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HIGH-RESOLUTION SEISMIC STUDIES APPLIED TO INJECTED GEOTHERMAL FLUIDS

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ABSTRACT

The application of high-resolution microseismicity studies to the problem of monitoring injected fluids is one component of the Geothermal Injection Monitoring Project at LLNL. The evaluation of microseismicity includes the development of field techniques, and the acquisition and processing of events during the initial development of a geothermal field. To achieve a specific detection threshold and location precision, design criteria are presented for seismic networks. An analysis of a small swarm near Mammoth Lakes, California, demonstrates these relationships and the usefulness of high-resolution seismic studies. A small network is currently monitoring the Mammoth-Pacific geothermal power plant at Casa Diablo as it begins production.

INTRODUCTION

The objective of the Lawrence Livermore National Laboratory Geothermal Injection Monitoring Project (GIMP) is to evaluate the use of geophysical techniques to monitor the movement of brine injected into geothermal systems. This project deals with questions such as: What anomalies would be produced by different assumed injection scenarios? What geophysical techniques would be sensitive to these anomalies and what are the present deficiencies of those methods? Can systems with the appropriate sensitivity be developed and demonstrated? Do the anticipated anomalies actually occur and can they be analyzed to learn useful information about the movement of injected fluid? Four methods are being evaluated by the project: 1. Response of Wellbores to Earth Tides, 2. Cross-borehole electrical measurements, 3. Detection of Microseismicity associated with injection, and 4. Self Potential Methods. The application of high-resolution microseismicity studies to the problem of monitoring injected fluids is discussed in this paper.

MICROSEISMICITY STUDIES

Microseismicity has long been associated with geothermal reservoirs. Early studies considered the spatial relationship of microearthquakes to geothermal regions (Lange and Westphal, 1969; Ward and Bjornsson, 1971; Ward, 1972). These studies depend on microseismicity delineating the faults that may act as conduits for hot fluids or steam, or suggesting zones weakened by geothermal activity. Microseismicity may also provide a technique to map the pressure front resulting from brine reinjection. This approach would depend on locating and evaluating discrete seismic events associated with the injection of fluids (Bufe, et al., 1981; Denlinger and Bufe, 1982). At the Los Alamos National Laboratory Hot Dry Rock site, injection-produced seismicity has been mapped with a variety of surface and down-hole sensors (Murphy and Fehler, 1984). We are evaluating the possibility of using microseismicity detected by a surface array to help track the migration of reinjected fluids in geothermal areas.

Our evaluation of microseismicity has two components: Development of field techniques for the detection, location, and characterization of microseismicity near magnitude zero; and the acquisition and processing of events during the initial development of a geothermal field. The Long Valley Caldera in eastern California provides a suitable region for this development and evaluation. A high rate of natural seismicity within localized, shallow swarms allows development of the seismic methodology. Development of a binary geothermal power plant at Casa Diablo Hot Springs by Mammoth-Pacific provides the opportunity to monitor reinjection before and during its operation.

To develop and demonstrate our capability of detection and location of very small seismic events, and to validate our designs of seismic networks, a seismic field test studied a region of swarm activity within the Long Valley Caldera in California. This is a region of high natural seismiaity between 2 and 9 km depth, strong temporal and spatial

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swarming, and probable association with either hydrothermal fluids or magmatic activity. Many events were expected from magnitude 0 to 1; consequently, the seismic network was designed with the intent to detect and locate these events and to constrain their source parameters. The network shown in Figure 1 contained 14 seismic stations with spacing between sites as small as 0.5 km. Ten sites used three-component seismometers, and all sites used digital event recorders sampling at 200 **samples/s** with an array trigger criterion to reject local noise and to ensure accurate relative timing. Finally, a simultaneous inversion for hypocentral location, velocity structure, and station corrections reducaa the relative location error to approximately 20 meters. Each of these elements in the deployment and analysis is essential to retain both the network sensitivity and location accuracy. Figure 2 illustrates the epicentral locations of a small swarm near Mammoth Lakes. The location accuracy allows delineation of a plane of seismicity, while focal mechanisms for one small event suggests that the plane of seismicity lies normal to the minimal stress axis. The depth section in Figure 3

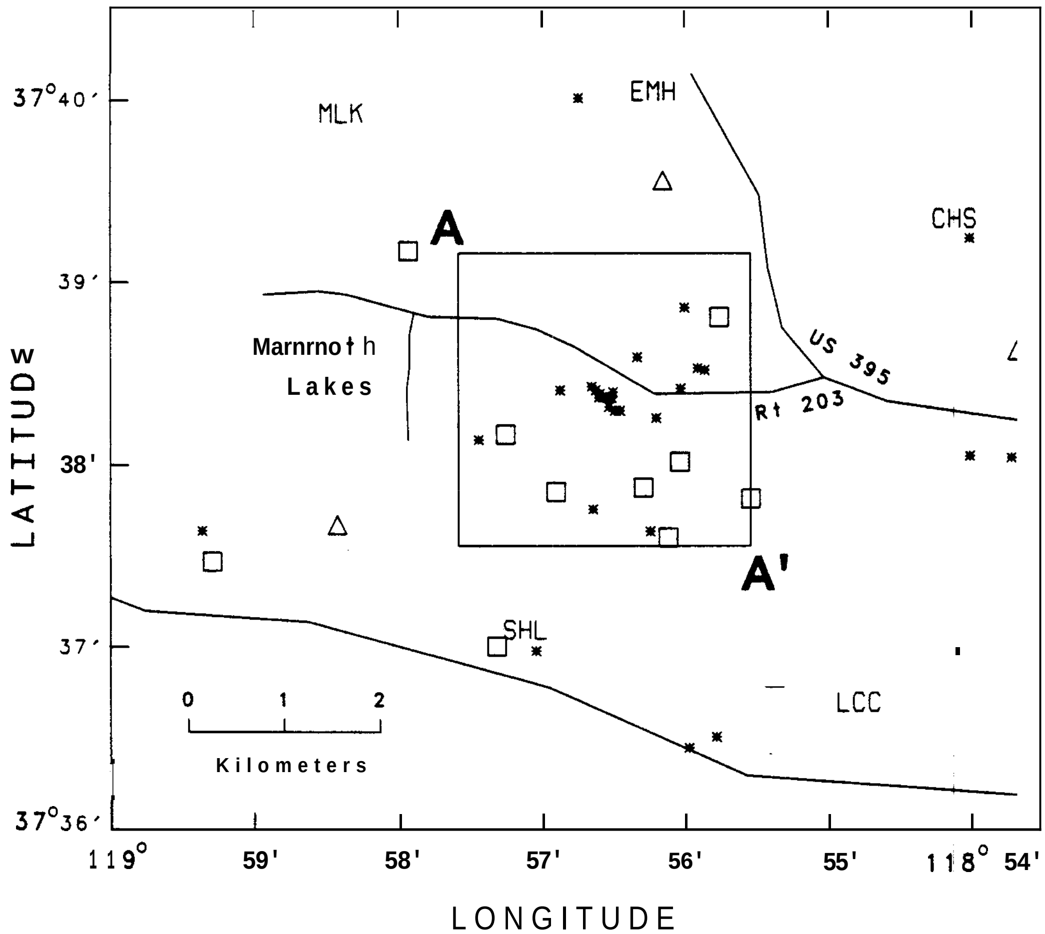

Figure 1. Map of the Mammoth Lakes-Long Valley region in Eastern California showing the epicenters and seismic stations used in the microearthquake survey. The map covers a region approximately 9 km square and includes the principal highways and the town of Mammoth Lakes. The line extending east-west across the plot represents the southern boundary of the Long Valley Caldera.

Three-component, digital stations are shown by squares. Single component, vertical stations installed by Lawrence Berkeley Laboratory are denoted by triangles. All these stations use 4.5 Hz seismometers except one which uses a 2 Hz seismometer. The central station in the network also includes a 1 Hz three-component seismometer and a forced-balanced accelerometer. The nearest University of Nevada, Reno, and USGS stations used for the first motion studies are SHL, EMH, CHS, LCC and MLK.

Epicenters of earthquakes used in the microseismicity survey are indicated by asterisks. A swarm on August 9, 1982, is apparent as a cluster of events near the center of the map. The box near the center indicates the region covered by Figure 2, while the depth sections in Figure 3 extend from A to A'.

further clarifies this interpretation. In a region geothermal fluid injection, this type of information would help delineate fractures which act as paths for fluid migration.

To assess the occurrence of microseismicity during injection at a geothermal power plant; we have deployed a small digital network around the injection wells of Mammoth-Pacific at Casa Diablo. A network of three vertical and one three-component seismometer are recorded at 100 samples/s using an event trigger. The stations are separated by 450 meters since reinjection occwrs at a depth of·500· meters. The background seismicity prior to production will be Uompared to the initial and later production phase of the power plant.

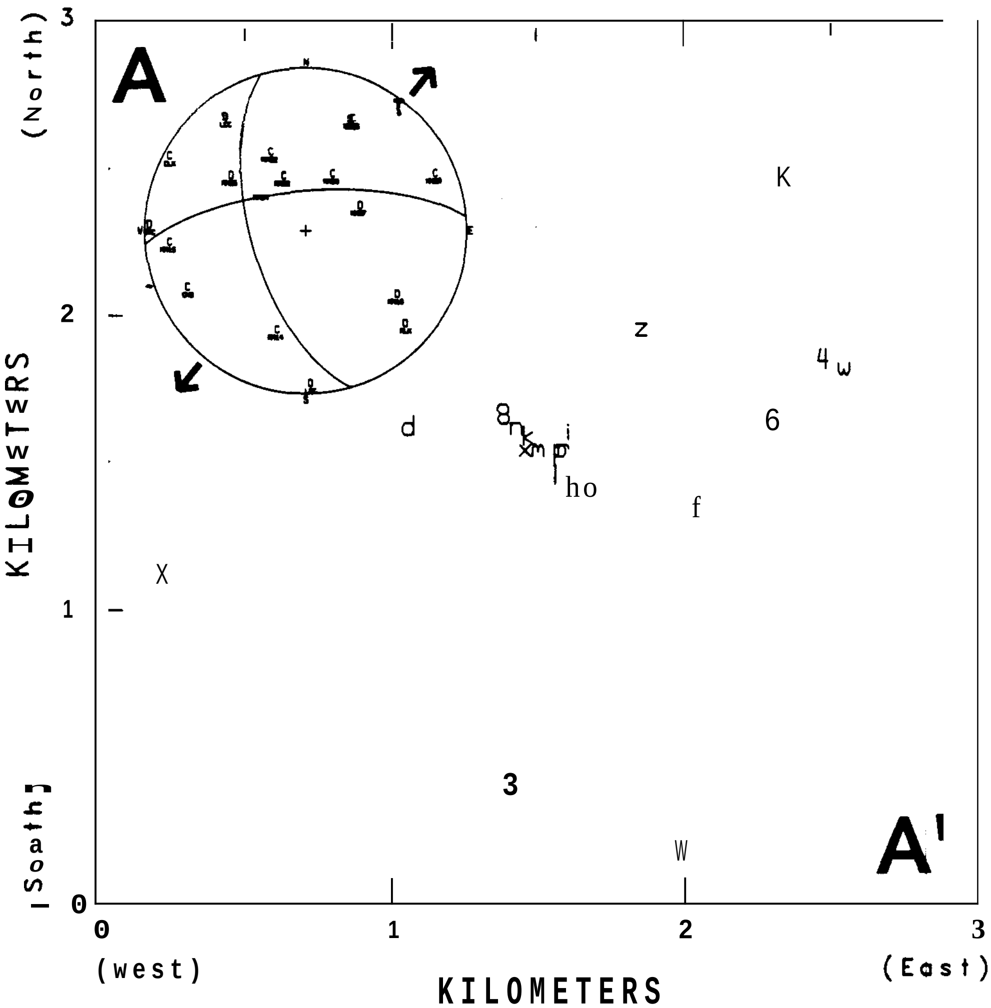

Figure 2. Expanded view of the swarm region on August 9, 1982. The map covers a 3 kilometer square as shown in Figure 1.

The epicenters are indicated by letters representing their order of occurrence: A through Z, a through z, and 0 to 9. Events h 'through r occurred during a three hour period starting at 0500. These events define a segment of a vertical plane oriented from A to A'. The maximum coda magnitude for these events was 1.5.

The focal mechanism for event k within the swarm is plotted in the upper left. First motions are plotted on a lawer hemisphere where C indicates compression and D represents dilatation. The plot combines the digital stations and UNR/USGS stations. A, double couple mechanism is plotted suggesting that the least compressive axis, T, is well constrained. A compensated linear vector dipole would also give an azimuth of approximately N30E for the T axis. The shallow events j, 1, m, and p, plus the deeper event x are also consistent with this mechanism, although not as well constrained. The deeper event 6, however, has a component of reverse slip.

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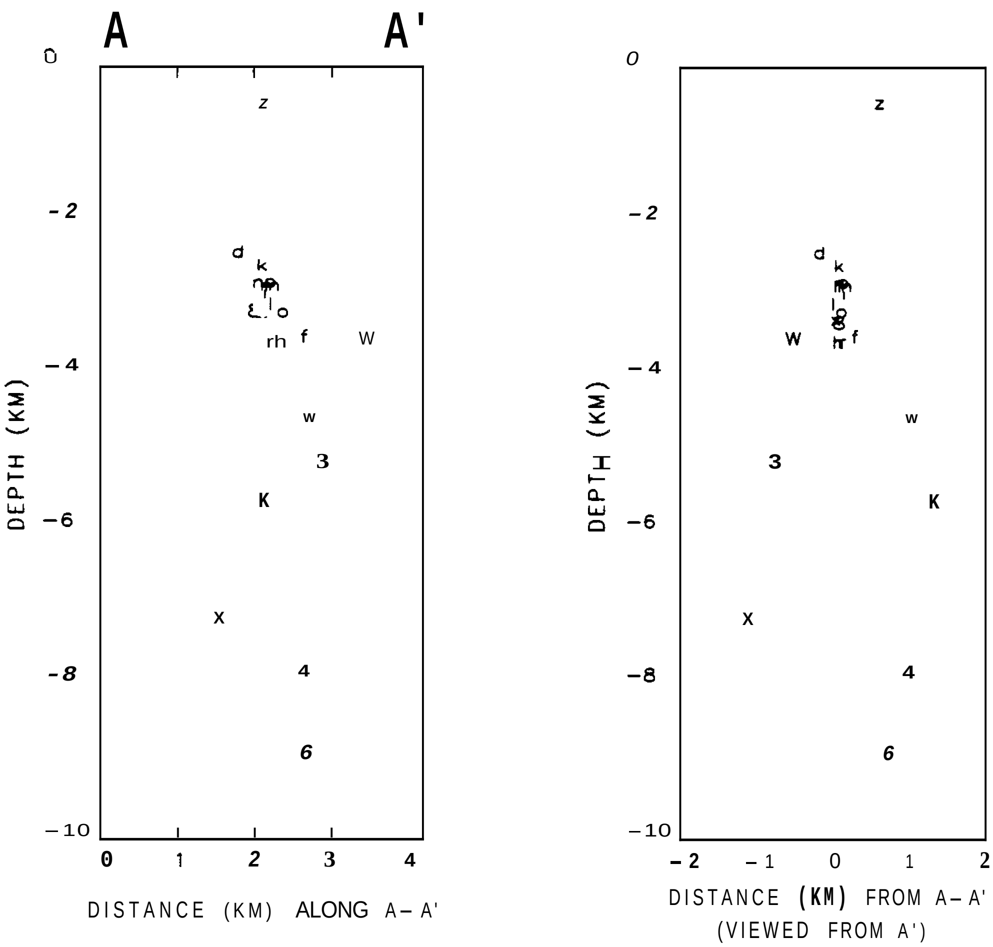

Figure 3. Depth sections from A to A' and perpendicular to A-A' in Figures 1 and 2. The hypocenters use the same symbols as Figure 2 and no exaggeration is used in the plots. The plot on the left Shows a depth section along the trend of seismicity, A to A'. The swarm now appears between depths of 2.5 to 3.5 km.