Title: DOWNHOLE SEISMIC MONITORING AT THE GEYSERS

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**Abstract**

A 500-ft length, 6-level, 3-component, vertical geophone array was permanently deployed within the upper 800 ft of Unocal's well GDCF 63-29 during a plug and abandonment operation on April 7, 1998 (Figure 1). The downhole array remains operational after a period of 1 year, at a temperature of about 150° C. Continuous monitoring and analysis of shallow seismicity (< 4000 ft deep) has been conducted over that same 1-year period. The downhole array was supplemented with 4 surface stations in late-1998 and early-1999 to help constrain locations of shallow seismicity. Locations occurring within about 1 km (~3000 ft) of the array have been determined for a subset of high-frequency events detected on the downhole and surface stations for the 10-week period January 6 to March 16, 1999. These events are distinct from surface-monitored seismicity at The Geysers in that they occur predominantly above the producing reservoir, at depths ranging from about 1200 to 4000 ft depth (1450 to -1350 ft elevation). The shallow seismicity shows a northeast striking trend, similar to seismicity trends mapped deeper within the reservoir and the strike of the predominant surface lineament observed over the productive field.

**Introduction**

Production-induced seismicity at The Geysers has been documented and characterized for several years (Marks et al., 1978; Denlinger and Bufe. 1982; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986). High resolution surface seismic networks at The Geysers provide the possibilities of characterizing the reservoir by associating 1) hypocenter patterns with fluid movement (Kirkpatrick et al., 1995), 2) seismic velocity anomalies with specific lithologies, reservoir processes and saturation levels (Romero et al. 1995; Kirkpatrick et al., 1997), and 3) source characteristics with extraction/injection operations and reservoir fracture mechanics (Julian et al., 1993; Kirkpatrick et al., 1995). Downhole seismic receivers deployed as deep as 2335 ft (~1300 ft above the reservoir) at The Geysers lowered the threshold of detection by 2 to 3 orders of magnitude below the limits of surface monitoring (Albright et al., 1998). Going downhole also results in a concomitant increase in event detection for a given volume of rock and, in general, greatly improves the resolution of mapping active reservoir fractures or faults (e.g. Rutledge et al, 1998a). Further, applying relative location techniques can provide mapping precision on the order of a few meters (~10 ft), resulting in remarkable resolution of fracture geometries and temporal patterns of seismicity associated with fluid movement, as well as, allowing better constraints on focal mechanisms (e.g. Moriya et al., 1994; Phillips et al., 1996; Gaucher et al., 1998; Rutledge et al., 1998b; Phillips, 1999).

Since fractures usually dominate the contribution to permeability in geothermal reservoirs, the ability to map them at large distance from boreholes has direct applications to reservoir development and management. It is well known that the gross flow paths affected by hydraulic fracturing can be mapped using the microearthquakes induced during the treatment. Barton et al., (1995) have shown correlations of high permeability along fractures that are oriented such that resolved shear stress is high. If this is generally true, it would imply that any reservoir stress changes even weakly promoting failure on critically stressed fractures could result in seismicity that reveals important or potentially important reservoir flow paths (stress changes caused by such processes as re-injection, mass exchange, poroelastic and thermoelastic volume changes
accompanying pressure and temperature drawdown, respectively, etc.).

In this paper we present some initial mapping results from monitoring with a vertical geophone array that was cemented within the upper 800 ft of Unocal's well GDCF 63-29 in the southeast Geysers (Figure 1). The array is 500 ft long with six 3-component sondes spaced at 100 ft (Figure 2). Deployment took place on April 7, 1998 during plug and abandonment of the well; all but the middle sondes S3 and S4 remains operational after a 1-year, continuous monitoring period. Maximum temperature over the array length is 150° C. Details of the deployment and array specifications are given in Albright et al. (1998). The array sits about 3000 ft above the reservoir and is best suited for monitoring near-surface deformation. Several wellbores of the GDCF 63-29 well pad have undergone progressive wellbore collapse at about 800 ft depth; in fact, GDCF 63-29 was plugged and abandoned because of this wellbore failure. Casing collapse, as documented by successive caliper-log runs, is a problem in many wells throughout the field. Monitoring shallow microseismicity could potentially provide information on the nature of deformation affecting borehole integrity, such as, is the deformation episodic, are the collapse zones associated with shallow faults zones intersecting the wellbores, and can intersection with active, shallow faults or deformation zones be avoided?

Data

The downhole array was supplemented with four 3-component, surface-deployed geophones surrounding the GDCF 63-29 monitor well in late 1998 and early 1999. It is possible to uniquely determine source locations from a single vertical array if good azimuthal data can be obtained from the horizontal component first-arrival-particle-motion trajectories (e.g. Rutledge et al., 1998a). All events detected on the borehole array occur beneath the bottom sonde, most with steep travel paths from source to receiver. This results in low signal-to-noise ratio first arrivals on the horizontal components and, hence, unreliable azimuthal data. Adding the surface stations allowed locations to be determined using the P- and S-arrival time data alone.

The downhole receivers and three of the surface stations were equipped with OYO GS-20DM geophones (28 Hz downhole, 14 Hz at surface); the fourth surface station is a Mark Products 1-Hz, L4-3C geophone. Using existing telemetry lines in the field, surface stations were hard wired into the same PC-based data acquisition system used for the downhole receivers. Data were sampled at a 0.2 msec interval per channel. Downhole signal bandwidth above the noise floor extends from about 20 to 400 Hz.

All data collected from April 7, 1998 to March 16, 1999 have been screened to find events occurring within about 3000 ft (~ 1 km) of the array. Details of event occurrence over an 88-day period in 1998 shows that the shallowest seismicity is episodic; within about 2000 ft of the array, relatively quiescent periods of up to 3 weeks are observed between swarms of events (Figure 3). In this paper we present the locations of events detected on the borehole array and at least 3 of the surface stations from January 6 to March 16, 1999. A total of 535 events were detected within ~3000 ft of the deepest station for this 70-day period (Figure 4). An example of a high quality event recorded on downhole sonde S5 (Figure 2) is shown in Figure 5.

Microearthquake Maps

Of the 535 events, 304 with at least six arrival time identified over the full length of the downhole array and three or more arrival time picks on the surface stations were considered for mapping. We averaged the upper two layers of Kirkpatrick et al.'s (1997) southeast Geysers velocity model.
Remarkably, median P-wave velocity ($V_p$) measured across the array from three surface calibration shots was within 1% of the Kirkpatrick model average. 300 location solutions converged, of which 195 had root-mean-square travel-time residuals less than 5 msec and location errors less than 200 ft (Figure 6). P and S station corrections were iteratively applied, based on the median travel time residuals determined from two initial location runs. Arrival-time errors were then estimated from the standard deviations of the travel-time residuals, and ranged from 1 to 5 msec. The location error ellipses displayed in Figures 6 and 7 only reflect the arrival-time data errors and array geometry; velocity model uncertainties are not considered.

The map view (Figure 6) shows a gross northeast striking trend, similar to seismicity trends mapped deeper within the reservoir (e.g. Romero et al., 1995) and the strike of the predominant surface lineament observed over the productive field (Nielson and Nash, 1997). A depth view projecting the locations on to a plane orthogonal to the trend is shown in Figure 7. The shallowest steam entries in this area occur at about -1000 ft elevation. The events mapped are distinct from most surface-monitored seismicity in that they lie above the producing reservoir. Three major clusters can be seen in depth view: 1) a low-angle feature dipping approximately 30 SE and intersecting the monitor well at about 1200 ft elevation (~1500 ft deep), 2) a deep cluster just above the shallow steam entries in this area, and 3) a more vertical fault zone to the NW of the monitor well.

**Conclusions**

These initial mapping results show that shallow deformation at The Geysers can be observed as episodic seismicity above the reservoir. Our ability to detect and locate the shallow seismicity can be attributed to placing geophones downhole and deploying surface station close enough to enable common receiver detection of these low-magnitude events. Follow-on work will include applying relative mapping techniques to resolve fault-planes and, if possible, determine composite focal mechanisms associated with specific failure planes. The shallow seismicity will then be interpreted in terms of production/injection data, subsurface geology and borehole deformation that has been documented in the study area.

**References**


at The Geysers, California, and Hengill, Iceland, geothermal areas, Geothermal Resources Council Transactions, 17, 123-128.


Fig 2
Fig S
Fig 6