CONF-890352--11

LBL-26899

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

Presented at the DOE Geothermal Program Review VII,
San Francisco, CA, March 21–23, 1989, and
to be published in the Proceedings

**GTO-DOE/Industry Cost Shared Research;
Microseismic Characterization and Monitoring**

E.L. Majer

March 1989

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

LBL--26899

DE90 014190

GTO-DOE/Industry Cost Shared Research; Microseismic Characterization and Monitoring

E.L. Majer

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1989

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Energy Technologies, Geothermal Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by Geothermal Resources International, Inc. (GEO) and Unocal Geothermal.

GTO-DOE/Industry Cost Shared Research; Microseismic Characterization and Monitoring in Geothermal Systems

E.L. Majer

Center for Computational Seismology, Lawrence Berkeley Laboratory,
Earth Sciences Division, University of California, Berkeley, California 94720

Abstract

The application of passive seismic studies in geothermal regions have undergone significant changes in the last 15 years. The primary application is now in the monitoring of subsurface processes, rather than exploration. A joint Geothermal Technology Organization (GTO) industry/DOE, monitoring project involving GEO, Unocal Geothermal, and LBL, was carried out at The Geysers geothermal field in northern California using a special high frequency monitoring system. This several-month-long experiment monitored the discrete and continuous seismic signals before, during, and after a fluid stimulation of a marginal production well. Almost 350,000 liters of water were pumped into the well over a four -hour, and a three-hour time period for two consecutive days in June of 1988. No significant changes in the background seismicity or the seismic noise were detected during the monitoring period. Analysis of the background seismicity did indicate that the earthquakes at The Geysers contain frequencies higher than 50 Hz. and possibly as high as 100 Hz.

Introduction

Seismic monitoring has been used for various objectives by the geothermal industry. The first use was for exploration. It was thought that the presence of microearthquake (MEQ) activity was an indication of boiling water or active geothermal processes. It was also reasoned that the microearthquakes were an indication of active tectonics associated with thermal processes. As time passed, however, the utility of MEQ surveys shifted to a monitoring application. This was brought about by several factors. The first was the observation that some thermal anomalies had little or no expression of microearthquake occurrence. In the cases where there was microearthquake activity it was often diffuse and was a secondary indication of economic geothermal potential. It was found that primary indicators such as heat flow measurements and thermal springs were more reliable for exploration purposes. In other words, MEQ activity may have been useful for inferring the general location of potential geothermal resources, but it was difficult to use the results as a reliable guide for to drilling targets. A second reason for the shift to monitoring applications was the observation that at many geothermal fields there was a change in the MEQ activity as a function of time. The most famous of these cases was at The Geysers geothermal field in northern California. As the production increased the MEQ activity also increased, in both numbers of events and in the maximum magnitude of events [1]. It was obvious that the rate of seismic energy release was controlled by the fluid and heat balance in the reservoir. However, based on our studies, as well as those of others, there are still questions remaining regarding the exact cause of the events and the reason for the increase in seismicity. Eberhart-Phillips and Oppenheimer [1] concluded that there was was no direct correlation between seismicity and injection wells. However there was no direct correlation between withdrawal wells and seismicity either. While it was obvious that seismicity was related to production activities, its cause is more complicated than originally thought.

Of the many mechanisms that have been proposed, only a few remain plausible. One such mechanism that was proposed by Majer [2] is that the increase in seismicity was due to volumetric contraction from the net withdrawal of mass and heat from the reservoir. Following the studies of McGarr [3] on seismicity in South African gold mines, Majer reasoned that similar volume change may cause seismicity change in The Geysers. The annual volume change of 5×10^{10} cm^3/yr calculated from the yearly moment rate correlated well with the observed subsidence of 6.3×10^{10} cm^3/yr. The other mechanism that still may explain the MEQ behavior was proposed by Allis [4]. He proposed a mechanism where the increase in seismicity was due to an increase in reservoir rock effective strength. Because The Geysers is in a tectonically active area, Allis reasoned that if the reservoir rock was aseismically slipping, then MEQ activity would increase if stick-slip behavior occurred. This would happen if there was a large fluid pressure decrease or an increase in the coefficient of friction due to the deposition of silica on fracture faces. In any case, the truth is probably a combination these and other mechanisms. In some parts of the field one mechanism may dominate over another, or in injection activities the mechanism may differ from withdrawal activities. The problem of determining the actual mechanism requires better resolution in the location of the events in order to separate the physical processes involved.

There are two ways to increase event resolution, high station density and higher frequency content. If one had a station every 100 meters in the field, in X, Y, and Z, directions, this would obviously solve the problem, but bankrupt the operator. On the other hand, if the frequency content of the recorded signal could be increased by an order of magnitude or even by several factors, then one could resolve MEQ activity more accurately. This would be accomplished by not only improved time picks, but by locating the events with similar frequency content and nature. An example of this cluster relocation technique is shown in Figure 1. The data are from an earthquake prediction experiment along the San Andreas Fault being conducted by the USGS, UC Santa Barbara and LBL. The data are from a digital (500 samples/sec) 10 station, 3-component, borehole array. The array dimensions are approximately 10 by 20 kilometers across the fault. It is obviously a very difficult velocity structure to deal with. Shown in Figure 1 are results from a soon to be published LBL/UCB report by Clymer, McEvilly, Foxall, and Michelini [5]. Using high frequency data and non-conventional location techniques it is possible obtain location precision on the order of 10's of meters using relatively large arrays. As seen in Figure 1 there is a large difference in the conventional locations (x's) and the locations obtained by using a 3-D model and using cluster analysis (solid circles). The "clouds" of events now become linear features. By timing similar events and locating these events by themselves marked improves the locations. The key is picking the proper times for the P- and S-waves. This is done by correlating the arrival times with the same events in the cluster. From the results in Figure 1 one can immediately see the benefit of this type of analysis for geothermal applications. The clouds of events seen in all of the geothermal MEQ studies may in reality be closely spaced linear features. If the mechanism for increased MEQ activity is either volume change, or silica deposition, then the location of these events could determine the location of the resource.

The Geysers High Frequency MEQ Monitoring Experiment

In an effort to answer some questions regarding the nature of the seismicity at a geothermal field, GEO, Unocal Geothermal, and LBL carried out a high frequency seismic monitoring of a stimulation project at The Geysers geothermal field. The project was a GTO joint industry/DOE project. The purpose of the experiment was to monitor high frequency seismicity associated with the injection of fluids in a geothermal reservoir. The experiment was carried out in a marginally producing GEO well, RA-25, located near Pacific Gas and Electric Unit 15 at The Geysers geothermal field. The well is a marginal producer, on the edge of the main production field. However, the goal of the injection was to increase the production through fluid stimulation, first through the hydrostatic pressure (which is much greater than the in-situ pressure) and then if necessary through pumping. In order to understand the fracture system and to monitor the fluid injection it was proposed to use high frequency seismic monitoring. GEO drilled five dedicated boreholes to bedrock around the injection well for the installation of a string of high frequency phones (also provided by GEO) in each borehole. The data was hardwired to a central site where it was recorded and monitored by two systems, the LBL ASP and a new high frequency monitoring system developed by LBL for the U.S. Army. The Army system was developed for monitoring acoustic emission data related to the injection of grout. It is capable of monitoring at up to 100,000 samples/sec on each channel. It locates and displays in 3-D the event location. In addition to the event location scheme, it also performs beam forming on coherent energy. Often it is the case that fluid injections do not create single discrete events, but an increase in the total seismic energy. By having arrays of geophones in the holes, which we had, the apparent velocity of the seismic energy can be measured. By having five of these arrays, we can triangulate on the coherent signals to trace the location of the fluid flow. The question in this case is: What is the level of discrete event activity associated with the fluid injection, what is the level of increase in coherent seismic energy associated with the injection, and can the events be used to trace the fluid injection, fracture pattern, and answer questions regarding the cause of microseismic activity in this area. In addition to the arrays of geophones in the holes provided by GEO, Unocal Geothermal provided 3 seismic stations that were telemetered

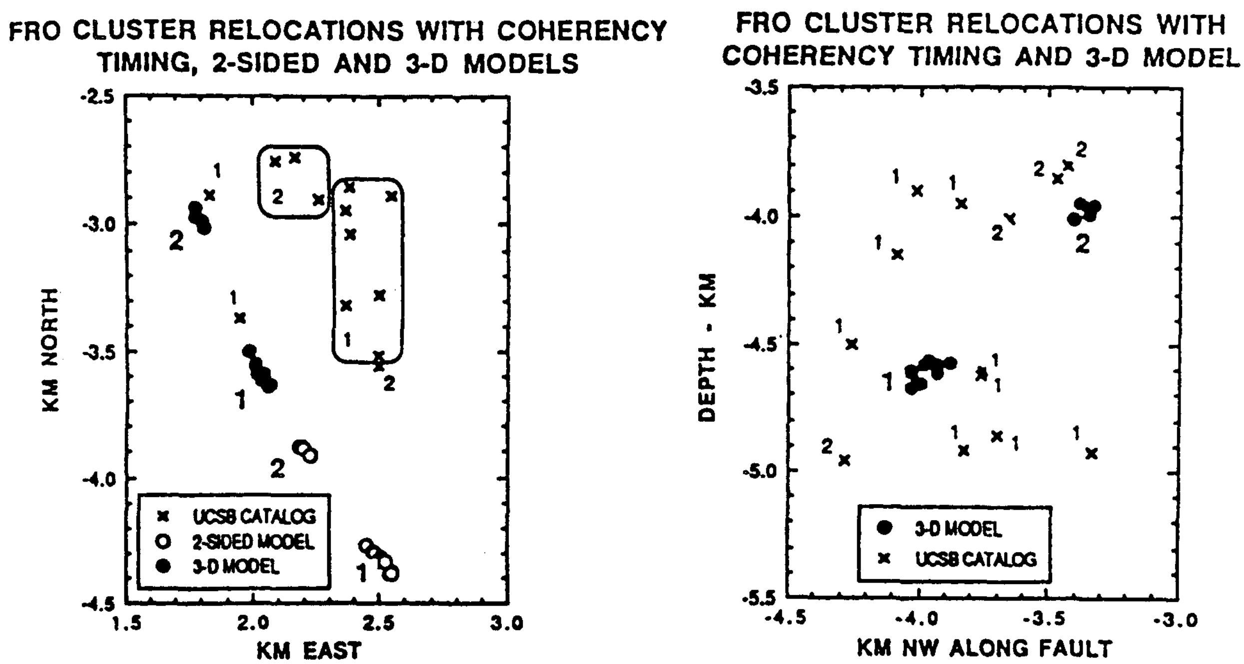

Figure 1. An example of the precision achievable when high frequency data are used to locate microearthquake activity using cluster analysis and coherency timing methods.

to the central recording site and recorded on ASP. The Unocal stations were also borehole stations, but with 3-component geophones in the boreholes. Two of the Unocal 3-component geophones were in 30 meter deep holes and the third (INJ) was in a 86 meter deep hole. This was for tracing the local microearthquake activity as a function of time. The reason the data were hardwired to the central site from the GEO wells was to preserve the high frequency content of the signals. On the telemetered Unocal stations the high frequency filters were at 50 Hz. On the GEO high frequency stations, the data were filtered at 250 Hz and digitized at 1000 samples per second. An important part of this experiment was to determine if the stations presently in use at The Geysers were missing high frequency data. This would be accomplished by comparing the same events recorded on the high frequency system to the Unocal stations.

LBL was responsible for the design, execution, and processing of the seismic data. As stated earlier, LBL provided two monitoring systems, a microearthquake monitoring system (ASP) and a high frequency (at least 1000 samples/sec over 16 channels) monitoring system. These systems were deployed at GEO's site at The Geysers. LBL also provided the wire to telemeter the signals to the central site as well as the electronics at the borehole sites. GEO provided the boreholes and geophones cemented into the boreholes. Unocal Geothermal provided the signals from three three-component stations on Unocal land that completed the azimuthal coverage of the GEO array. GEO was responsible for all injection activities. Shown in Figure 2 is the location of the GEO array relative to the injection well RA-25. In each of the monitoring holes GEO cemented a 3 element string of vertical geophones. The wells were approximately 30 to 45

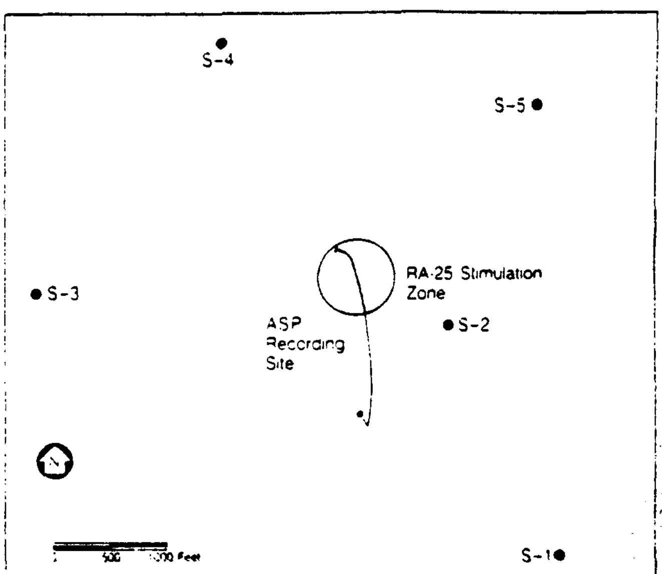

Figure 2. The layout of The Geysers high frequency monitoring experiment. Shown are the GEO wells and the location of the RA-25 injection area. The Unocal seismic stations are off to the northeast.

meters deep. The geophones were high frequency, 30 hz, commercial phones. The signals were amplified by differential amplifiers by a factor of 10,000 before the signals were sent by wire to the central recording site were they were digitized and processed. A 3-month monitoring program was scheduled around the injection experiment. This included one month of background monitoring and two months of monitoring during and after the injection.

Results and Discussion

As stated above, there were two monitoring schemes used for this experiment. ASP was used to monitor background seismicity, and the high frequency Army system was used to monitor the same data channels but at a much higher digitization rate. The experiment began in late April 1988. After the telemetry wires were laid and the electronics at the well sites installed, there was a considerable effort in eliminating the electrical noise associated with this area. Finally in mid-May the array came on line. From mid-May to mid-June over 155 "good" events were located by the ASP system. However, none of the events were within the GEO array. All events were located within the Unocal array across the canyon. During this monitoring period there was an injection in RA-25. On June 6, 1988 approximately 200,000 liters of water over a four hour time period was put in RA-25 under hydrostatic pressure. On June 7, another 150,000 liters over a three hour period was put in RA-25. During this time we were visually watching the signals from the array, as well as recording on the two monitoring systems. No change was seen in the discrete seismic activity, i.e., there were no events recorded. In addition, we were monitoring the background noise for a change in character, no change was seen. Shown in Figure 3 are the spectra of typical events recorded on the Army system. Shown are the spectra from a hardwired telemetered system, the solid line, and from a telemetered Unocal station, the line with large dashes. The line with small dashes is the cross power. The time series recorded at S1, S2, and S3 are shown in Figure 4, i.e., channels 1, 2, and 3, respectively. The time series recorded at one of the Unocal stations (INJ) (3-component) are shown in Figure 5. The spectra from the two different sites are different, as would be expected, but there is one difference to note. As in the data shown, the general trend was that the events recorded on the GEO array were slightly higher in frequency content. They rolled off from 10 to 20 Hz. higher. This implies that the microseismic signals generated at The Geysers have a broader bandwidth than is being recorded. Most systems now stop at 20 to 50 hertz, this should possibly be expanded to 100 hertz. The spectra shown have not been corrected for gain or attenuation. The event shown is much closer to the Unocal station than the GEO stations. Therefore the difference in frequency content is probably more than shown.

It is disappointing that there was no significant change in the seismicity or noise level associated with the fluid injection at RA-25. However, the experiment was somewhat inconclusive in that there was no follow up injection at pressures higher than hydrostatic. Also, the volumes injected were relatively small compared to other injections at The Geysers. Also, it was not certain where the interval in the

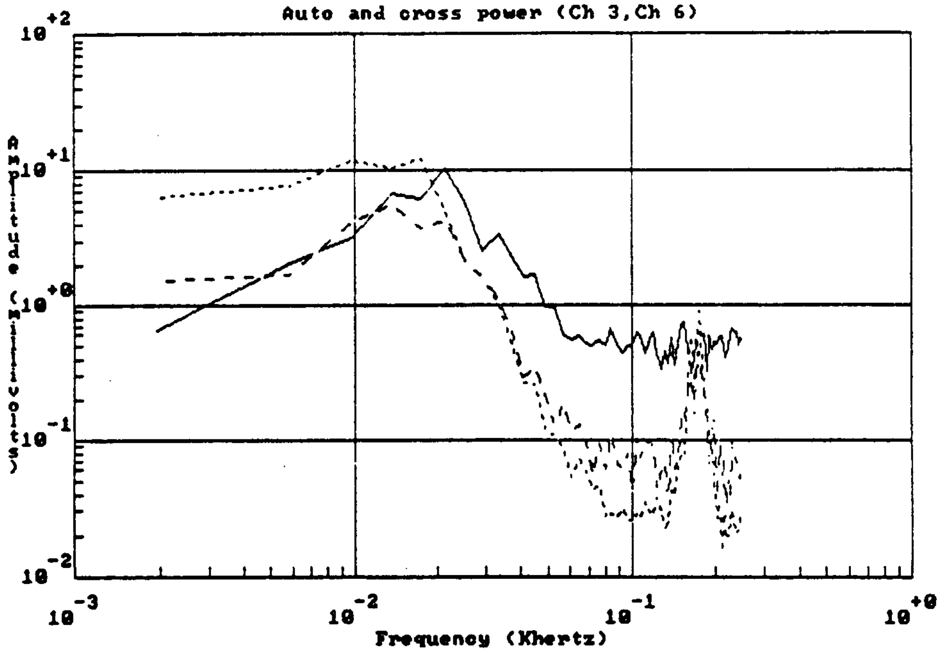

Figure 3. The spectra from a typical event recorded on the Army system. Shown are the spectra from a hardwired telemetered system, solid line, and from a telemetered Unocal station, line with large dashes. The line with small dashes is the cross power. The time series are shown in Figures 4 and 5.

well where the water was flowing. The water may not have been reaching the production depth. In future experiments it may be worthwhile to inject at pressures higher than hydrostatic, and to use a well that is thought to have higher fracture permeability. It is now possible to obtain very precise locations using high frequency data. A longer term monitoring of an injection well may be worthwhile with a high frequency system.

This experiment has shown that by pooling resources between the private and public sector there is a potential for all to benefit. Similar cost share arrangements, such as the

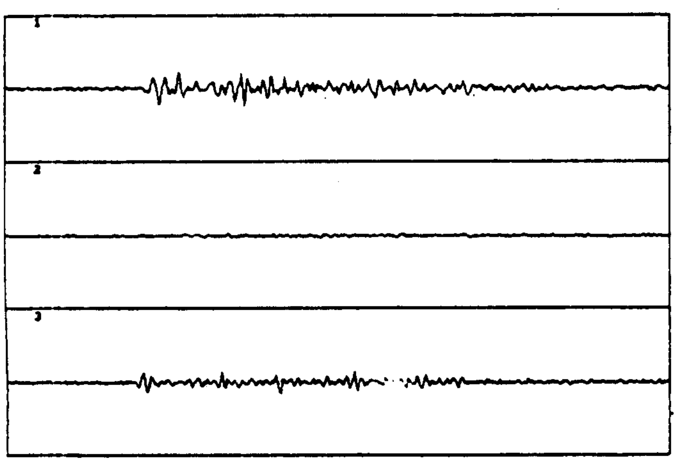

Figure 4. A typical time series from a MEQ recorded at stations S1, S2, and S3. The event is approximately 3 km. from these stations. The spectrum of the time series recorded at S3 is the solid line shown in Figure 3.

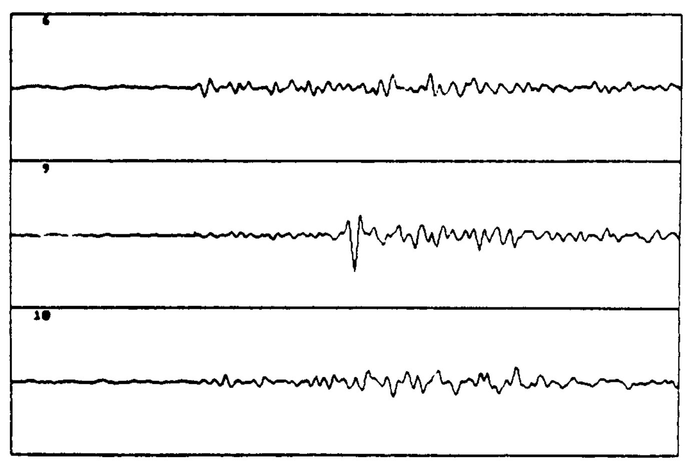

Figure 5. The event shown in Figure 4 as recorded on a three component Unocal station. The event is approximately 2.00 km. from this station. The spectrum of channel 6 is shown in Figure 3, the line with large dashes.

VSP and MEQ surveys in The Geysers between GEO/LBL, Unocal/LBL and Geysers Geothermal/LBL have all produced useful results that would not have been possible without joint cooperation. These projects have demonstrated that it is possible to bring the research from the DOE labs into practical application and hopefully benefit the geothermal industry.

Acknowledgments

This research was supported by Geothermal Resources International, Inc (GEO) and Unocal Geothermal companies, by the Geothermal Technology Organization and by the Geothermal Energy Division of the U.S. Department of Energy under contract DE-AC03-76SF00098. I would also like to thank the personnel at the U.S. Army Waterways Experimental Station in Vicksburg, Mississippi for their help and use of their equipment.

References

(1) Eberhart-Phillips D., and D. H. Oppenheimer, 1984, Induced seismicity in The Geysers geothermal area, California, *Jour. of Geophys. Res.*, Vol. 89, No. B2, pp. 1191-1207.

(2) Majer, E. L., 1978, Seismological studies in geothermal regions, *Ph.D. Thesis* Univ. of Calif. at Berkeley, Berkeley, California, 223 pp.

(3) McGarr, A., 1976, Seismic moments and volume change, *Jour. of Geophys. Res.*, Vol. 81, No. 8, pp. 1487-1494.

(4) Allis, R. G., 1981, Comparison of mechanisms proposed for induced seismicity at The Geysers geothermal field, in *Proc. 1981 New Zealand Geothermal Workshop*, Univ. of Auckland Geothermal Institute, Auckland, N.Z., pp. 57-61.

(5) Clymer, R.W., T.V. McEvilly, W. Foxall, and A. Michelini, 1989, High precision earthquake monitoring at the Parkfield, CA. site, In Preparation.