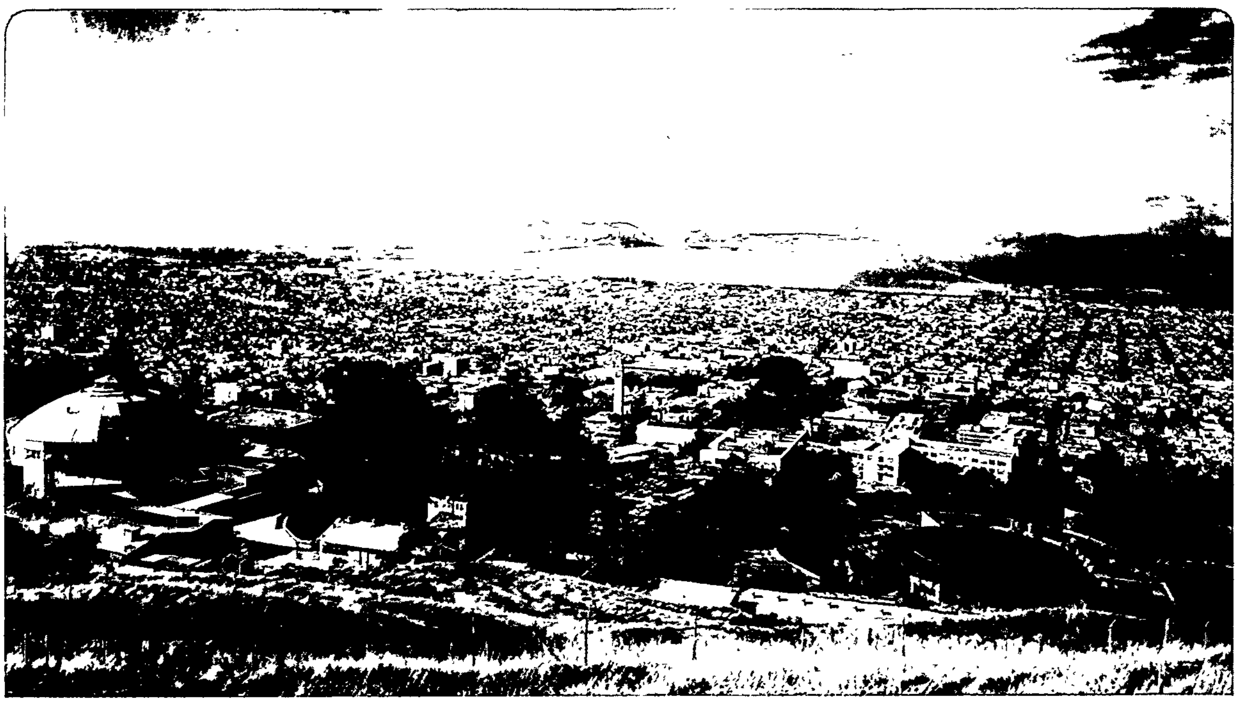

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ABSTRACT

Source mechanisms of 1697 microearthquakes at the Northwest Geysers, and 985 microearthquakes at the Southeast Geysers geothermal fields are investigated using a moment tensor formulation. P- and S-wave amplitudes and polarities are utilized to estimate the full, second-order moment tensor, which is then decomposed into isotropic, double-couple, and compensated linear vector dipole components. The moment tensor principal axes are used to infer the directions of principal stress associated with the double-couple component of the source mechanism. Most of the events can be modeled as primarily double-couple; however, a small but significant isotropic component, which can be either positive or negative, is also needed to explain the observed waveforms. In the SE Geysers, events with positive isotropic components and events with negative isotropic components both occur in areas of steam extraction and in areas of fluid injection. In the NW Geysers, however, events with a positive isotropic component occur mainly in the area of fluid injection. In both the SE and NW Geysers, principal axes of moment tensors with negative isotropic components are roughly aligned with the regional stress field, while those of moment tensors with positive isotropic components differ significantly from the regional stress field. This suggests that two differing inducing mechanisms are required: negative-type events involve local stress perturbations that are small compared to the regional stress, while positive-type events involve stress perturbations which locally dominate over the regional stress.

INTRODUCTION

Many investigators have demonstrated that steam extraction and fluid injection are associated with microearthquake (MEQ) activity at the Geysers, California, geothermal field (e.g., Eberhart-Phillips and Oppenheimer, 1984; Stark, 1992). However, until recently few detailed studies of the nature of the mechanisms have been carried out. Seismic waveforms contain information about the characteristics of the source which generated them. If this information can be extracted it can be used to infer properties of the earthquake source and thus provide constraints on possible inducing mechanisms.

In this paper we discuss moment tensors obtained from inversion of MEQ waveform data recorded at the Southeast (SE) and Northwest (NW) Geysers geothermal areas by the high-resolution seismic networks operated by Lawrence Berkeley National Laboratory (Berkeley Lab) and the Coldwater Creek Geothermal Company (now CCPA) (Figure 1). The network in the SE Geysers consists of 13 high-frequency (4.5 Hz), digital (480 samples), three-component, telemetered stations deployed on the surface in portions of the Calpine, Unocal-NEC-Thermal (U-N-T), and Northern California Power Agency (NCPA) leases. The network in the NW Geysers is a 16-station borehole array of three-component geophones (4.5 Hz), digital at 400 samples/sec, and telemetered to a central site.

One of the main objectives of Berkeley Lab's program at the Geysers is to assess the utility of MEQ monitoring as a reservoir management tool. Discrimination of the mechanisms of these events may aid in the interpretation of MEQ occurrence patterns and their significance to reservoir processes and conditions of interest to reservoir managers. Better understanding of the types of failure deduced from source mechanism studies, and their relations to production parameters, should also lead to a better understanding of the effects of injection and withdrawal.

Moment tensors contain information regarding the possible orientations of principal stresses involved in an event nucleation. They also provide a measure of how well a particular event can be modeled by shear displacement, or whether a more complicated source model is required. Non-shear earthquake mechanisms have been reported in geothermal and volcanic areas in recent years (e.g., Julian et al, 1993; Shimizu et al, 1987). Seismic P-wave radiation patterns from these areas appear to indicate that positive or negative volumetric change is involved in the source process of many of these events. We compare our results to these, and to other previous studies of earthquake source mechanisms at the Geysers, and investigate evidence for non-shear source processes.

METHOD

The displacement at a seismic source can be represented as a set of forces and force couples, which are sufficient to cause the seismic wave displacements observed at a receiver at some distance from the source. The seismic moment tensor represents the moments of these so-called "equivalent body forces." By making the assumption that the source can be approximated as a point in time and space, the moment tensor reduces to a symmetric, rank 2 tensor and therefore contains six independent elements.

It is possible to compute the equivalent body forces and resulting moment tensor for any arbitrary source model, and, conversely, it is also possible to estimate the moment tensor of an actual source by solving the following set of equations:

$$u_i = G_{ij} m_j$$

where u, i=1-n, are the n observations of the P- and S-wave pulse amplitudes of all waveforms recorded at all receivers for one event; m, j=1-6, are the six independent elements of the moment tensor; and G_{ij}, derivatives of the Green's functions for the appropriate source-receiver paths (Stump and Johnson, 1977). To compute m_j, we must first calculate Green's functions from the estimated path properties such as seismic velocity and attenuation. Surface effects are also included. Errors in our computed moment tensors will reflect errors in these quantities, which are also affected by mislocations of hypocenters, as well as observational errors in determining accurate waveform amplitudes. Because our instruments record ground velocity, which is the time derivative of ground displacement, we obtain displacement amplitudes by integrating over the width of the recorded P- and S-wave pulses.

The eigenvalues and eigenvectors of the moment tensor describe the magnitude and orientation, respectively, of the equivalent body forces. We identify the eigenvector corresponding to the minimum eigenvalue as the "compression," or "P" axis, and the eigenvector corresponding to the maximum eigenvalue as the "tension," or "T" axis. For a double-couple source (a double-couple is the body-force equivalent for a shear displacement), the P and T axes bisect the quadrants of the focal sphere (a small imaginary sphere centered on the source) corresponding to areas of downward and upward P-wave first arrivals. The well-known fault-plane solution method utilizes this concept by tracing polarities of first motions back to their positions on the focal sphere, and then separating them into quadrants defined by nodal planes (the slip plane and the auxiliary plane). The P and T axes are then determined as the poles which bisect these quadrants. Our moment tensor approach improves upon this method by utilizing the amplitude as well as the polarity of both P- and S-wave pulses, and by allowing models other than double-couple ones to be considered.

The eigenvalues of the moment tensor are used to decompose the solution into isotropic, double-couple, and compensated linear vector dipole (clvd) components. For a purely isotropic source (i.e., an explosion or implosion), all three eigenvalues of the moment tensor are equal. For a purely double-couple source (i.e., a shear displacement), one eigenvalue is zero, and the other two are of equal magnitude and opposite sign. For a clvd (representing an opening or closing in one direction accompanied by corresponding closing or opening in orthogonal directions so that there is no net volume change), two of the eigenvalues are equal to each other and to 1/2 the third. We consider that the source could be composed of a combination of any of these three source models, and "decompose" our moment tensor solution into the relative contributions of each.

An example of a moment tensor solution for an event recorded by our network in the SE Geysers is shown in Figure 2. Orientations of P, T, and I ("intermediate") axes (the eigenvectors) are plotted on a lower-hemisphere equal-area projection of the focal sphere. The stippled area represents the area of upward first motions that are predicted by the computed moment tensor. The dipping planes represent nodal planes for the double-couple component of the source. The departure of the stippled area from the quadrants defined by these planes is a measure of the departure of the moment tensor from a pure double-couple.

The moment tensor decomposition result for this example is shown on the ternary diagram in Figure 2. The apexes of the triangle represent the end-member models. The diagram shows that this event can be modeled as predominantly double-couple, with some isotropic component and some clvd component. The sign of the isotropic component is negative (i.e., $\lambda_1 + \lambda_2 + \lambda_3 < 0$, where the λ's are the moment tensor eigenvalues), which, if real, would indicate a small volume decrease in the source region accompanying this event. The orientations of the P and T axes indicate a predominantly strike-slip-type mechanism for this event's double-couple, or shear displacement, component. The example has a moment-magnitude (Mw), of approximately 2.1, which is a large event for the SE Geysers.

SE GEYSERS RESULTS

Hypocenters of 1605 events in 1994 were determined from hand-picked P- and S-wave arrival times. Uncertainties in the locations are estimated to be less than 200 m. A three-dimensional P- and S-wave velocity model, derived from a subset of the data using the joint hypocenter-velocity inversion method of Thurber (1983) as modified by Michellini and McEvilly (1991) was used. Event epicenters are shown in Figure 3; and the vertical distribution of seismicity is shown on the north-south depth sections in Figure 4. Figure 3b shows the locations of injection wells in the UNT, NCPA, and Calpine lease areas, and the approximate area of steam extraction in the Calpine lease area.

The plots show that the MEQs tend to occur in spatial clusters, as well as in more diffuse patterns. Comparison of Figures 3a and 3b shows that few events occur in areas where steam extraction or fluid injection are absent; however, not all injection areas and not all steam extraction areas have associated seismicity. For example, no MEQs were detected near the Calpine injection well at 1,803,000 E, 400,000 N (Figure 3). Likewise, very few events are detected in the area of steam extraction on the northeast edge of Calpine's portion of the reservoir. It appears that fluid injection and/or steam extraction is a necessary, but not sufficient condition to induce MEQs at the SE Geysers.

The base of the seismicity zone varies from -1 to -2 km msl (2 to 3 km below the surface), and appears to be roughly coincident with the base of the current producing zone (Kirkpatrick et al, 1995). Localized MEQ "stringers", however, do extend below the maximum depth to which producing wells are drilled in several areas. This could reflect preferential fluid flow in the vertical over the lateral directions, as also postulated by Stark (1992), and supported by the fracture model developed by Beall and Box (1991). Their work suggested the existence of zones of many, small, randomly-oriented horizontal and low-angle fractures, cut by fewer, larger, high-angle fractures which extend to an unknown depth, and in some cases, correlate with mapped surface faults.

Moment tensor inversions were performed on the waveforms from these events; solutions for 985 events were obtained. Because a higher signal-to-noise ratio is required for accurate P- and S-wave pulse amplitude determination than for arrival time determination, and because 6 observations are required for moment tensor inversion, while only 4 for hypocentral inversion, moment tensors could not be calculated for all located events.

Moment Tensor Decomposition:

Decomposition of the moment tensors (Figure 5) showed that some could be modeled as predominately double-couple events and that over half (approximately 53%) of the events had double-couple components comprising over 50% of their moment tensor solution. In contrast, few events, if any could be modeled as predominantly isotropic, excluding purely explosive or implosive source processes. The isotropic component is not insignificant, however, as it is present in the moment tensors in percentages up to approximately 30%. This result is quite robust, occurring even when only the most well-constrained moment tensor solutions are considered (those having the highest number of observations and the most complete coverage of the focal sphere). Errors in velocity structure or hypocentral locations can introduce errors in the decomposition of the computed moment tensor (O'Connell and Johnson, 1988); however, because volumetric changes might be expected in areas where large amounts of fluids and gases are being injected and withdrawn, we will cautiously assume that the results are significant and proceed to investigate the implications.

Of the 985 moment tensor solutions, 556 have positive isotropic components, while 429 have isotropic components which are negative (56% and 44%, respectively). The pattern of moment tensor decomposition shown in Figure 5 also suggests that a positive volumetric component (upper triangle) is slightly more predominant overall than a negative component (lower triangle). Although this appears to be a small difference and may be due to methodological inadequacies, it is consistent with the observations of Julian et al. (1993), who found evidence for significant numbers of non-shear earthquake source mechanisms at the central Geysers using P-wave polarity data. They found that, of the events which could not be fit to a double-couple model, most had predominantly compressional first arrivals, indicating a positive volumetric component, while only a few had predominantly dilitational first arrivals. These results are intriguing because the Geysers is undergoing lateral contraction and vertical subsidence in response to reservoir depletion (Denlinger et al., 1981). If, as ours and Julian et al.'s results indicate, positive volumetric strain predominates over negative volumetric strain in the MEQ sources, then most of the field-wide negative volumetric change must be a product of aseismic processes.

Volumetric components to earthquake source mechanisms at the Southeast Geysers are feasible because large amounts of steam are being extracted from the reservoir, and large amounts of fluids are being injected into the reservoir. It might be expected that positive isotropic source mechanisms would occur predominantly in areas of fluid injection, and negative isotropic mechanisms in extraction areas. However, comparison of Figures 6a and 6b with Figure 3b shows that this is not the case. Both positive and negative isotropic moment tensor components occur in both injection and extraction areas. The ratio of positive to negative components varies in the injection areas; for example, near the NCPA injector Q-2, the ratio is 68% to 32%, while in the DV-11 area the ratio is similar to that in the field as a whole (56% to 44%). No injection areas show substantially higher percentages of negatively isotropic events, however.

Moment Tensor Principal Axes:

The orientations of the P and T axes of the 985 moment tensors obtained for the SE Geysers are shown in Figure 7a. These axes can be thought of as representing principal stress axes for the part of the source modeled as a double-couple.

A consistent pattern in the orientations of the axes is not evident in Figure 7a. The orientations correspond to shear slip of both strike-slip and normal type, with few thrust-type mechanisms. The results are similar to those obtained by Oppenheimer (1986), who determined fault plane solutions using P-wave polarities for 210 events in the central Geysers. Our solutions depart from his in the more variable orientation of the T axes. The T axes determined by Oppenheimer were mostly restricted to W-E and WNW-ESE directions, roughly coincident with the direction of maximum tensional stress of approximately N70°W and horizontal, derived from analysis of regional events outside the Geysers (Bufe et al, 1981). Bufe's analysis also indicated a horizontal, maximum compressional stress orientation of N20°E, which reflects the dominant regional strike-slip mode of faulting.

If the events at the SE Geysers were caused by these regional stresses, it would be expected that all the P and T moment tensor axes would cluster around these orientations, which is not the case. However, when the event moment tensors are separated according to whether their isotropic component is positive or negative, a regional tectonic signature is seen for the double-couple component of moment tensors having a negative isotropic component (i.e., the principal axes do cluster around the regional stress axes) (Figure 7b). The double-couple component of moment tensors whose isotropic component is positive, however, is seen to reflect predominantly normal-type modes of failure, with vertical P axes and horizontal T axes of variable azimuthal orientation (Figure 7c).

This relationship between the sign of the isotropic component of a moment tensor (indicating a small component of positive or negative volumetric change in the event rupture process) and the orientation of P and T axes associated with the double-couple component of the moment tensor (indicating simultaneous shear displacement) has strong implications for the mechanisms inducing these events. It suggests that two differing mechanisms may be involved in MEQ generation at the SE Geysers. The mechanism causing events with a negative volumetric component must involve changes in the local stress state which reduce the local stresses opposing the regional stress and allow the material to respond seismically to the regional tectonic stress. Similarly, the mechanism causing events with a positive volumetric component must involve local perturbations in the stress field which dominate over the regional.

NW GEYSERS RESULTS

The seismicity at the NW Geysers geothermal area is shown in a plan view and an east-west cross section in Figure 8. The seismic network and geothermal wells are also shown. (Geothermal wells exist south of 38.83° latitude but are not shown.) The events were processed in a similar manner to the SE Geysers events. Hand-picked P- and S-wave arrival time data were used along with a 3-D velocity model to obtain accurate locations. The P- and S-wave amplitudes were then processed to obtain moment tensor solutions.

The hypocenters shown in Figure 8 are coded according to the characteristics of their isotropic component. The circles represent MEQs with high positive isotropic components (defined as greater than 20%). The squares represent MEQs with high negative isotropic components (less than -20%). These values are interpreted as indicating opening and closing components, respectively, to these MEQ sources. Events with isotropic components between -20% and 20% are shown as crosses.

The event cluster centered at approximately -122.827°, 38.824° (Figure 8) is centered around the bottom of the only injection well in the CCPA lease active at the time. About 45% of these events had high positive isotropic components to their moment tensors, while only 4% had high negative isotropic components. Overall, 80% of these injection-associated events had positive isotropic components, and 20% had negative isotropic components. The principal axes of the positive-type events indicate mostly normal-fault-type mechanisms for the double-couple and CLVD components of their moment tensors (the P-axis vertical and the T-axis horizontal), a result similar to that found for the positive-type events at the SE Geysers. The events with negative isotropic components have principal axes indicating strike-slip-type behavior, also similar to the SE Geysers. The least principal stress axis is rotated slightly from the regional orientation, which may indicate that the injection activity has perturbed the regional stress direction slightly.

Outside the injection area, 27% of the events had high positive isotropic components, and only 16% had a high negative isotropic component. Most of these events with high negative isotropic components occurred in the SE portion of the study area (Figure 8a), and were deeper than the other events (Figure 8b).

DISCUSSION

Mechanisms to account for seismicity induced by geothermal exploitation activities have been discussed by many investigators. Majer and McEvilly (1979) considered stress perturbations caused by mass injection and withdrawal, and Denlinger et al (1981) proposed thermal contraction due to reservoir cooling. Allis (1982) presented a mechanism whereby aseismic slip was converted to stick-slip behavior through an increase in the coefficient of friction along fractures due to deposition of exsolved silica, and Stark (1992) concluded that a reduction in effective normal stress due to fluid injection could result in MEQ generation.

More specific consideration of possible inducing mechanisms is needed to account for the crack or cavity opening and closing that is suggested by the positive and negative isotropic components of the moment tensor results. Crack or cavity opening could be caused by increased extensional stress caused by thermal contraction of the rock matrix, local increases in pore pressure due to injected fluid, or to a sudden local increase in pore pressure caused by the flashing of superheated water to steam. Closing could be caused by fluid pressure decreases within preexisting fractures or cavities due to withdrawal of steam ("fracture deflation"). It has also been proposed that localized injectate flashing could cause increasing pressure on adjacent, preexisting fractures, thereby inducing closing-type events.

The results discussed in the previous section provide constraints on which, if any, of these inducing mechanisms are valid. The candidate model must account for the following observations:

1) Fluid injection and/or steam withdrawal are necessary, but not sufficient conditions to cause MEQs at The Geysers.

2) Almost half the events at the SE Geysers cannot be modeled with a predominantly double-couple source mechanism.

3) Most event mechanisms indicate a small but significant component of volumetric strain.

4) Event moment tensors can have either a positive or a negative volumetric component, and both types are found in all parts of the seismically active area. Positive-type events occur in slightly higher numbers than negative-type events, and occur in higher ratios around some, but not all, injection wells.

5) The orientations of the principal axes of the moment tensors of events with negative volumetric components at the SE Geysers approximately coincide with those of the regional tectonic stress.

6) The orientations of the principal axes of the moment tensors of events with positive volumetric components at both the NW and SE Geysers are consistent with a normal-faulting-type mechanism and are not consistent with the regional tectonic stress.

At this time, for the following reasons, we believe that the flashing of superheated water to steam is the most feasible mechanism to explain the occurrence of the events with positive volumetric components. Water is present in the reservoir as both injectate and as a naturally-occurring component of the mixed vapor/fluid reservoir. Thus, as observed, positive-type events would not be restricted to injection areas, although they could be expected to occur there with greater number. It also could account for the absence of MEQs from some areas of injection and extraction: if the reservoir pressure is high enough, water present in the system will not flash to steam. Only after the pressure drops to some threshold value will conditions allow flashing and consequent seismic activity. If the magnitude of the tensional stresses generated by flashing were much larger than the magnitude of the regional tensional stresses, and less than the overburden pressure, then the observed, variable, horizontal orientations of the T axes, and the vertical orientation of the P axes would result. Conversely, if thermal contraction due to cooling by injected fluid caused the positive-type events, they might be predicted to occur in all injection areas, which is not observed. Additionally, the presence of positive-type events at large lateral distances from injection wells probably could not be accounted for.

While the flashing of water to steam might cause the positive-type mechanism as described above, it has also been suggested that it might simultaneously cause an increase in compressive stress on a nearby, preexisting fracture, leading to the nucleation of a closing-, or negative-type event. This type of event could also reflect simple fracture deflation due to withdrawal of fluids or gases. It is unclear, however, how these mechanisms account for the dominance of the regional stress regime in the negative-type events, shown by the orientations of the moment tensor P and T axes. The mechanism proposed by Allis (1982) of the exsolution of dissolved silica onto fracture surfaces might account for this regional tectonic signature to these events, because it involves only an increase in the effective strength of the material which then allows it to respond seismically to the regional stress. This process might also be enhanced by cooling due to fluid injection, and to lowering pressures caused by steam extraction.

FUTURE WORK

The conclusions derived from the analysis of the moment tensor solutions from The Geysers field considered as a whole provide a framework for evaluating seismicity and source mechanisms in individual areas of the field. Future work will focus on detailed analysis of MEQ activity in specific areas of fluid injection and steam extraction. Available information on injection and production rates, values of temperature and pressure, fracture patterns, and other reservoir parameters will be incorporated. We hope the results will further constrain ideas of MEQ inducing mechanisms, contribute to the understanding of the effects of injection and extraction, and ultimately provide useful information to SE Geysers reservoir managers.

ACKNOWLEDGMENTS

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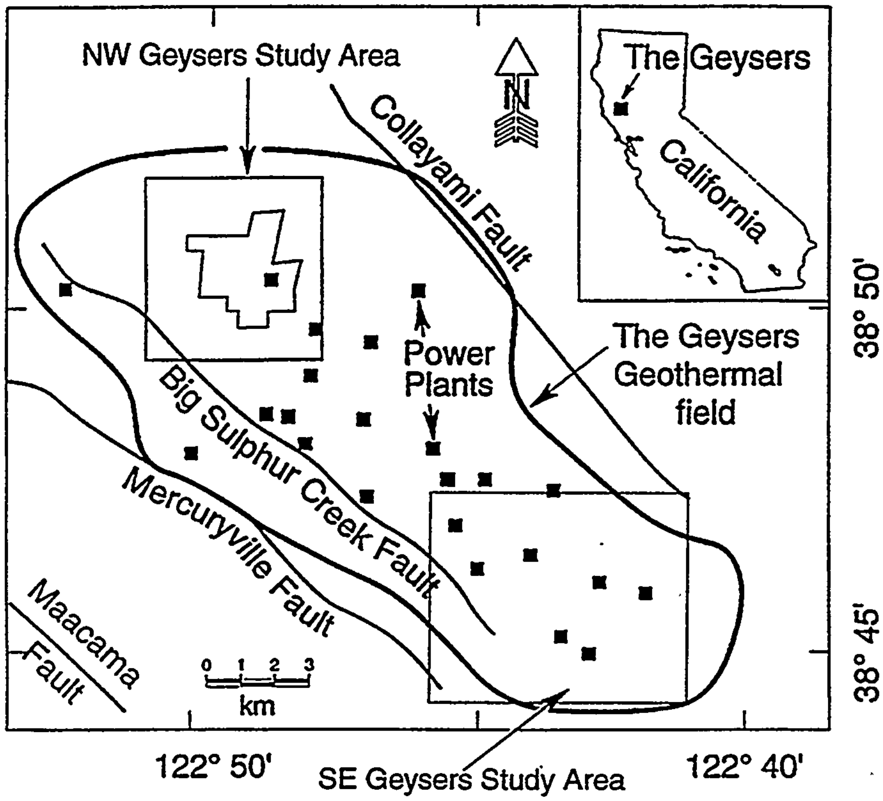
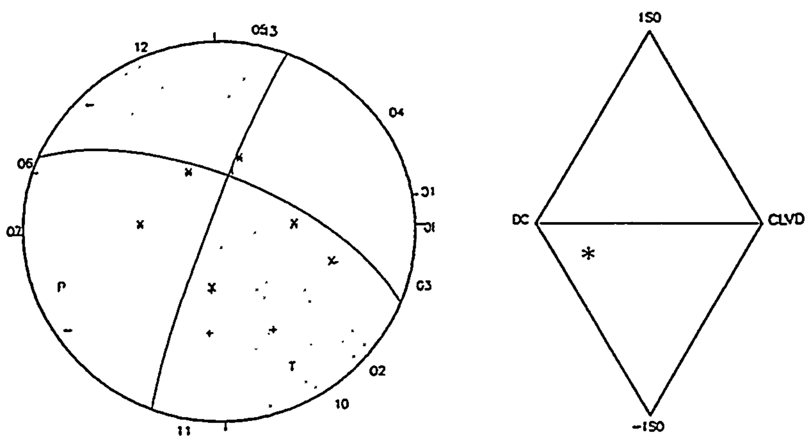


Figure 1. Location of stations in the Lawrence Berkeley National Laboratory (LBL) MEQ network at the Southeast Geysers, California.

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N     EVALUE
1   0.8912E-01
2  -0.1143E-01
3  -0.1450E+00

DECOMPOSITION OF MOMENT TENSOR
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           DYNE-CM           %
ISO     -0.2245E+19        15.48
DC      -0.1006E+20        69.33
CLVD    -0.2203E+19        15.19

Mo        0.1450E+20        Mw      2.07
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Figure 2. Example moment tensor solution output.

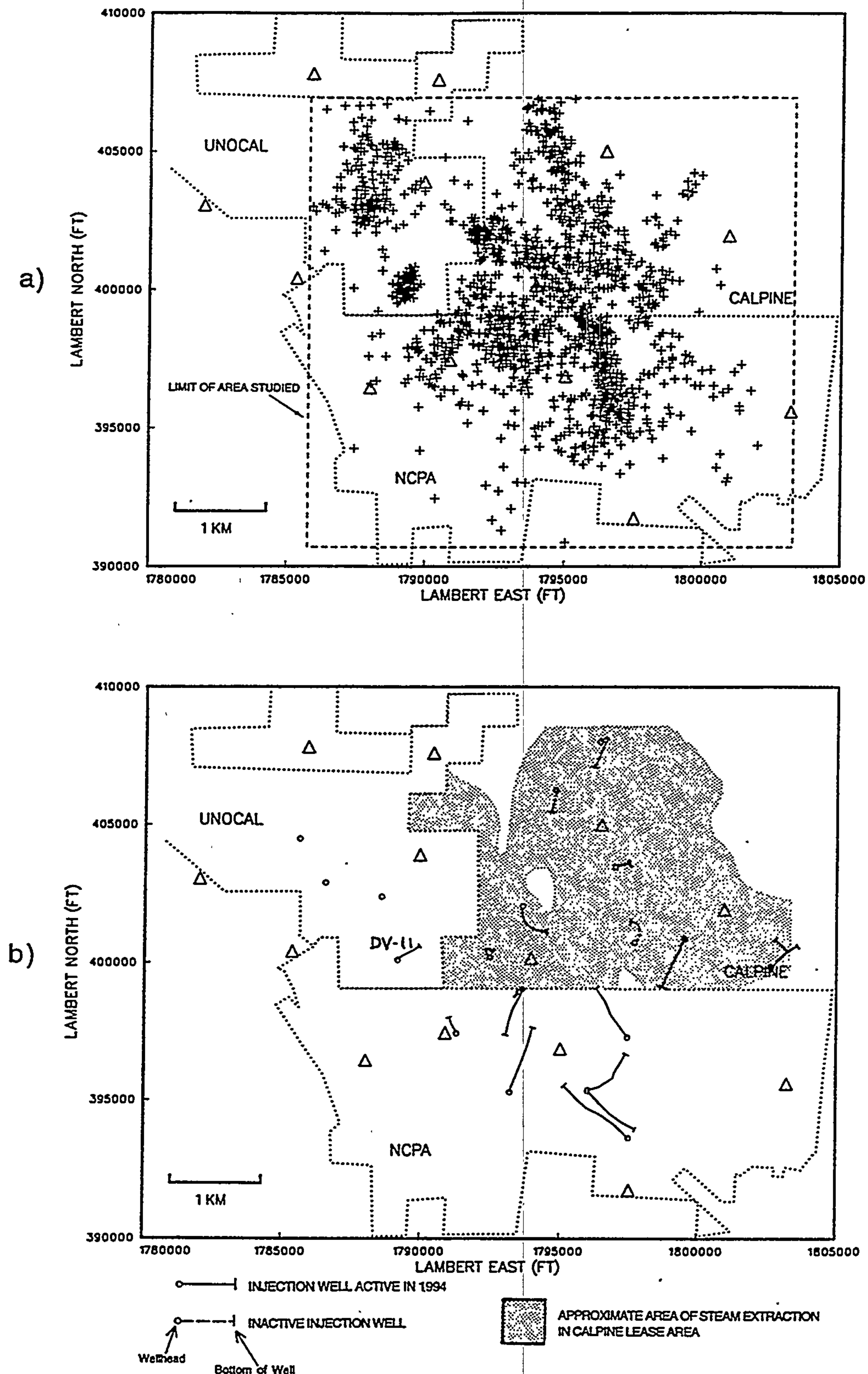

Figure 3. a) Plan view of the 1605 MEQ hypocenters located by the LBL SE Geysers seismic network in 1994. b) Injection wells and approximate area of steam extraction. Well bore traces not available for the injection wells in the Unocal lease area, except for DV-11. Data on extent of steam extraction area not yet available for the Unocal and NCPA lease areas.

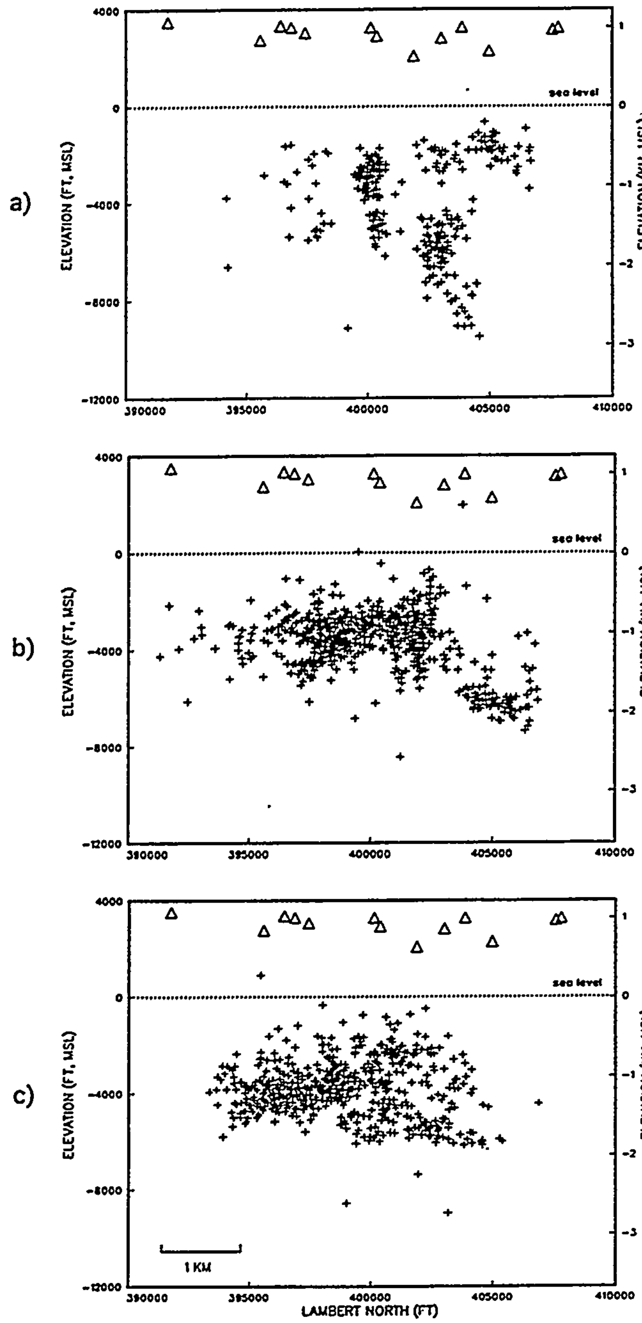

Figure 4. Series of north-south vertical sections of MEQ hypocentral locations. View looking to west; section a) shows events with Lambert east coordinate 1785000 to 1790000; section b) 1790000 to 1795000; and section c) 1795000 to 1800000.

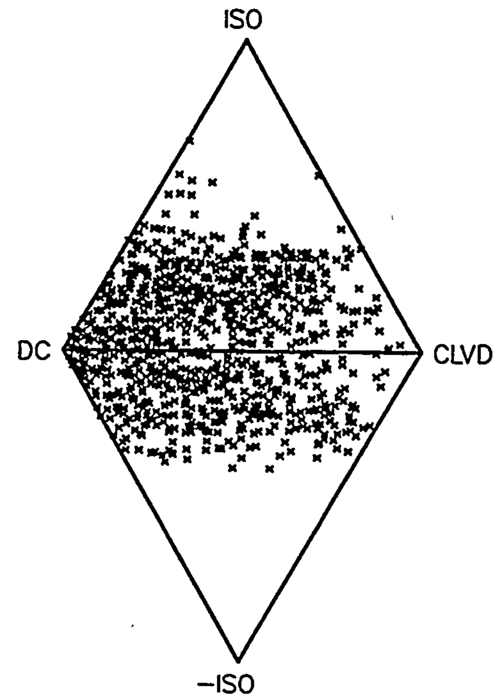

Figure 5. Ternary diagram showing decomposition of the 985 event moment tensors into isotropic (ISO), double-couple (DC), and compensated linear vector dipole (CLVD) components. Moment tensors plotted in the upper triangle have positive isotropic components; those in the lower triangle have negative isotropic components.

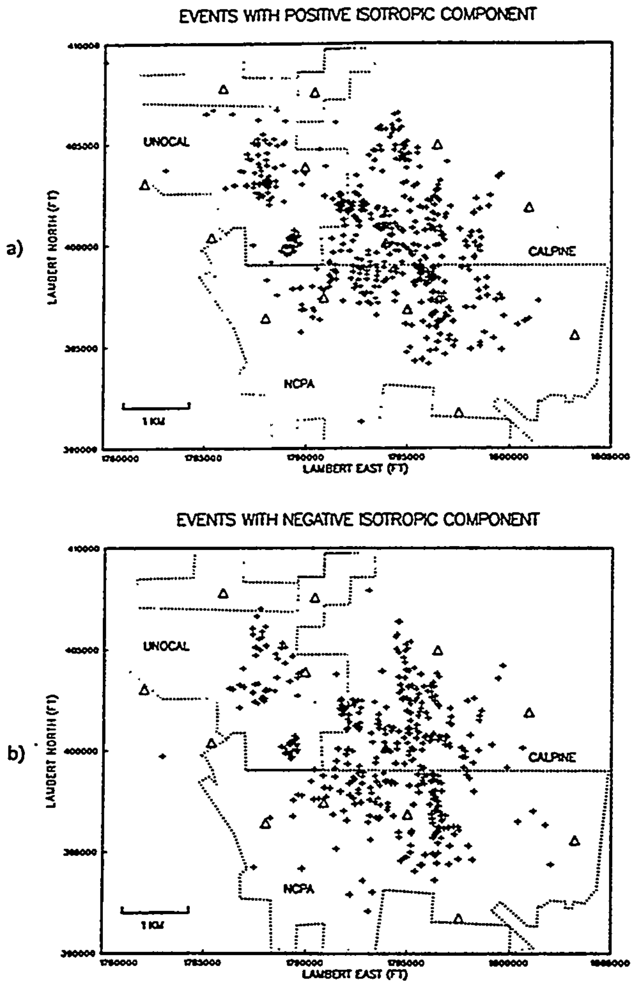

Figure 6. a) Locations of MEQs having positive isotropic moment tensor components (events plotted in upper triangle in Figure 5). b) Locations of MEQs having negative isotropic moment tensor components (events plotted in lower triangle in Figure 5).

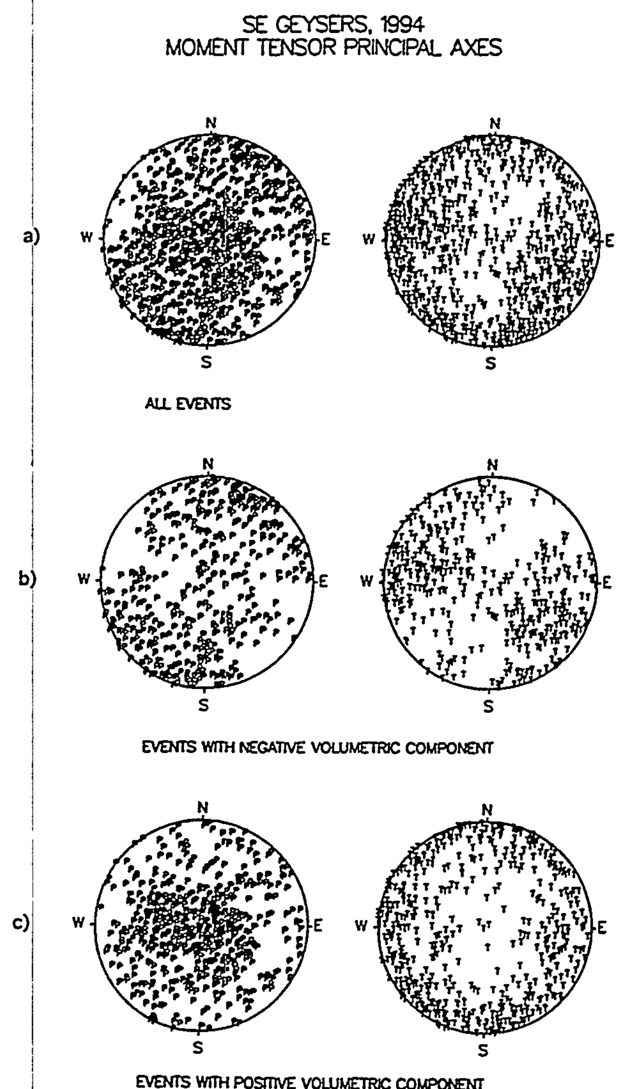

Figure 7. Moment tensor principal axes. a) All 985 events. b) The 429 events with negative isotropic moment tensor components. c) the 556 events with positive isotropic moment tensor components.

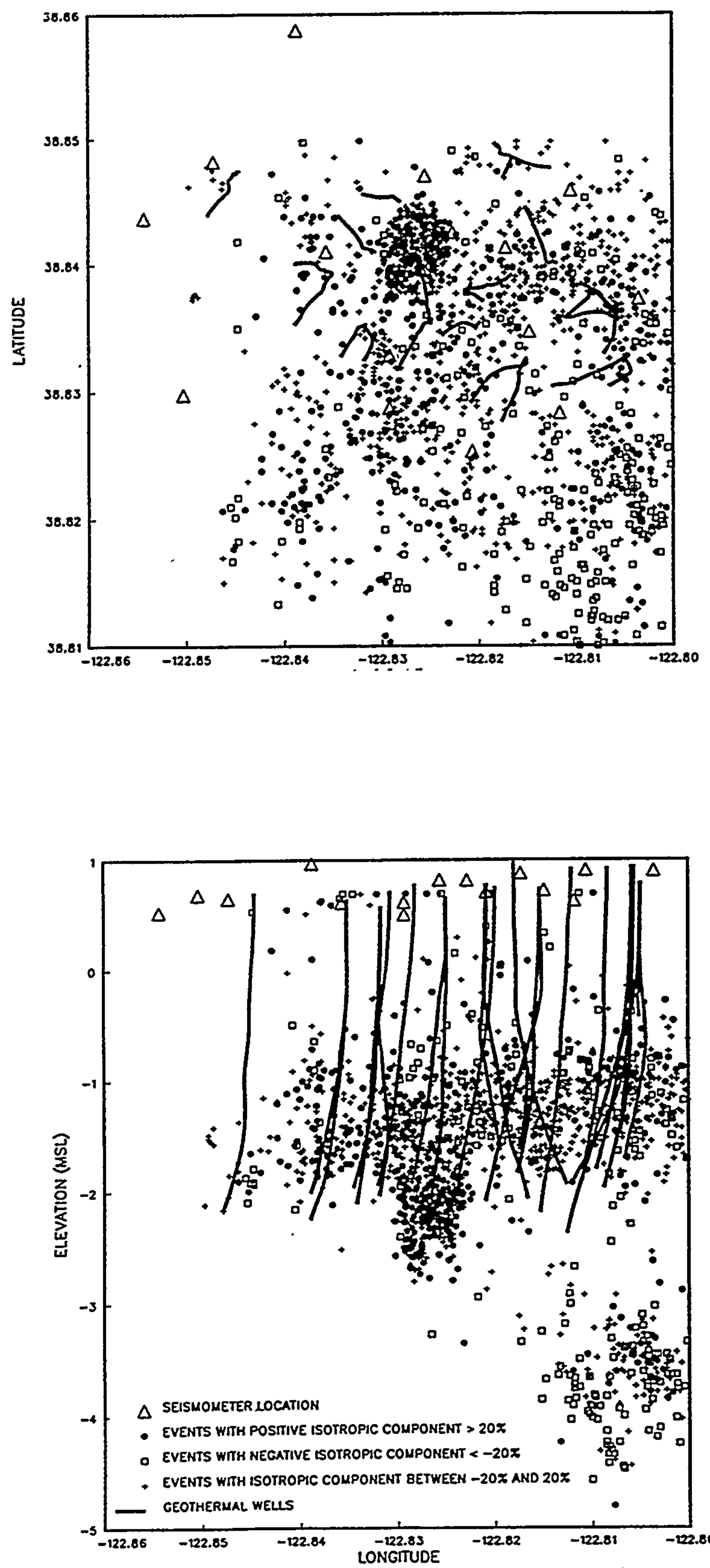

Figure 8. a) Plan view of MEQ hypocenters located by the LBL/CCPA NW Geysers seismic network in 1994. b) Hypocenters projected onto East-West plane.