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Title: VERTICAL ARRAYS FOR FRACTURE MAPPING IN GEOTHERMAL SYSTEMS

CONF-980917--

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Submitted to: GRC 1998 Annual Meeting Proceedings
San Diego, CA 9/20 - 23

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Vertical Arrays for Fracture Mapping in Geothermal Systems

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Abstract

In collaboration with UNOCAL Geothermal Operations, Los Alamos National Laboratory assessed the feasibility of using vertical arrays of borehole seismic sensors for mapping of microseismicity in The Geysers geothermal field. Seismicity which arises from minute displacements along fracture or fault surfaces has been shown in studies of seismically active oil reservoirs to be useful in identifying fractures affected by and possibly contributing to production. Use of retrievable borehole seismic packages at The Geysers was found to reduce the threshold for detection of microearthquakes by an estimated 2-3 orders of magnitude in comparison to surface-based sensors. These studies led to the design, materials selection, fabrication, and installation of a permanent array of geophones intended for long term seismic monitoring and mapping of fractures in the vicinity of the array at The Geysers.

Introduction

The existence of seismicity accompanying production at The Geysers (Marks et al., 1978; Denlinger and Bufe, 1982) presents the possibility of locating reservoir fractures participating in or affected by production and injection processes. Earthquake magnitude distribution at The Geysers follows a well known trend for seismically active regions of the earth; that is, the number of earthquakes increases logarithmically with decreasing magnitude. Thus, events detected by subsurface instruments having magnitudes below the threshold for surface detection should be much more numerous than the events actually detected at the surface. In general, event magnitudes scale with earthquake source dimensions (i.e. fracture or fault rupture area) and smaller source dimensions, in turn, result in higher frequency seismic waves (Abercrombie, 1995). High frequency seismic waves carry higher resolution information concerning their point of origin and propagation paths, thus enabling imaging of discrete reservoir fracture systems (Rutledge et al., 1998). Detection of microeathquakes at the surface is limited by the smaller source energies of these microearthquakes; high surface noise levels, both natural and cultural; and, the more rapid attenuation of higher frequency energy over a given propagation path, an effect most pronounced in the weathered, near-surface rocks and soil. To gather the more numerous, high-frequency microearthquake data needed for discrete fracture imaging, seismic receivers have to be placed in the relatively quiet environment of boreholes, close to the reservoir volume of interest.

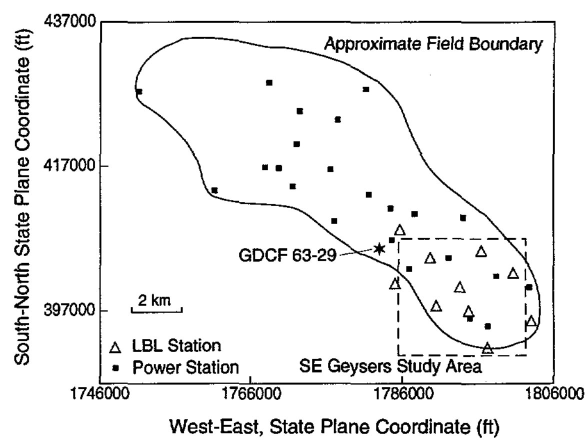

Figure 1. *Location of study location and well GDCF 63-29 at The Geysers, California.* The Lawrence Berkeley Laboratory (LBL) and the Unocal-NEC-Thermal (UNT) partnership microearthquake surface arrays are also shown. The dashed box shows the approximate area monitored by the LBL array in Kirkpatrick et al. (1995).

While existing borehole instrumentation is adequate for the acquisition of microseismic data in oil and gas reservoirs, instrumentation capable of withstanding high temperatures for long periods of time in geothermal wells is not readily available. To the best of our knowledge, the seismic instrumentation currently available is only capable of withstanding high temperatures for periods on the order of hours-to-days. These include the Los Alamos experimental packages (Dennis,

1990) and, possibly, a very few commercial geophone tools in use outside the United States. These packages and tools are suitable for monitoring reservoir microseismicity for short periods but not for the long period of time often necessary for imaging fractures. In addition, existing wireline retrievable instrumentation is generally limited in the number of levels that can be deployed and are prohibitively expensive for long-term deployment. Vertical arrays of geophones offer greatly improved ability to discriminate arriving waveforms and locate fractures. The need thus exists for low cost, expendable sensor arrays capable of operation for periods of weeks to months under geothermal conditions. Recognizing this, Los Alamos in cooperation with Petroleum Geo-Services (PGS) undertook the design, development, and permanent installation of a high temperature geophone array for use in The Geysers.

After a large data set of microseismic waveforms is obtained, the application of recently-developed methods enables high resolution identification and mapping of individual fractures and fracture networks (Phillips, et al., 1997; Rutledge et al., in press, 1998).

This paper reviews the preliminary downhole seismic measurements at The Geysers that led to the development of the permanently-installed, prototype high temperature geophone array. The objective of the downhole measurements was to quantify for an area in the southeast Geysers, the occurrence rate of microearthquakes and the nominal distance-to-fracture, or detection range, obtainable using borehole seismic instrumentation.

Borehole Seismic Measurements

An abandoned production well (GDCF 63-29) in the southeast Geysers was made available to fulfill the objectives of the study (Figure 1). Seismicity is frequently detected on a high-resolution digital surface array in an area near the well location and has been associated with production and injection operations (Kirkpatrick et al., 1995). During initial plugging and abandonment of the well, a 3-component, wireline-deployed geophone sonde was cemented into the well at 707 m depth on October 20, 1996. In late November, 1996, a second retrievable 3-component instrumentation package was subsequently deployed at 183 m depth in the upper section of the well, which was left open prior to final abandonment. Figure 2 illustrates the final configuration of the instrumentation. Both of these packages were developed in the 1980's as part of the US DOE Hot Dry Rock Geothermal Project.

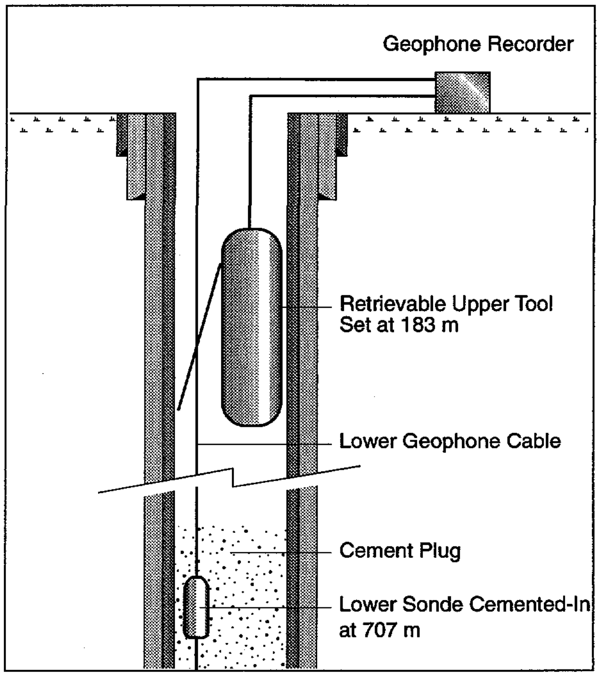

Figure 2. Well completion diagram and geophone sonde placement of GDCF 63-29 after partial abandonment.

Downhole signal amplifiers were removed from the deeper sonde to increase the survival period. The upper, retrievable tool had 40 dB downhole amplifiers custom designed and fabricated by Los Alamos for long-term operations at 185° C. The telemetry from the packages were sampled at 0.2 msec intervals High quality data recorded on two 3-component receivers in a single well can be used to determine 3-dimensional microearthquake source locations (Rutledge et al., 1994; Rutledge et al., 1998). Multiple stations deployed in a single-well also aid in discriminating microearthquake seismic signals from discretely-occurring wellbore noise.

The data analysis and evaluation reported here covers the initial 11-day period of 2-station monitoring from November 26 to December 7, 1996. Over the 11-day period, 437 events in which P- and S-wave phases could be identified on the upper package were detected and, of these, 232 were detected on both tools. An example of a high-quality event recorded on both sondes is shown in Figure 3.

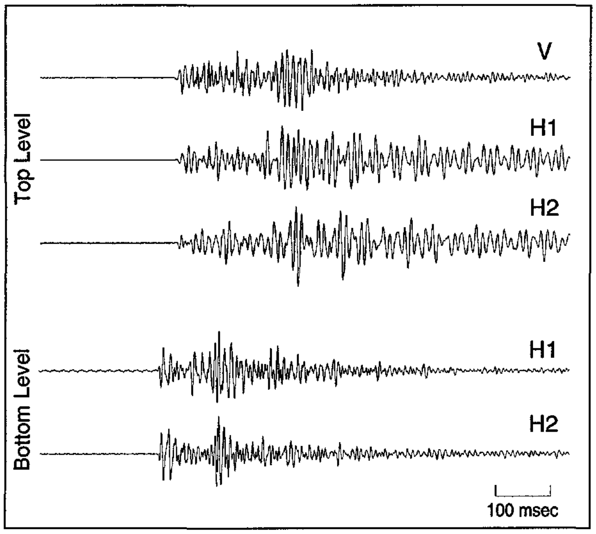

Figure 3. An example of a high-quality microearthquake recorded on both geophone sondes. Vertical component of the lower sonde was not operational and is not shown. The traces of the upper tool are amplified 5x with respect to the bottom tool traces in this display.

Although the upper package was more distant from most of the detected seismicity, its downhole amplification resulted in a nearly 2-order-of-magnitude increase in sensitivity for equivalent signal amplitudes detected at each package. A search of the National Seismic System Earthquake Catalog for the same 11-day period indicated 19 events detected on the U.S. Geological Survey's Northern California Seismic Network (NCSN) within 3 km radius and 5 km depth of the GDCF 63-29 wellhead. All 19 surface-detected events are a subset of our 437 downhole detected events. USGS magnitude estimates ranged from 0.4 to 4.0. We determined an empirical magnitude scaling relationship between the USGS magnitudes and the log of peak P-wave amplitudes for the common downhole-recorded waveforms, after correcting for geometric spreading, thereby allowing us to arrive at magnitude estimates for all 437 downhole-detected events (Figure 4).

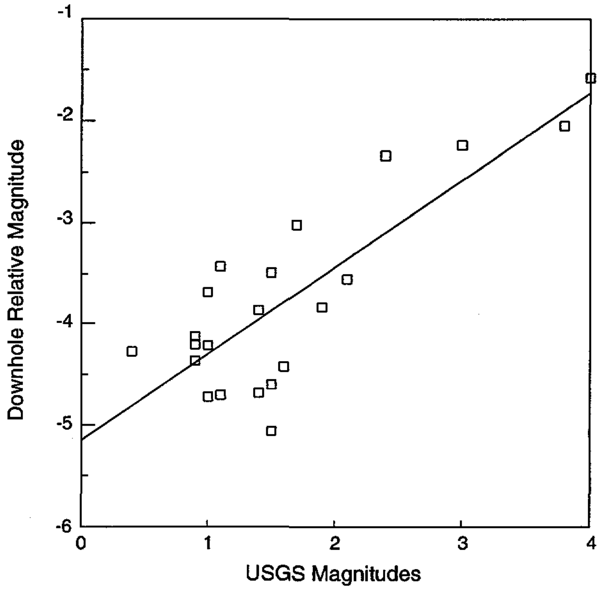

Figure 4. Empirical relationship of the downhole relative magnitudes versus USGS magnitude estimates for 19 common events. The downhole relative magnitude scale is the log of peak P-wave amplitudes after correcting for geometric spreading. The least-squares linear fit to the data is also shown and was used to scale all other downhole-detected events to USGS magnitude estimates.

Figure 5 compares the magnitude distribution of the downhole and NCSN-detected events in a histogram format. The threshold of detection on the LBL high-resolution digital surface array in the southeast Geysers (Kirkpatrick et al., 1995) corresponds to a seismic moment of about 10^{15} dyne-cm or magnitude 0 using Hanks and Kanamori (1979) moment-magnitude scale (A. Kirkpatrick, personal communication, 1998). The practical threshold of detection (of sufficient signal-to-noise ratio to determine locations) at our shallowest downhole receiver (183 m) is about magnitude -2.5, or seismic moment $\sim 10^{12}$ dyne-cm using the same Hanks and Kanamori moment-magnitude relationship, thus implying a 2-to-3 order-of-magnitude increase in detection sensitivity by placing receivers downhole. Low-frequency spectral seismic moment estimates of induced reservoir microearthquakes using the same downhole instrumentation at Fenton Hill, New Mexico (Fehler and Phillips, 1991), southcentral Kentucky (Rutledge et al., 1998), and the Ekofisk oil field, North Sea (J. Rutledge, personal communication, 1998) also show a detection limit of about 10^{12} to 10^{13} dyne-cm.

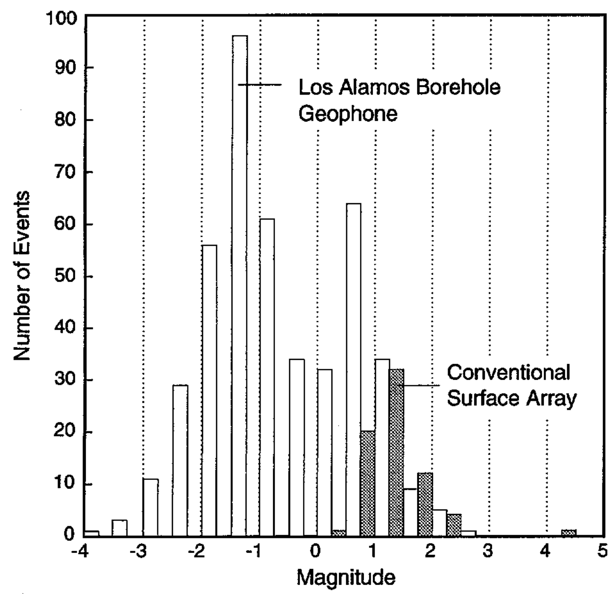

Figure 5. Comparison of the event magnitude distribution for the Los Alamos downhole-detected event population and the USGS NCSN detected events within a 3 km radius of the monitor well over the 11-day monitoring period November 26 to December 7, 1996.

As would be expected, event rates are higher with downhole monitoring after normalizing for the volume of rock sampled and for monitoring time. The hypocenter distribution for the LBL event population collected over a 8-month period (243 days) in 1994 corresponds to approximately 40 km^3. The majority of the downhole detected events (55% or 240 events) occur within a 350 m radius of the shallow geophone tool (a 0.2 km^3 volume) based on S- and P-wave arrival time differences and average velocities obtained from Kirkpatrick et al. (1997). Assuming uniform temporal and spatial distribution of seismicity, the mappable event rate for the 11-day monitor period was, on average, about 1000 times greater than the LBL located events presented in Kirkpatrick et al. (1995). The volume of rock sampled by the majority of the downhole-detected events occur above the reservoir (< 550 m), whereas the surface-detected event population occurs predominantly within the reservoir (1.5 to 3 km).

The depth-radial location of hypocenters with respect to the monitor wellhead is shown in Figure 6. The orientation of the geophones was not determined in the pilot test, so absolute azimuthal locations cannot be determined. The cluster of events at about 600 m lies just above top of the reservoir in the study area.

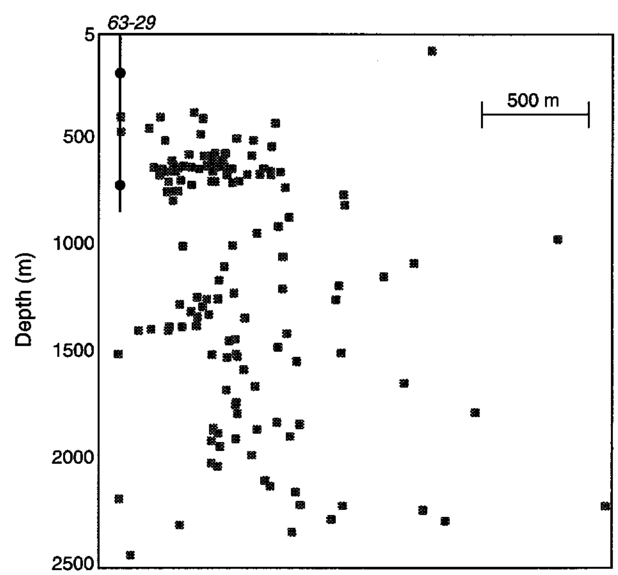

Figure 6. Radial and depth location of microseismicity located using the 2-level seismic array for events with P- and S-wave identified on both geophone sondes. Geophone sondes are shown as filled circles along borehole.

Prototype high temperature array

In May, 1997 a contract was competitively awarded to Petroleum Geo-Services (PGS) to collaborate with Los Alamos in the design and manufacture of a six-level, 3-axis, high temperature vertical borehole array to be cemented in GDCF 63-29. PGS is an industry leader in marine seismic surveying and brought to the collaboration years of experience with towed and borehole sensors arrays.

During the process of materials selection and array design, only a few materials were found that met the required temperature rating of 165° C. Each had manufacturing problems. The ideal configuration would have included a continuous impermeable elastomeric jacket over the cable and geophone nodes, thus assuring a watertight assembly. This would have been accomplished by injection molding an elastomeric material over the instrument pod and melting back into the cable jacket material. This is done routinely for marine applications, however, the high processing temperature of jacket materials appropriate for this application precluded the use of the overmolding/meltback technique. The jacket material candidates were limited to fluoropolymers (Teflon-type elastomers), which are very resistant to adhesion, or EPDM (ethylene propylene diene monomer) compounds, which require a rather elaborate post-manufacturing curing process. Ultimately, an off-the-shelf plenum cable with .020-inch thick PVDF (polyvinylidenedifluoride) fluoropolymer jacket material and Teflon FEP (fluoroethylene polymer) wire insulation was located and procured after downhole temperature measurements in well GDCF 63-29 indicated that the temperature had cooled to 150° C. Although PVDF's continuous temperature rating is 150° C, all other materials used in the borehole array are rated to 200° C or higher.

The concept of using aluminum "clam-shells" (Figure 7) to enclose the instruments and seal against the cable jacket was developed in lieu of a continuous covering. The shells were designed to encapsulate PGS's 3-axis geophone cradle, allow unused signal wire pairs to pass around the cradle, and provide a tight tolerance and sufficiently long interface with the outside of the cable jacket to obtain a watertight seal. Viton adhesive and caulk compounds, developed and provided for evaluation by Pelmor Laboratories, Inc., were found to provide excellent adhesion to the aluminum clam shell material, PVDF, and FEP when the elastomeric surfaces were sanded and chemically etched. One concern was that the 0.020" jacket thickness of the cable would not provide sufficient strength and stiffness to prevent kinking and tearing of the jacket at the clam shell ends, so Kynar shrink tube was installed over a thick layer of Viton adhesive to strengthen the areas near the clam shells.

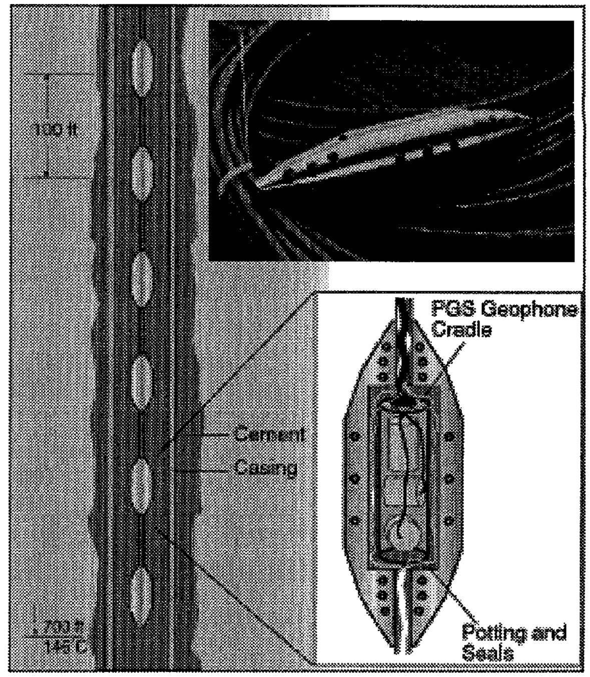

Figure 7. Photograph of six-level array prior to installation at The Geysers. Schematic of array and "clam shell" encapsulating PGS geophone cradle.

This layer also served to make the outer diameter of the cable more concentric, creating a more uniform surface to seal against the clam shell ends. The PGS cradle was hydrostatically tested to 8,000 psi and a series of additional moisture barriers were incorporated in the final assembly design. The cradle's wire feed-through insert was re-designed by PGS to incorporate a pressure-energized seal and provide an upset to receive shrink tube installed on the individual conductors on the outside of the cradle. A combination of Viton adhesive, o-rings, shrink tube, and high temperature silicon potting compound was used to seal the area around the cradle's wire feed-through. Viton caulk was used to seal the clam shell/cable jacket interface. A high temperature silicon water-blocking compound was pumped into the clam shells through fill/vent ports after the shells were assembled, then exothermically cured. A layer of self-fusing silicon tape was then applied to the outside of the clam shells and Kynar shrink tube with Viton adhesive was used to seal the tape to the cable jacket.

Future assemblies of this type should ideally be built using a cable with a thicker jacket and a more concentric cross section. Due to the relatively high cost of fluoropolymers, standard commercial cables aren't built with a jacket thickness greater than 0.020 inch, so a more durable cable would likely have to be custom built. Assembly of the clam shells is a labor intensive and time consuming task. An alternative may be to design a mechanical seal for use with a compression molding process to encapsulate the instruments and seal to the cable jacket material.

The array was completed and installed at the Geysers on April 7,1998. Initial results showed that 15 of 18 downhole channels were fully operational and more than 1000 microearthquakes were detected within the first 12 days of operation. The array has continued to record large numbers of seismic signals and these data are now being analyzed.

Summary

Studies with retrievable and cemented-in geophone instrumentation packages indicate that in the southeast section of The Geysers, the threshold for detection of mappable high frequency microearthquakes was lowered by an estimated factor of 2 to 3 orders of earthquake magnitude through the use of borehole instrumentation at depths less than 200 meters. Microearthquakes with frequency content of up to 500 Hz were recorded at the rate of 40 events per day on average in the vicinity of the test well, GDCF 63-29. A prototype multilevel geophone array was designed, appropriate materials identified, and the array fabricated based on consideration of the technical requirements for seismic monitoring as well as the requirement for materials that would assure reliable long-term service in geothermal fields.

Acknowledgments

This work was supported by the Office of Geothermal Technology of the U. S. Department of Energy and UNOCAL Geothermal Operations. In particular, the authors wish to acknowledge the guidance and contributions of Marshal Reed of the USDOE, Tim Anderson of *UNOCAL* (who will be 2nd author pending his company's approval), and Baljit Singh, of UNOCAL during this study and now with Burlington Industries.

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