NON-SHEAR FOCAL MECHANISMS OF EARTHQUAKES AT THE GEYSERS, CALIFORNIA, AND HENGILL, ICELAND, GEOTHERMAL AREAS.

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ABSTRACT

Earthquakes with anomalous focal mechanisms, produced by processes other than shear faulting, have recently been reported at many geothermal and volcanic areas. The physical causes of these earthquakes are not yet well understood, but probably they involve tensile cracking and are closely related to fluid pressures and thermoelastic effects. Understanding non-shear earthquakes will increase our understanding of geothermal processes, and is likely to have direct application to exploration and to monitoring the effects of exploitation. This work has already led to the discovery of previously unidentified heat sources at the Hengill geothermal area, Iceland, which were later confirmed by geochemistry and drilling. In 1991, high-quality data for detailed focal-mechanism studies were collected in The Geysers and the Hengill geothermal areas by supplementing existing seismic networks with digital three-component stations. Several thousand earthquakes were recorded in each area. We report an initial investigation of the focal mechanisms based on P-wave polarities. Distortion by complicated three-dimensional crustal structure was minimized using tomographically derived three-dimensional crustal models. Events with explosive and implosive source mechanisms, suggesting cavity opening and collapse, have been tentatively identified at The Geysers. Such volumetric processes may be induced by exploitation activities that involve mass transfer, such as steam and heat removal and fluid reinjection. Further study of this phenomenon will shed light on the geometry of the fracture system and its response to exploitation. Many earthquakes from the Hengill area exhibit radiation patterns that clearly are non-shear, with large explosive deviatoric components, confirming earlier findings (e.g. Foulger and Long, 1984). The new data show that some of these events do not fit the model of tensile cracking accompanied by isotropic pore pressure decreases that was suggested in earlier studies, but that they may instead involve combination of explosive and shear processes. However, the confirmation of earthquakes dominated by explosive components supports the model that the events are caused by crack opening induced by thermal contraction of the heat source.

INTRODUCTION

Most earthquakes are caused by shear slip on faults. Such earthquakes are said to have "double-couple" source mechanisms, because the seismic waves and deformation field of a shear fault are identical to those produced by a pair of force couples. As seismic networks have improved, however, many earthquakes have been found whose data are inconsistent with double-couple interpretations and difficult to dismiss as effects of observational error. These data provide evidence that many earthquakes involve non-shear source processes. Examples range from large earthquakes hundreds of kilometers deep to near-surface microearthquakes, and involve a variety of data types and analysis methods.

Many reported non-shear earthquakes occur at geothermal and volcanic areas, for example the Hengill and Krafla geothermal areas, Iceland (Foulger, 1988b; Arnott, 1990), Miyakejima volcano, Japan (Shimizu et al., 1987) and the Kilauca Iki lava lake (Chouet, 1979). The radiation patterns of many of these events have isotropic components, which require volume changes at the sources. Suggested physical explanations for these include crack opening in the presence of restricted pore-fluid flow, crack opening or closing accompanying shear faulting, and cavity collapse. Understanding non-shear earthquakes is likely to shed light on geothermal processes and to find application in geothermal exploration and in monitoring the effects of exploitation.

Earthquake focal mechanisms are usually derived from the polarities of first motions observed on seismograms. These data are analyzed by projecting rays back to a small imaginary sphere centered at the earthquake focus. The distribution of polarities on this "focal sphere" is diagnostic of the equivalent force system. For shear sources, compressional (outward-directed) and dilatational (inward-directed) polarities occupy quadrantal fields of the focal sphere that are separated by two orthogonal planes. These are candidate fault planes, and slip directions may be deduced for each of them, as well as the approximate orientations of the axes of principal stress.

In this paper, we present preliminary analyses of recently obtained high-quality data from earthquakes at The Geysers, California, and the Hengill geothermal area, Iceland. Hengill is the richest known source of non-shear earthquakes. The Geysers, on the other hand, is not known to produce non-shear earthquakes, although it is a geothermal area of exceptionally high seismic activity.

The Geysers is a dry-steam field under intensive exploitation, from which 10^7 - 10^8 tons of steam currently are extracted per year (Oppenheimer, 1986). The removal of steam and reinjection of condensate induce tens of thousands of small earthquakes per year (e.g. Oppenheimer, 1986; Stark, 1992). Suggested induction mechanisms include stress perturbations caused by mass injection and withdrawal (Majer and McEvilly, 1979), thermal contraction due to cooling (Denlinger et al., 1981), a transition from aseismic to stick-slip deformation (Allis, 1982) and reduction in effective normal stress due to injection (Stark, 1992).

Several earthquake-mechanism studies have been made. Early studies used relatively sparse networks (e.g. Hamilton and Muffler, 1972; Majer and McEvilly, 1979). A later, more detailed study used data from the U. S. Geological Survey's northern California seismograph network, supplemented by temporary stations, and analyzed P-wave polarities for 210 earthquakes, each with at least 15 observations (Oppenheimer, 1986). The mechanisms were constrained to be double couples, and strike-slip or normal-faulting mechanisms were obtained for most events, with some reverse-faulting mechanisms in the upper 1 km. It was concluded that the earthquakes occurs on rather randomly orientated fault planes in response to a stress field orientated similarly to the regional one. The results cannot determine which of the proposed earthquake-induction mechanisms (if any) is correct.

Double-couple models fit most of the events studied by Oppenheimer (1986), and non-shear source mechanisms were not considered. However, compressional polarities are more numerous than dilatational polarities (about 55% and 45% of the arrivals, respectively), and some of the double-couple interpretations require either that almost all of the unsampled part of the focal sphere be dilatational (e.g. events 65 and 75) or that compressional observations lie within the dilatational quadrants (e.g. events 7, 14 and 98). A few events appear to be dominantly dilatational (e.g. events 27, 91 and 191). Waveform modeling to determine the variation with time of the moment tensors of three small earthquakes revealed relatively large non-shear components in two of them (O'Connell and Johnson, 1988).

The dominance of compressions over dilatational arrivals can be explained if many events have normal-faulting mechanisms and the polar regions of the focal spheres are poorly sampled. However, the data hint that non-shear source mechanism components might exist for some events and justify studies with higher-quality data. Because of the large volumes of fluid being removed and reinjected in The Geysers and the large heat withdrawal, it is possible that non-shear, volumetric failure might occur. Detection of this phenomenon could cast light on the earthquake-induction process.

The Hengill area, Iceland, contains an extensive two-phase geothermal system associated with a young volcanic complex. Modest exploitation recently commenced in a small region of the geothermal area, where approximately 30 wells have been drilled and a 30 MW electricity generating plant has been built. Continuous natural seismicity, unassociated with exploitation, occurs over the entire geothermal area and is thought to result from natural heat loss (Foulger and Long, 1984), which is about 350 MW (Bodvarsson, 1951).

A detailed seismological study at Hengill in 1981 yielded P-wave polarity distributions for 178 earthquakes (Foulger, 1988a). Approximately 50% of the events are consistent with double-couple source models involving normal and strike-slip faulting consistent with the orientation of the regional deviatoric stress. Compressional arrivals dominate the focal spheres of the remaining 50% of events and shear interpretations are impossible for them. It was proposed that these events result from tensile cracking in the heat source of the geothermal area cause by thermal contraction as heat is removed by circulating ground water (Foulger and Long, 1984; Foulger, 1988b). This model also explains the continuous, small-magnitude nature of the activity and its close spatial correlation with the geothermal area. It also implies that the seismically active volumes are cooling heat sources, and led to the realisation that the geothermal area is fed by more than one heat source. This finding was later confirmed by geochemistry and drilling. Like the double-couple events, the tensile-crack events are orientated consistently with the regional stress field.

In 1991, existing permanent networks at The Geysers and the Hengill geothermal areas were temporarily augmented with three-component digital seismic stations (Julian and Foulger, 1992a, b). High-quality data sets were collected for thousands of earthquakes in each area, and we present here preliminary focal mechanisms obtained using P-wave polarity data from a few well constrained events. In the case of The Geysers, both predominately explosive and implosive earthquake radiation patterns are tentatively identified. For the Hengill events, we confirm the common occurrence of events with large explosive components.

THE DATA

The Geysers.

Within an area about 20 km in diameter, the UNOCAL Corporation operates a dense network of 22 radio-telemetered seismic stations (Figure 1a) and the U.S. Geological Survey operates eight stations. These permanent networks were supplemented for one month in April-May 1991 by 15 digital, three-component stations. To achieve an even distribution of stations on the focal sphere for optimal focal mechanism constraint, ray-tracing computations were performed using the best crustal model available for the area (Eberhart-Phillips and Oppenheimer, 1984) and the results were used to guide the siting of the stations. This approach was feasible because the locations of the seismically active volumes were known beforehand (Oppenheimer, 1986; USGS earthquake catalogs).

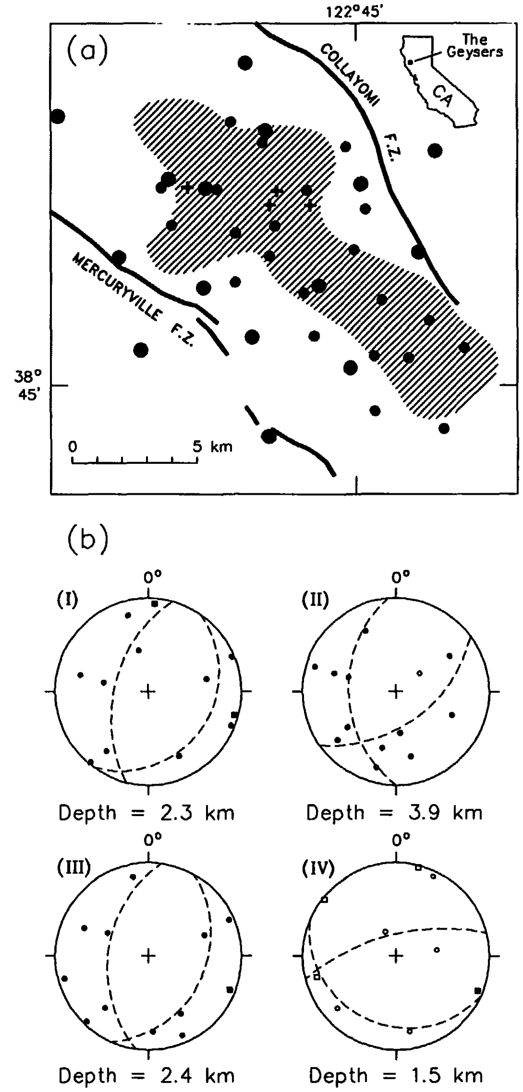

Fig. 1 a) Schematic map of The Geysers geothermal area, showing the main fault zones, the main production area (shaded) (Walters and Combs, 1991), the temporary seismometer stations deployed in April 1991 (large dots), the permanent UNOCAL stations (smaller dots) and the locations of the earthquakes whose focal mechanisms are shown in (b) (crosses).
b) P-wave polarities for four events, shown in equal-area upper-hemisphere projection. Solid symbols: compressions. Open symbols: dilatations. Circles: upper-hemisphere rays. Squares: lower-hemisphere rays. Nodal lines corresponding to the best fit double couple interpretations are dashed. None of these events can be interpreted as shear sources without violations. Locations are indicated in (a).

Data were sampled at a rate of 100 Hz and recorded continuously to avoid data loss resulting from distant stations failing to trigger. Instrumental polarities were verified using signals from a regional earthquake. High-quality recordings of more than 3900 earthquakes were acquired on up to 37 stations.

The Hengill area.

A similar but larger-scale experiment was conducted in the Hengill area, Iceland, July-September 1991 (Figure 2a). Thirty three-component stations were operated for two months. We traced rays through a three-dimensional P-wave velocity structure for the area obtained in an earlier

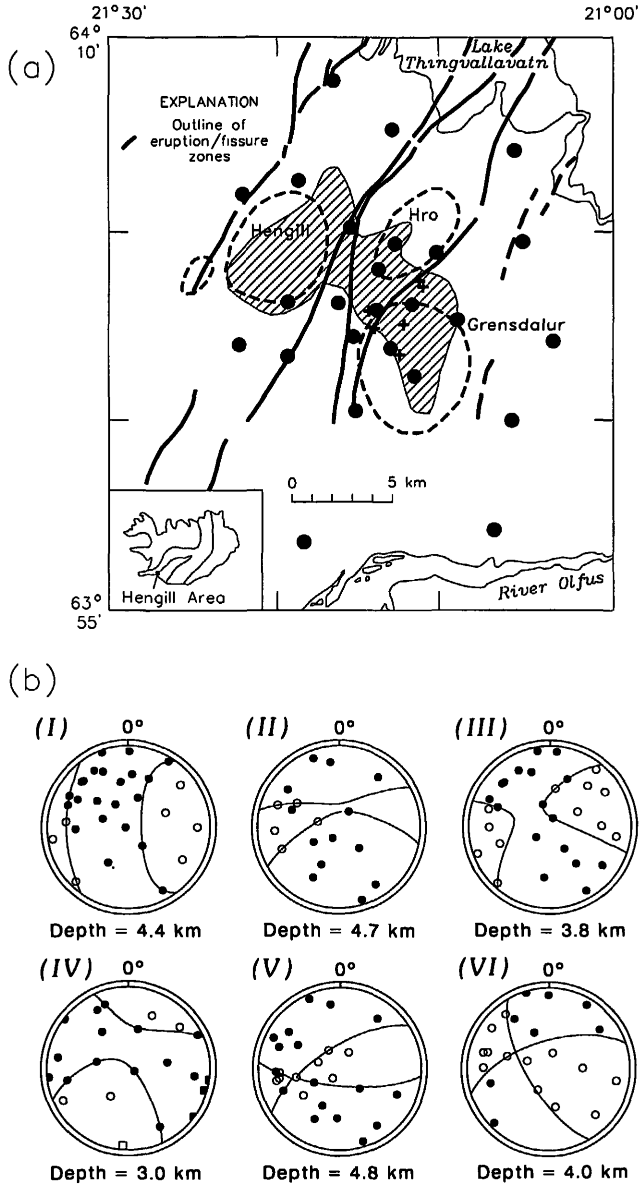

Fig. 2 a) Schematic tectonic map of the Hengill area showing the outlines of the Hengill, Grensdalur and Hromundartindur (Hro) volcanic systems, the temporary and permanent seismometer stations (black dots) and the locations of the earthquakes whose focal mechanisms are shown in (b) (crosses).
b) P-wave polarity plots for six well constrained events. Projections and conventions as in Figure 1(b). Events (i) - (v) cannot be explained as shear (double-couple) sources without substantial violations. The nodal curves shown for events (i), (iii) and (iv) correspond to maximally implosive interpretations, are illustrative, and are not unique fits to the data. Nodal curves shown for events (ii) and (v) fit data in an optimal sense but still have minor misfits. Event (vi) can be interpreted as a shear event and the nodal lines that correspond to that interpretation are shown. Locations are indicated in (a).

tomographic study (Toomey and Foulger, 1989), and used the results along with knowledge of the locations of the most seismically active areas (Foulger, 1988a) to site the seismic stations to achieve uniform coverage of the upper focal hemisphere. A 25-kg explosion in a lake near the center of the network was used to verify instrument polarities. Excellent recordings of more than 3700 small earthquakes were obtained.

P-WAVE POLARITY DISTRIBUTIONS

P-wave polarities were mapped onto the upper focal hemisphere to study focal mechanisms. Downward-departing rays were plotted at the antipodal points, because theoretical polarity distributions are symmetric with respect to inversion through the center of the focal sphere. Impulsive polarities only were used, and these and the arrival times used for locations were measured by hand.

Inaccuracies in the crustal model used in constructing P-wave first motion plots distort the apparent radiation field, since they lead to incorrect azimuths and take-off angles being calculated for the rays. This incorrect mapping of observations onto the focal sphere arises both from hypocentral mislocation and from the effects of refraction in a laterally inhomogeneous crustal structure (Foulger and Julian, 1993).

We minimized errors from these two sources using the method of Foulger and Julian (1993). The earthquakes were located using the three-dimensional P-wave velocity structure derived from tomographic analyses (Toomey and Foulger, 1989; Julian et al., this volume). Rays were then traced from these refined hypocentral locations to obtain improved estimates of take-off angles and azimuths. This was done using the bending method of Julian and Gubbins (1977), in which an initial path is perturbed until it satisfies Fermat's principle of stationary time.

Differences in the focal-sphere positions of rays computed using one-dimensional and three-dimensional crustal models are in general small and in only a few cases reach 20°. The effects of refraction in laterally varying structures usually amount to only a few degrees, because ray paths are short. Changes in inferred hypocentral depths produce larger and more systematic differences. Decreasing depth causes decreases in computed takeoff angles (moves points toward nadir on the focal sphere). For upgoing rays, this moves data points toward the perimeter of the upper focal hemisphere, and usually degrades their ability to resolve focal mechanisms. Conversely, increasing depth usually improves resolution. Thus the accuracy of the estimated hypocentral depth strongly influences the fidelity of the inferred radiation field. This fact should be borne in mind when investigating earthquake focal mechanisms.

We interpret the polarity distributions conservatively, and contemplate non-shear source mechanisms only if double-couple solutions cannot fit the observations without relatively severe violations. In practice, this means that numerous polarities and good network geometry with respect to earthquake hypocenters are needed to detect non-shear mechanisms, since unsampled areas of the focal spheres may be assigned either polarity. Because of this cautious policy, the evidence presented here for non-shear source components is the minimum allowed by the data.

RESULTS

The Geysers.

We present only data collected on our temporary network in this paper, because the polarities of the USGS and UNOCAL instruments are less certain and because their frequency responses are different. The best focal sphere coverage was achieved for events centrally located within our network.

Of the events with good focal sphere coverage, many cannot be interpreted as shear sources without violations. The four best such events are illustrated in Figure 1b, along with nodal planes for the the best double-couple interpretations that can be made. For two of these events (Figure 1b(i) and (iii)), all the arrivals are compressional and the largest unconstrained region comprises less than 50% of the focal sphere. A single dilatational arrival was measured for the event illustrated in Figure 1b(ii), but the more numerous compressional arrivals still occupy more than 50% of the focal hemisphere. These three events were located at depths of 2.3-3.9 km, which are fairly typical for earthquakes in The Geysers.

A few events with predominately dilatational arrivals were recorded, and a well-constrained event of this kind is illustrated in Figure 1b(iv). The calculated hypocentral depth is 1.5 km, making this a relatively shallow event for the area.

The Hengill area.

Our network achieves excellent constraint of P-wave polarity fields for earthquakes in the center of the geothermal area. Many events have polarity distributions that cannot be interpreted as shear sources, and for all of these events, the compressional fields of the focal spheres are larger than the dilatational fields (Figures 2b(i)-(v)). The dilatational fields are constrained by several arrivals, and occupy minor parts of the focal spheres. No well constrained events that are predominately dilatational were found. The computed hypocentral depths lie in the range from 3.0 to 4.8 km.

Nodal curves computed by the linear-programming method (Julian, 1986) are shown in Figure 2b(i)-(v) for those earthquakes that cannot be interpreted as shear. These curves are not uniquely determined, but illustrate some of the polarity patterns that are possible. For Figures 2b(i), (iii) and (iv) the maximally dilatational solutions are shown. For Figures 2b(ii) and (v) some violation of the data is necessary and the curves shown are those that minimise the misfit.

Some well constrained events can be interpreted as having shear source mechanisms. An example is the event shown in Figure 2b(vi), whose hypocentral depth was 4.0 km.

DISCUSSION

The Geysers.

The fact that the compressional fields are larger than the maximum possible dilatational ones for the events shown in Figure 1b(i)-(iii) suggests isotropic explosive components in the source mechanisms. Similarly, the large dilatational field illustrated in Figure 1b(iv) suggests that the source mechanism of this event has an isotropic implosive component, which may result from cavity collapse.

These results suggest that earthquakes with non-shear source mechanisms occur at The Geysers. Because large numbers of events with very dense focal sphere coverage have not yet been studied, however, and because the crustal model is preliminary, the evidence for non-shear earthquakes at The Geysers remains tentative. Future work will provide more detailed and accurate crustal models and the inclusion of data from the UNOCAL and USGS will improve focal-sphere coverage, giving us more confidence in the identification of non-shear focal mechanisms.

Most of our non-DC earthquakes have first motions dominantly of one polarity, indicating volume changes at the sources. Most of these events have explosive mechanisms, indicating cavity opening, and a few have net implosive mechanisms, indicating cavity closure. If the events in Figure 1b were constrained to have double-couple interpretations, some violations would occur, the explosive events would be interpreted as normal faulting and the implosive event (Figure 1b(iv)) as thrust faulting at shallow depth. It is not yet fully understood how cavities can exist beneath overburdens of kilometers of rock, as volumetric earthquakes imply. However, explosive and implosive mechanisms have now been demonstrated for earthquakes from many geothermal and volcanic areas, (e.g. Shimizu et al., 1982; Shimizu, 1988; Foulger and Long, 1984; Foulger, 1988b; Foulger et al., 1989; Arnott, 1990; Arnott and Foulger, 1993). The Geysers is a likely place for such earthquakes, because large volumes of steam are being extracted from the reservoir, condensate is being reinjected, and large amounts of heat are being removed also. Sudden cavity opening at depth might result from increased extensional stress caused by thermal contraction of the rock matrix (Foulger and Long, 1985) or from local increases in pore pressure, caused, for example, by the flashing of superheated water or by fluid injection. Cavity collapse might result from fluid pressure decreases within preexisting cavities, (resulting, for example, from the extraction of steam) or from increases in pressure adjacent to cavities (e.g. from fluid injection). In a low-pressure system such as The Geysers, large cavities probably cannot exist under overburdens of several kilometers of rock, and events of these kinds are probably limited to small magnitudes and shallow depths.

The modest evidence for non-shear earthquake focal mechanisms at The Geysers provides impetus for continued study of this phenomenon. Confirmation of volumetric failure and investigation of the spatial distribution of different types of events and the dependence of mechanisms on magnitude and induction process (e.g. steam withdrawal, injection) could improve our understanding of exploitation-induced reservoir processes.

The Hengill area.

Dominantly compressive polarity distributions of earthquakes at the Hengill geothermal field indicates explosive components in the source mechanisms and confirms earlier findings (Foulger and Long, 1984; Foulger, 1988b; Foulger and Julian, 1993). Better coverage of the focal sphere was achieved in the 1991 experiment than in earlier ones (Foulger and Long, 1984) because more stations were deployed and the network design was improved using the results of earlier work (Julian and Foulger, 1992b). As a result, the dilatational fields of the non-shear events are constrained by several arrivals instead of just one or two.

Tensile-crack or explosion source models form the basis of most interpretations of dominantly compressional earthquake radiation patterns. Such models predict entirely compressional first motions, however, and therefore some additional effect is required to explain the observation of dilatational arrivals. Foulger and Long (1984) suggested for the Hengill events that restricted pore-fluid flow causes a pressure drop at the source and results in a small isotropic dilatational component being superimposed on the field of the tensile crack. This would result in a mechanism with nodal lines that are small circles, with the dilatational field occupying the band between them. Foulger and Long (1984) and Foulger (1988b) interpreted many of their non-shear earthquakes in this way, though not all of the events fit that model.

Most of the events studied here clearly do not fit this model. For the earthquakes shown in Figures 2b(i), (iii) and (iv) it is the dilatational fields that occupy two separate areas of the focal spheres, and the compressional fields that consist of continuous bands. These events would fit better a model involving a combination of a tensile crack and a shear fault. Such a mechanism has been invoked to explain some Japanese volcanic earthquakes (Shimizu et al., 1987). The events illustrated in Figures 2b(ii) and (v) can be made to fit the model of Foulger and Long (1984) best.

The polarity data alone do not tightly constrain the nodes shown in Figure 2b, and the particular curves we have chosen to draw are illustrative only. Until more quantitative constraints (for example based on wave amplitudes) are available, interpretation of the source mechanisms remains qualitative. However, this analysis confirms the large compressional isotropic components that were the basis for the hypothesis that many earthquakes at Hengill are caused by thermal contraction in the heat source (Foulger and Long, 1984; Foulger, 1988b).

Comparison of The Geysers and Hengill geothermal earthquakes.

At present, earthquakes from The Geysers are less well constrained than those from the Hengill area, and this difference may distort a comparison. Nevertheless, an initial comparison of the non-shear events in the two areas is attempted below:

The Geysers	Hengill
Moderate focal sphere coverage.	Good focal sphere coverage.
Activity production induced.	Activity natural.
Shear, explosive and implosive events.	Shear and explosive events only.
Dilatational arrivals rare for explosive events.	Dilatational arrivals cover substantial areas of the focal spheres of explosive events.
Depth of explosive events 2.3-3.9 km.	Depth of explosive events 3.0-4.8 km.
~10-20% of events may be non-shear.	~50% of events may be non-shear.

CONCLUSIONS

This study.

1. Available data suggest tentatively that non-shear earthquakes with both explosive and implosive source mechanisms occur at The Geysers.
2. These events apparently involve both cavity opening and closure, which may be induced by processes such as mass removal, cooling, and fluid injection.
3. Such events are likely to oe confined to small magnitudes and shallow depths.
4. Further analysis of existing data will cast light on the earthquake induction process at The Geysers.
5. High-quality data obtained in 1991 confirm that non-shear earthquakes with explosive components occur at the Hengill geothermal area, Iceland.
6. Improved resolution of the radiation patterns at Hengill weakens the case for the dilatational fields being generated by isotropic pore pressure decreases, as suggested by Foulger and Long (1984). However, tensile cracking caused by thermal contraction at the heat source remains the most likely explanation for the non-shear source components.

Future Work.

We present here early results for a few events from The Geysers and the Hengill area based on P-wave polarities only. Incorporation of information from the UNOCAL and USGS networks will greatly improve our data set from The Geysers. The quality and large sizes of the data sets will enable many more events to be studied in greater detail and using more sophisticated analysis methods based on S-wave polarizations and P- and S-wave amplitudes and waveforms. Analyses of this kind will yield better estimates of the moment tensors with associated confidence limits, compared to interpretations obtainable using P-wave polarities only. In the case of The Geysers, this work will address questions about the amount of non-shear seismic deformation and its nature. As has already been demonstrated in the case of the Hengill area, this work may clarify the earthquake-generation process at The Geysers and enable us to seek variations in the injection- and extraction-induced activity, as well as spatial variations in reservoir response to exploitation. Continued study of the focal mechanisms of the Hengill earthquakes will refine our understanding of these rare, natural, non-shear earthquakes. This work as a whole may lead to methodological developments that will enable geothermal seismicity to be monitored with sparser and less expensive seismometer networks than is possible with current analysis techniques.

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