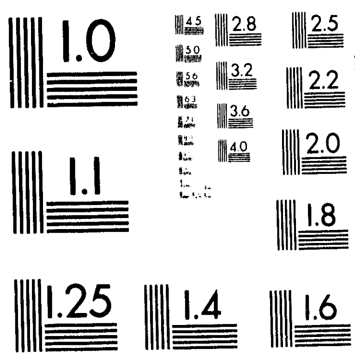
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Seismic Monitoring at The Geysers

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Introduction

During the last several years Lawrence Berkeley Laboratory (LBL) and Lawrence Livermore National Laboratory (LLNL) have been working with industry partners at The Geysers geothermal field to evaluate and develop methods for applying the results of microearthquake (MEQ) monitoring. It is a well know fact that seismicity at The Geysers is a common occurrence, however, there have been many studies and papers written on the origin and significance of the seismicity. The attitude toward MEQ data ranges from being nothing more than an curious artifact of the production activities, to being a critical tool in evaluating the reservoir performance. The purpose of the work undertaken by LBL and LLNL is to evaluate the utility, as well as the methods and procedures used in of MEQ monitoring, recommend the most cost effective implementation of the methods, and if possible link physical processes and parameters to the generation of MEQ activity.

One of the most promising uses of MEQ monitoring that has been proposed is monitoring the flow of fluids during injection activities. Another proposed use has been to define active fault and fracture patterns that could be possible targets for in-fill drilling. A more recent use has been to use the microearthquakes as sources to image the physical properties within the reservoir area. The success of all of these proposed uses, as well as any other, will depend upon the resolution obtained and the understanding of the physical and chemical processes causing the MEQ activity. The use, or misuse, of MEQ data is critically dependent upon the quality and resolution of the data. In this sense The Geysers offers an excellent and unique test case due to the diversity of MEQ studies carried out at The Geysers and the supporting geological, geophysical, hydrological, and geochemical information potentially available.

To address the objectives above the MEQ work can be categorized into two types of studies. The first type is the direct analysis of the spatial and temporal distribution of MEQ activity and studying the nature of the source function relative to the physical or chemical processes causing the seismicity. The second broad area of study is imaging the reservoir/geothermal areas with the energy created by the MEQ activity and inferring the physical and/or chemical properties within the zone of imaging. The two types of studies have obvious overlap, and for a complete evaluation and development require high quality data from arrays of multicomponent stations. Much of the effort to date at The Geysers by both DOE and the producers has concentrated establishing a high quality data base. It is only within the last several years that this data base is being fully evaluated for the proper and cost effective use of MEQ activity. Presented here are the results to date of DOE's effort in the acquisition and analysis of the MEQ data.

Background

One of the earliest published reports on MEQ's at The Geysers was done by Langue and Westphal in 1969. In this paper, it was reported that the recorded seismicity was shallow (≤ 5 km) and at a rate of 4 events per day. In 1972, Hamilton and Muffler observed activity of similar amounts, with the activity localized in the production area. At this time, the power generation was 82 MW. As time passed and the steam production rate increased, the MEQ activity also increased. By September of 1976, with a power generation of 550 MW, the activity rate had increased to 25 to 30 events per day (Majer, 1978). In these early studies, the magnitudes and detection thresholds were not well defined but magnitude zero seemed to be the lower detection threshold of these surveys. By 1984, when the production had increased to 1000 MW, it had become quite clear that there was a direct relationship between production and seismicity. Since the early work on microseismicity at the Geysers, a number of authors have reported the empirical link between production activities and seismicity (Marks, et al, 1978; Ludwin and Bufe, 1980; Peppin and Bufe, 1980; Bufe, et al, 1981; Allis, 1982; Denlinger and Bufe, 1982; Ludwin, et al, 1982; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986; Stark and Majer, 1989) just to name a few. Oppenheimer, (1986) quite clearly showed the that the location of earthquakes with $M \geq 1.2$ for the periods 1976-1984 spatially correlated with the growth in the number of power plants. Most of these authors agree that the seismicity is not associated with any dominant through going fault system. The activity seemed to occur somewhat at random and appeared to be clustered in the production region. Most of the events recorded in these studies were strike-slip and normal in nature (Oppenheimer 1986), but also exhibited some thrust activity at shallow depths. Again, as noted on the early surveys, the seismicity was very shallow, and almost all less than 5 km in depth below the surface.

The arrays that were used in locating the above-mentioned events were mostly analog recording with low frequency (< 50 hz) response. Also, the stations spacings were on the order of several kilometers at best, thus yielding location error of ± 1 km to $\pm .5$ km, in general. In the last several years, however, several arrays with high frequency digital borehole 3-component recording have been installed at The Geysers, (Figure 1). One such array is in the Northwest Geysers, which was installed by Geothermal Energy Operators (GEO), and now owned by the Central California Power Association (CCPA) and is operated by the Russian River Energy Company. Its intended purpose is to monitor MEQ activity associated with production activities. The CCPA array is unique in its capability because of the dense station coverage (16 stations), high frequency digital sampling on three components (400 samples/second/channel), and its boreholes sensors. The data from this array make it ideal for evaluating MEQ monitoring techniques. In addition to CCPA array, Unocal operates an analog array in the central and southeast Geysers region. The

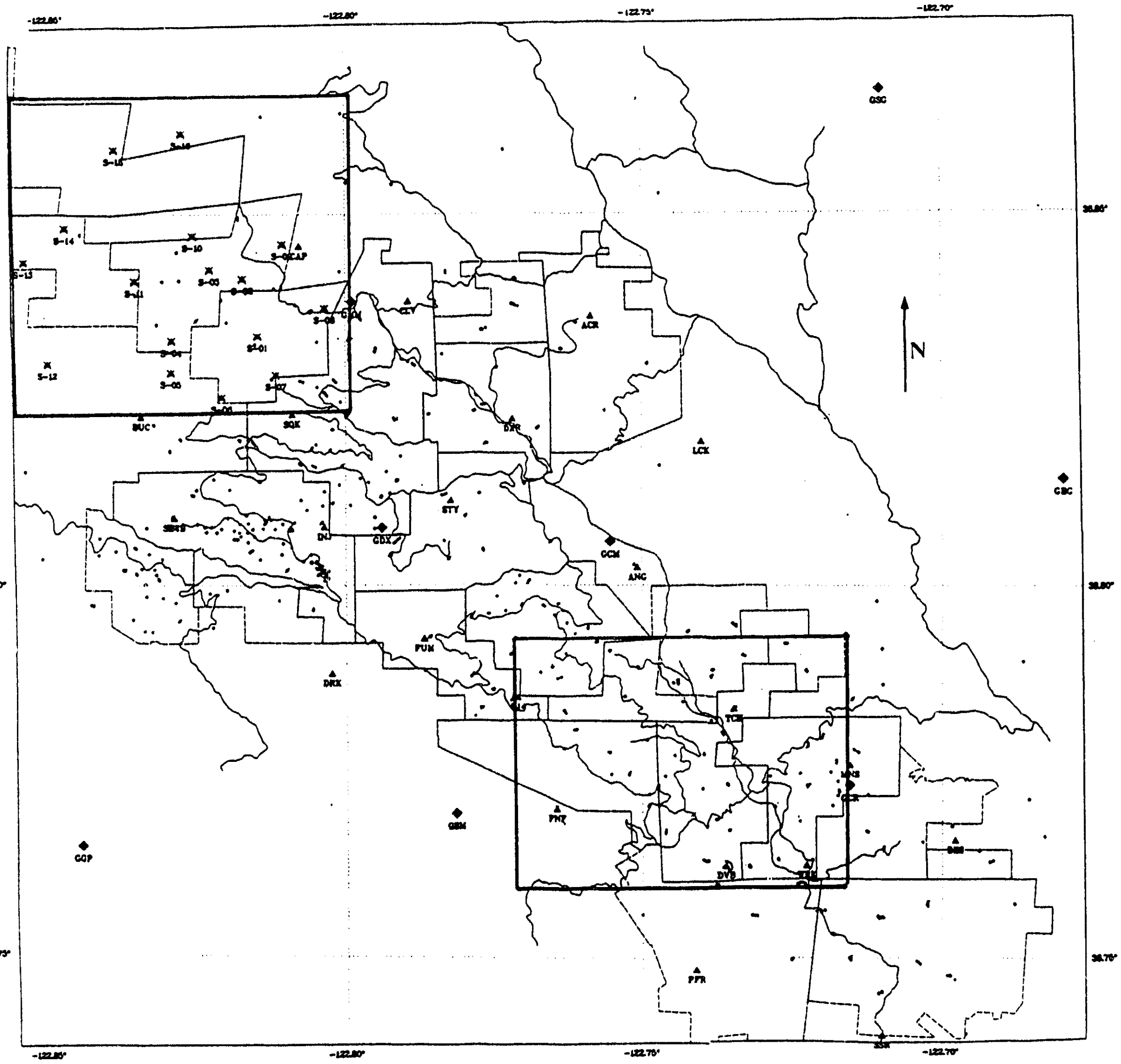


Figure 1. The locations of the seismic monotoring stations in The Geysers area. The northwest and southeast Geysers microearthquake arrays being used in this study are highlighted. Also shown are some of the USGS stations used in previous studies. Note the density of the stations used in this study to the station spacing used in the studies using the USGS stations.

Unocal southeast array has been augmented by equipment from LBL and LLNL with 13 high frequency (480 samples/second/channel) digital three component stations. The CCPA array and the southeast array have been the source of the majority of the data for the results reported here. These arrays are routinely collecting microearthquakes down to magnitude -1. With this improved capability the goal is to be able to improve on early studies and hopefully determine a more precise relation between production activities and seismicity. Overall the objectives of the MEQ work are:

(1) Demonstrate the utility of high resolution, multicomponent, microearthquake data (MEQ) for:

(a) Locating high permeability paths in the reservoir.

(b) Aid in the location of in-fill well drilling.

(c) Monitor effect of condensate injection in real time.

(2) Develop 3-D model of reservoir.

(a) P- and S-wave velocity and amplitude structure.

(b) Poissons ratio model.

(c) 3-D structural model using MEQ locations for inferring flow paths.

To fully understand the relation between microearthquakes and a geothermal environment, many different factors must be considered. A crucial question to answer is: does such a phenomenon as a "geothermal earthquake" exist? If so, a useful exploration and/or monitoring tool would be provided. On a fundamental level, the basic mechanism of an earthquake is a sudden loss of cohesion or strength of a material. The factors controlling failure are: rock type, confining pressure, temperature, amount and manner of directed stress, solubility of the material, time and rate of strain (Spencer, 1969). Although all these factors are closely interrelated, an obvious characteristic to examine in geothermal regions is the temperature. Though not always consistent, the effect of increasing temperature is to lower the brittle-ductile transition pressure, (Griggs, Turner, and Heard, 1960). Increasing temperature may also tend to decrease the rate of microearthquakes (McNally, 1976). However, only at temperatures in excess of 400°C does this effect begin to dominate. At these temperatures, the motion on a fault becomes stable gliding rather than a series of discrete, rapid slips or "stick-slip" (Stesky, 1977). Therefore, in a region that is anomalously hot, microearthquakes may be expected to be absent or to exist only at shallower depths. An increase in temperature also tends to increase the fault angle with respect to the principal stress direction (Handin, 1966). In a region that is under relatively uniform stress, a hot area may be indicated by anomalous fault plane solutions compared to the cooler surrounding areas. In the Geysers, one mechanism in particular that may be causing MEQ activity is the conversion of a seismic slip to seismic slip due to an increase in coefficient of friction due to exsolved silica into fracture surfaces (Allis, 1982).

Increased temperature may also have an indirect effect by influencing the content of the pores. If the temperature is high enough, steam, rather than water, may be present. A common failure criteria is the Coulomb relation, the total shearing resistance offered by an isotropic material to failure, is proportional to the effective normal stress , the difference between the actual normal stress , and the pore pressure . If the pores contain steam, which is highly compressible, is small; thus is larger than in an adjacent area where the pores are filled with water and is large. Therefore, would be expected to be higher in a steam filled region, thus resulting in fewer earthquakes compared to an adjacent region. This assumes, of course, that all other parameters remain constant, which is not the case. Injection, or withdrawal of fluids may also affect the normal stress, thus either decreasing or increasing the threshold of failure, respectively.

In a convective geothermal system, the temperature gradients in the zone of convection are not as large as the temperature gradients on the edges of the reservoir. If the reservoir is a vapor dominated resource, pore pressure may also remain relatively constant within the steam zone, especially compared to a hydrostatic gradient. However, the pressure differential between the outside and inside of the reservoir would vary considerably from the top to the bottom. These pressure differentials may be evident in the stress drops or available stresses for an earthquake. If there is a systematic variation in the magnitude of microearthquakes with depth, or in relation to steam zones, such a differential pressure effect may be responsible.

Another parameter most likely to be affected by geothermal activity would be the rock type. The high temperatures and hydrothermal activity undoubtedly alter the rocks within the reservoir. A possible mechanical effect is to weaken the rocks in certain regions and possibly strengthen the rocks in certain regions and possibly strengthen the rocks where the hydrothermal solution cools and deposits its dissolved solids. Along with hydrothermal activity, such factors as differential expansion due to larger temperature gradients, weakening from dehydration erosion, and hydrolytic weakening of quartz may all lower the failure criteria of the material, thus encouraging seismicity.

Unfortunately, geothermal reservoirs are not describable in steady-state terms, especially if the resource is being exploited. Continual fluid movement, phase-changes, and heat transfer will change the state of the reservoir. If microearthquake activity is related closely to these processes, then the seismicity will also be in continual state of flux. Microearthquake activity may indicate the balance between the withdrawal of fluids and the recharge of fluids from the surrounding water supply. Volumetric changes occur when the fluid is withdrawn, and, because of finite permeability, the recharge is not instantaneous. McGarr (1976) has shown that for volume changes due to mining operations, there is a close relationship between the volumetric moment due to seismic failure and the amount of rock removed. Although rock is not being removed in the geothermal case (other than the amount by dissolution), compaction would be expected to occur with possible failure consistent with the direction of the maximum principal stress. If more fluid is being withdrawn than replaced by ground water recharge or reinjection, an increase in microearthquake activity could be expected. Also, as this occurs and pore pressure drops a steam zone may develop if ample heat is available. Therefore, rather than an exploratory tool, microearthquake monitoring may prove useful for determining areas of recharge and depletion within a producing reservoir.

Microearthquake Location and Occurrence Studies

As stated earlier the two broad areas of investigation have been in the characterization of the MEQ activity (space and time) and in the use of the MEQ activity for imaging the subsurface. Presented in this section are the results of the location and occurrence work in the northwest Geysers and the southeast Geysers. The data from this work has come from the CCPA network and the Unocal network augmented LBL/LLNL stations in the southeast Geysers.

Northwest Geysers

In March of 1990 LBL, in conjunction with the Coldwater Creek Operator Company (CCOC), (Now CCPA) undertook the collection, analysis processing, and interpretation of the microearthquake (MEQ) data from the 16 station, digital, 3 component, high frequency CCOC array in place at the northwest Geysers geothermal field. To date the processing has concentrated only on data collected prior to full production and injection in the NW Geysers and for approximately after one year full production and injection activities started (1988). (This involved detailed analysis and processing of approximately 5000 events.) During this time the injection occurred at two different sites, Prati 8 and 9, but with the main injection at Prati 8. The array has been out of operation due to legal and technical complications, however, it is anticipated that the array will be brought back into operation in 1993 to begin background monitoring prior to new injection activities.

Several previous studies have concluded that the high seismicity in The Geysers region is related to geothermal development (Eberhart-Phillips and Oppenheimer, 1984; Stark, 1990). Results of the present study indicate further that seismicity rate is related to production and injection and that reservoir property changes due to exploitation may be detected. Figure 2 presents in plan view the relocated hypocenters of the events around the CCPA area. Microearthquakes are concentrated within the CCPA field extending south and east into the older sections of the producing field. Seismicity is low to the north and west in the direction where the field is undeveloped. Seismicity occurs in two distinct 2 zones: a broad, shallow zone between 1 and 3 km depth, presumably related to the production zone, and a deeper cluster between 3.5 and 5 km depth just beyond the southeast edge of the field, (see Figure 3). A cluster of microearthquakes with focal depths between 2 and 3 km is located beneath the injector

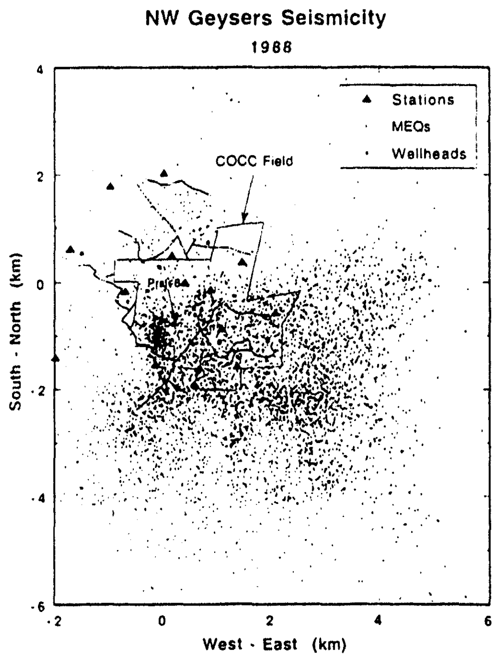


Figure 2. Map view showing the locations of microearthquakes during 1988 in the CCPA geothermal field. Microearthquakes are concentrated within the central part of the field extending south and east. Seismicity is low to the north where the field is not being produced.

well Prati-8, as shown in Figure 3. The microearthquake distribution seems to define a vertical planar structure striking roughly north-south. Figure 4 is an expanded view of the seismicity around Prati 8. As can be seen there is a strong spatial correlation of the seismicity to zone around the bottom of Prati 8 and extending several hundred meters beneath the well. Current pressure data from Prati 9 suggest that injection does have an effect on the saturation of the formation an fluid is invading the zones around the well. (Pers Comm, M. Walters, Russian River Energy Corp) If this also occurred around Prati 8 then the seismicity may indeed be an indication of the zone of invasion of the fluid.

In terms of temporal correlation, Figure 5 presents a comparison between the seismicity rate within the CCPA area and the field-wide steam production rate. Beginning at Julian day 90, 1988, seismicity increased significantly to approximately 20 events per day, more than double the pre-production seismicity rate. High seismicity was sustained during the course of steam production except during a short lull between Julian days 225 and 270 when production rate decreased temporarily. Figure 6 presents a comparison between Prati 8's injection history and seismicity rate nearby. Note the good correlation between peaks in seismic activity and injection rate. Seismicity increased with the start of sustained injection, and peaks in seismicity occurred during periods of maximum injection. Spatial and temporal correlation between injection activity and seismicity provide compelling evidence for induced seismicity around Prati 8.

In addition to investigating the characteristics of the microearthquakes themselves, the temporal changes in the velocity structure and seismicity patterns in response to geothermal activity are also being investigated. Particular attention has focused on the changes in the Vp/Vs structure because of its sensitivity to fluid

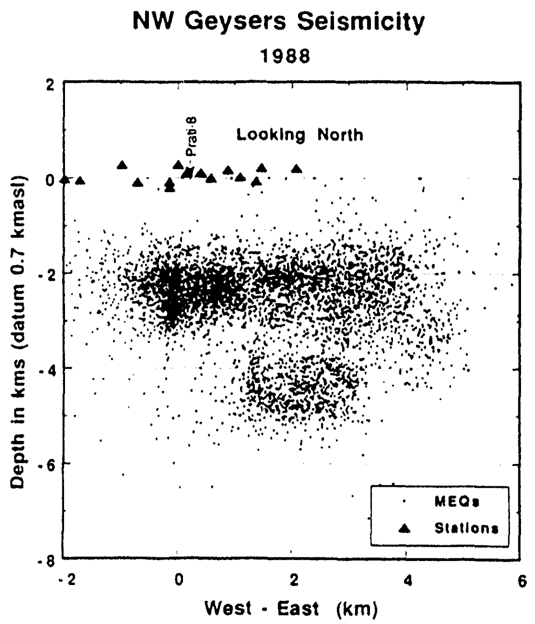


Figure 3. Cross section (East to West) of seismicity through the northwest Geysers. Note the two distinct zones of seismicity, shallow in the production zone and deep below the production zone. Note the clustering of events beneath the injector Prati 8. Datum plane is 0.7 kmasl.

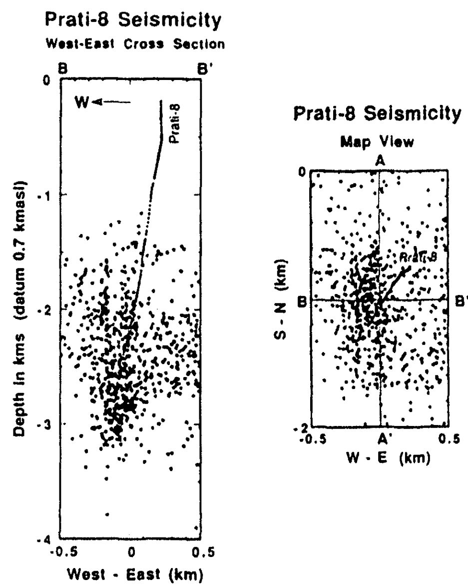


Figure 4. Expanded and cross sectional view, and map view of microearthquake locations around the injector Prati 8. The microearthquake distribution seems to define a vertical plane striking N-S. Datum plane is 0.7 kmasl.

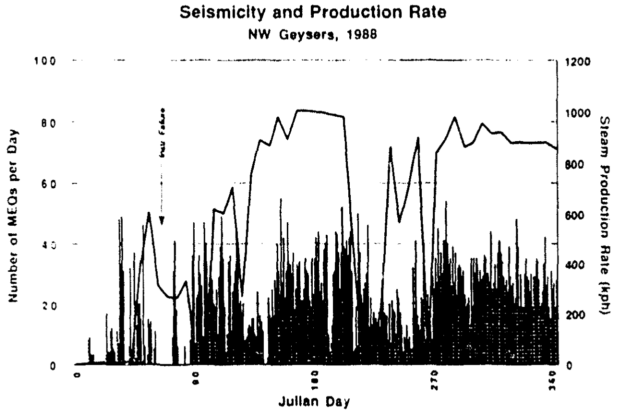


Figure 5. Comparison between the seismicity rate within the CCPA area and field-wide steam production rate. Seismicity more than doubled with the start of sustained production.

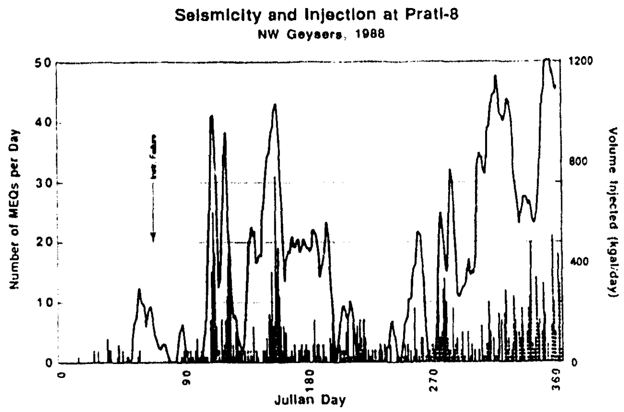


Figure 6. Comparison between injection history of Prati 8 and seismicity rate nearby. Note the good correlation between peaks in seismic activity and injection rate.

saturation changes expected in a geothermal region. The data set consists of carefully hand-picked P- and S-wave arrival times recorded by the 16- element borehole network. From the 5000 events recorded in 1988, 300 high-quality events distributed evenly through-out the field were selected for each of the time periods for the joint hypocenter-velocity inversion. The region was parameterized into a 3-D rectangular grid with velocities assigned to each nodal point. The grid contains 294 nodes spaced at 1 km horizontally, and 0.5 km vertically. The joint problem for 3-D velocity structure and hypocenter locations is solved using the progressive inversion scheme proposed by Thurber (1983) with cubic spline interpolation (Michelini, 1991).

No substantial change in the Vp/Vs structure was evident during the monitoring period. One possible reason is that one year may not be sufficient time to detect appreciable changes in reservoir properties. However, note in Figure 7 the high Vp/Vs ratio at the location of Prati 8, again possibly indicating an invaded zone around the bottom of Prati 8. The production zone is marked by a low Vp/Vs ratio between depths of 1 and 4 km, suggesting undersaturation of the reservoir rocks in response to continued steam withdrawal. The zones to the northwest indicate that the structure in this area may be controlled by a southwest to northeast cross cutting structure, possibly separating the high temperature reservoir from the main reservoir body to the southeast.

The results of the work to date in the northwest Geysers study have shown that the velocity structure and the seismicity pattern in the northwest Geysers area seem to be related to geothermal exploitation. The low Vp/Vs ratio within the producing zone is consistent with continued depletion of reservoir rocks as the field is produced. Ongoing monitoring of Vp/Vs maybe useful in tracking the expansion of the steam zone, or as seen in high Vp/Vs ratios around Prati 8, the tracking of injectate with time. Spatial and temporal correlation between seismicity and geothermal activity provide compelling evidence for induced seismicity. High resolution microearthquake locations hold promise for inferring fluid flow paths, especially in tracking injectate. Processing of the data has revealed a strong correlation between injection and seismicity. However, in addition it can be said that the injection seismicity is superimposed on a more general pattern of seismicity related to such factors as "natural" seismicity and effects of withdrawal. At this point in time we have a good characterization of the seismicity patterns in this area and their relationship to various reservoir parameters. In 1993 the NW Geysers Array will be brought back into operation (the legal and technical problems have been overcome) in order to collect background data for future injection experiments.

Southeast Geysers

In addition to the work in the northwest Geysers several operators (Calpine, NCPA, and Unocal) in the southeast Geysers region have undertaken a cooperative effort to more fully understand the mechanisms associated with reinjection activities. To date, MEQ rates and location have shown a good correlation with injection activities (Stark, 1990). UNOCAL is presently operating an analog array of MEQ stations in the injection region. Although this array has been very useful, precision location of events dictates digital acquisition at higher frequency contents using three component data. The work in the northwest Geysers has demonstrated the utility of multicomponent, high-frequency, digital data. During the last year LBL (8 stations) and LLNL (5 stations) installed a high frequency array in the SE Geysers to apply this technology to an injection experiment. It has become obvious that the split array operation is not providing reliable data on a timely basis, however, LBL is now in the process of buying 5 stations to replace the LLNL stations in order to have all of the data coming to one central point. This would streamline the data collection and processing. The data rates (seismicity) are not as high as in other areas of the field (150 to 200 events per month) so it is reasonable expect that with the split array problem solved the data processing could be done on a more timely basis than now. The objectives of the southeast MEQ study is to demonstrate the utility of high resolution, multicomponent, microearthquake data (MEQ) for understanding the effect of condensate injection. The study has been underway for a year and is not as far along in data processing as the northwest Geysers study. The work in the southeast Geysers to date has concentrated on collecting data for location and occurrence studies as well as for imaging the injection activities. With high frequency data it is also hoped that one can correlate source mechanisms (size, slip, moment, etc.) with injection activities and available stress information, as well as monitor changes in the above parameters as a function of time.

Shown in Figure 8a is the station distribution in the southeast Geysers. Also shown in Figure 8a are the locations of 610 high quality (recorded on 5 or more stations) events during the time

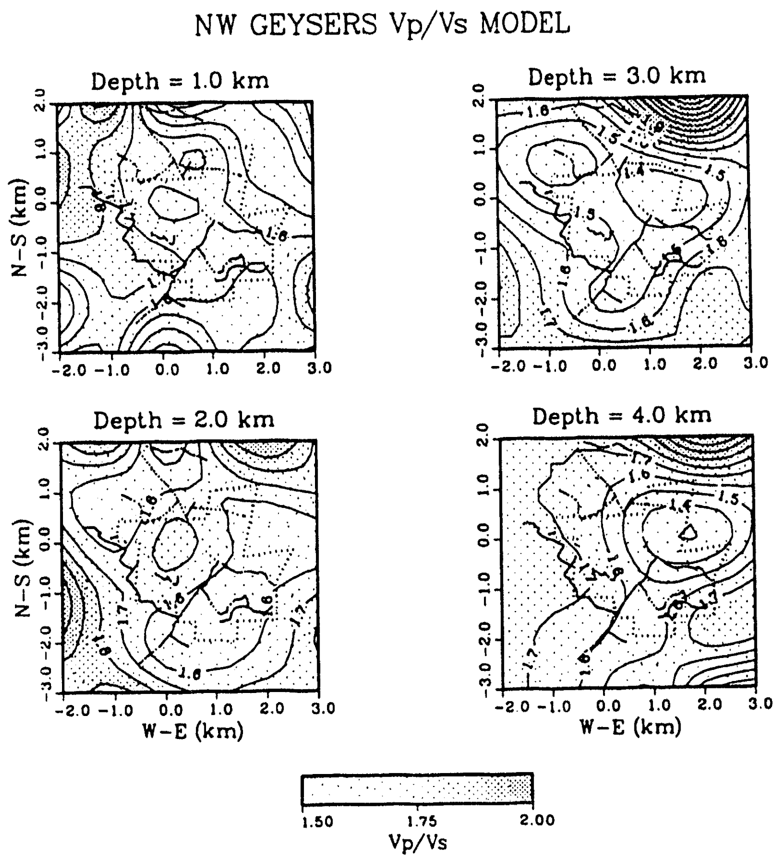


Figure 7. The Vp/Vs model of the CCPA field derived from inverting the 1988 MEQ data. Each square is a horizontal slice through the model at different depths.

period of January to September 1992. Figure 8a shows an East-West cross section projected onto a plane running through the origin (0) on Figure 8b. Figure 9 shows the reservoir pressure in isobars as of 1988, and the location of some of the MEQ stations used in this study. Also shown in Figure 9 are the locations of the wells NCPA is using for injection and the traces of the wells projected to the surface. As observed by Enedy et al. (1993) the events cluster around the injection wells. In depth, the events also cluster around the wells and less so beneath the wells, unlike the northwest Geysers. Also, as Enedy et al. (1993) showed the events do not locate within the felsite, but above it. The locations also show a good correlation to the zone of injectate, as inferred from deuterium analysis, (Enedy et al., 1993).

The locations shown in Figure 8 were derived using the same methods as developed for the analysis in the northwest Geysers, using a 3-D velocity model. In the case of the southeast Geysers the rate of activity is lower so only 231 events were used for the inversion to obtain the 3-D velocity model. Also, the spatial coverage throughout the field is not as complete as the northwest Geysers, so the resolution near the edges of the model suffers. Figure 10 is a horizontal slice of the velocity model at 1.0 kilometers below the datum. The model was derived from the joint inversion of 231 events. Also, plotted on this figure are the 610 events located with this model. As seen in the northwest Geysers there is a strong degree of lateral heterogeneity reflected in the velocity model. Correlation with the geologic structure has not been done at this time.

Seismic Imaging for Saturation Conditions

In-situ knowledge of saturation conditions at the Geysers is important for understanding the role of fluid injection in resource replenishment and to prospect for new drill sites. LLNL is engaged in a three phase project to infer these properties from seismic imaging data. Phase 1 of the project is complete and the results are reported here. The objective is to compute seismic compressional-wave velocity and attenuation images in terms of the geologic structure and fluid saturation. Data are still being collected as part of the southeast Geysers study to provide information on the injection experiments. Later phases of the work will concentrate on applying the methods to specific zones within the field, and expanding the analysis to include such parameters as amplitudes from spectral ratios and spectral matching.

Fluid saturation conditions of the matrix rock of a reservoir have traditionally been estimated from core samples. However, the data obtained in this manner tend to have a large uncertainty since the fluid in the pores tends to flash to steam due to the drop in pressure bringing the sample to the surface. If saturation data could be reliably obtained in-situ this information could be used to manage production and understand the role of injection. We are attempting to use seismic imaging to determine fluid saturation. Compressional wave velocities are sensitive to both lithology and saturation conditions so it has been traditionally difficult to separate the two effects. Our method is to include compressional wave attenuation in the analysis to try remove the effect of lithology.

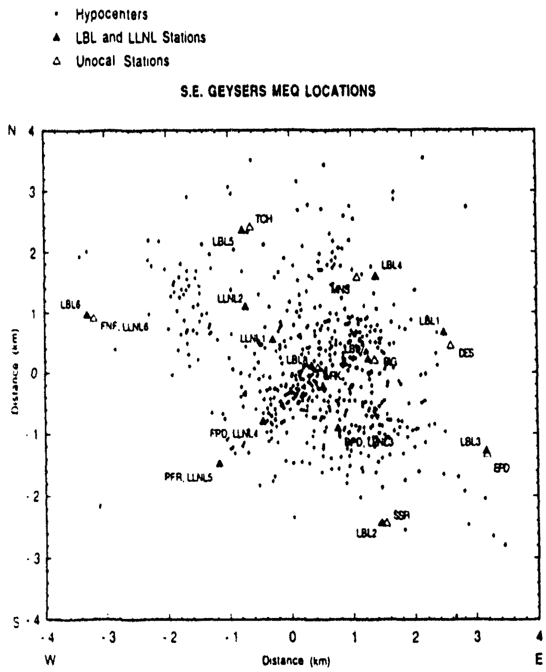


Figure 8a. The station locations and a plan view of the 610 high quality events located in the southeast Geysers during January to September, 1992 using a refined 3-D velocity model.

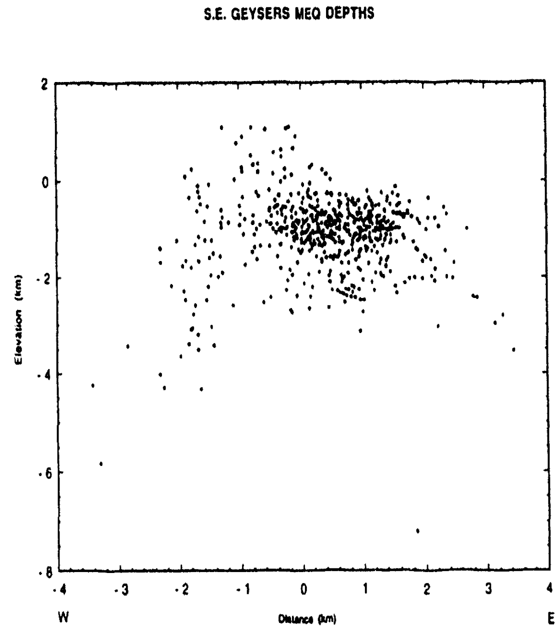


Figure 8b. An East-West cross section of Figure 8a.

Figure 11 shows the location of the study areas with respect to the boundaries of the known steam reservoir. The LLNL project consists of three phases. Phase 1 has a large target area and was an attempt to get more or less field-wide definition of saturation conditions. The data consist of approximately 300 earthquakes that are of magnitude 1.2 and distributed in depth between sea level and 2.5 km. The data were collected by the UNOCAL-NEC-Thermal (U-N-T) partnership. Phases 2 and 3 are smaller scale studies focused on specific fluid injection experiments. At the time of the writing of this paper (April 1993), the collection of the phase 2 data set is almost complete , but the analysis has not yet started. The collection of the phase 3 data is planned to begin in the Spring of 1993. Both of these projects are cooperative with the Lawrence Berkeley Laboratory as part of the southeast Geysers experiment. We base our interpretation of the velocity and attenuation data on the laboratory results of Ito et al. (1979) who carried out velocity and attenuation measurements on Berea sandstone samples at elevated temperatures and varying degrees of saturation to approximate reservoir conditions. Their measurements show that P- velocity increases with saturation but that Q (seismic quality factor = change in energy/energy per cycle) decreases. In addition, Q falls dramatically when the rocks are partially saturated. These laboratory results were for frequencies near 10,000 Hz, raising the question of their applicability to field measurements at lower frequencies. However, results from Evans and Zucca (1988) and Zucca and Evans (1992) show that P-wave attenuation and seismic velocity structure contain complimentary information at Medicine Lake and Newberry volcanoes, and may be used to predict the location of geothermal drilling targets. They found that regions with low and normal-to-high P-wave velocity are suggestive of boiling water, in areas independently identified as good geothermal prospects by other means.

Method and Data

Compressional-wave (i.e. P-wave) arrivals are used in the analysis. A first arrival is picked to measure the P-wave arrival time and the elapsed time between this arrival and the first zero crossing to measure the pulse width. The P-wave travel times and pulse widths are related to the velocity and attenuation, and related through an empirically determined constant. Integration is carried out along the ray path. Velocity is held constant during the calculation of the attenuation structure. To compute velocity and attenuation structure, we used the Thurber inversion method (Thurber, 1983) as modified by Eberhart-Phillips (personal communication, 1989) to compute a three- dimensional model of velocity. We modified the algorithm to compute attenuation structure recognizing the similar nature of the two parameters. U-N-T provided us with waveforms and hand-picked first arrivals (Debbie Turner, Unocal Inc., personal communication, 1990). Because of the abundance of data, we selected the best events to further process and obtain P-arrival times and pulse widths. We used only arrivals with at least 10:1 signal-to-noise ratio of the first pulse observed at 8 or more stations. We examined each pulse by eye for evidence of multipathing. The first arrival pick was also examined by eye to see if further adjustment was necessary. The estimated error in the arrival time reading is less than +0.01 s (one sided error). The measurement error in the first zero crossing is small compared to the error in the first arrival pick.

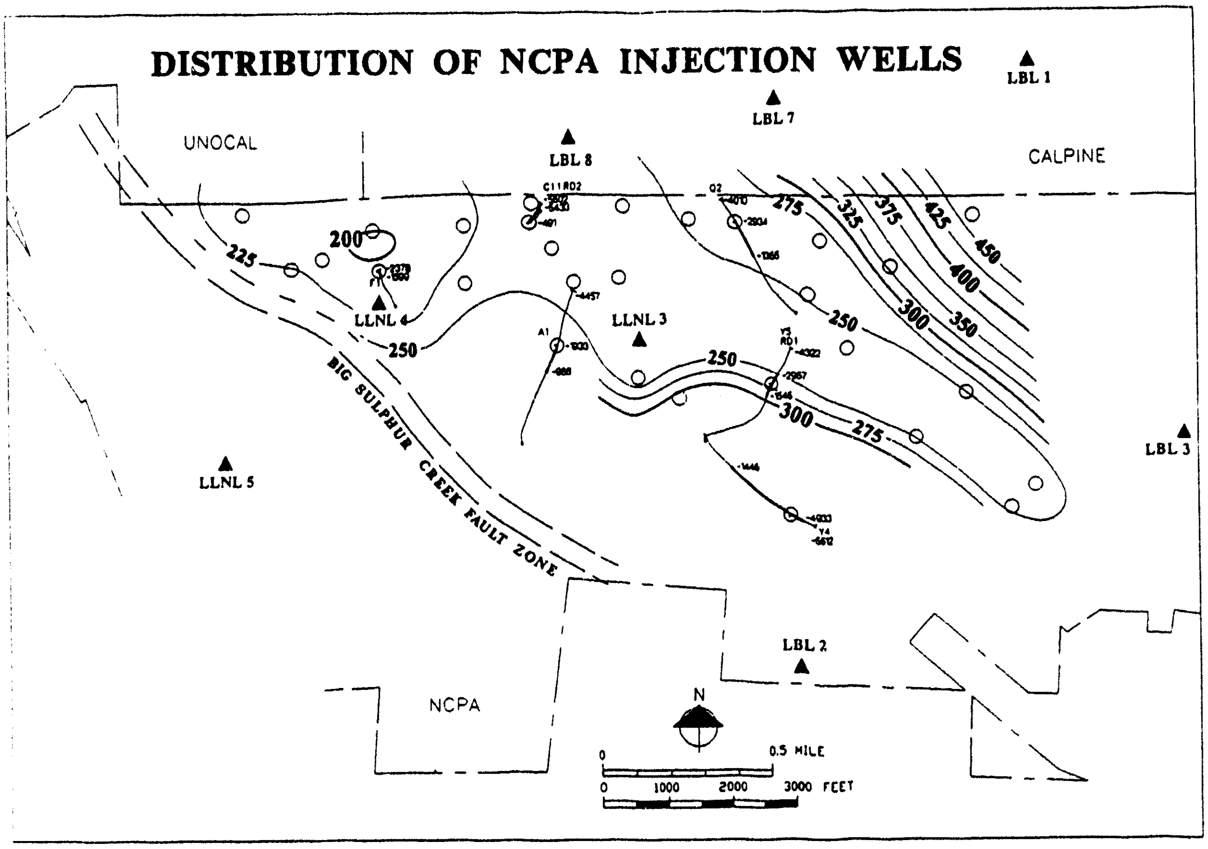


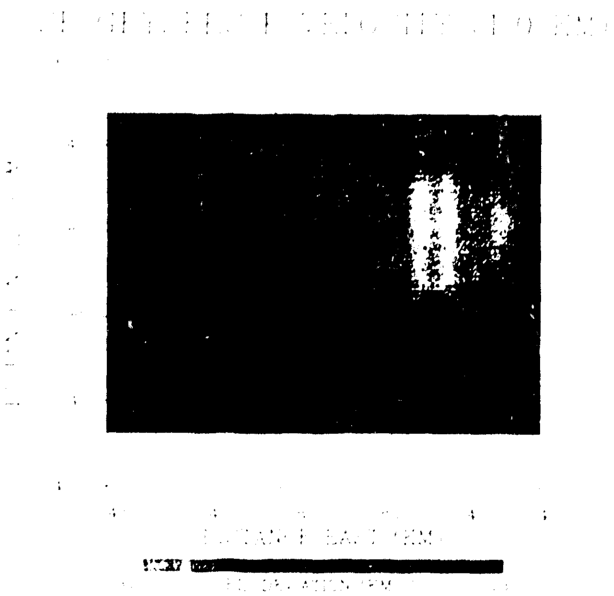
Figure 9. A map showing the distribution of seismic stations and the distribution of the NCPA injection wells. Also shown are the isobars of the reservoir pressures.(this figure was provide by NCPA)

Inversion Results

The three-dimensional inversion for velocity resulted in a 75% weighted variance reduction over the one-dimensional starting model. The velocity inversion results are shown in Figure 12. The results are displayed as horizontal slices through the three-dimensional velocity volume. Although the model extends from the surface to a depth of almost 4 km, we present only the two layers at 0.9 and 1.5 km depth for the sake of brevity. In general, the velocity increases with depth. The central portion of the model tends to have the highest relative velocities down to at least the 0.9 km depth level. At the deepest level shown at 1.5 km depth, the lower (i.e. south) part the image has the highest overall velocities. For the attenuation inversion, we were only able to achieve significant data variance reduction with the one-dimensional model. The 1D model had a starting data variance of 0.000309 s and a final data variance of 0.000073 s after calculation of the source term and variations. This is a net variance reduction of 76%, however most of this is due to solving for, the source contribution to the pulse width. Only about 15% of the variance reduction is due to the structure. The results are shown adjacent to the velocity results in Figure 12.

Interpretation

We find that the velocity structure correlates with known mapped geologic units and the location of reservoir. In Figure 12, the layer at 0.9 km depth shows low velocity correlated with the reservoir. The next layer down is at 1.5 km depth and shows the felsite intrusion associated with a blotchy series of high velocity anomalies. Although the felsite and the indurated graywacke reservoir rocks should have roughly equivalent velocity, the felsite is likely to be less fractured and could exhibit slightly higher velocity. The weak velocity contrast could explain the blotchy nature of its signature in the velocity image. The high Q in the upper part of the reservoir is consistent with the earlier results of Majer and McEvilly (1979) who also found relatively high Q in this region. The low Q in the lower part of the reservoir

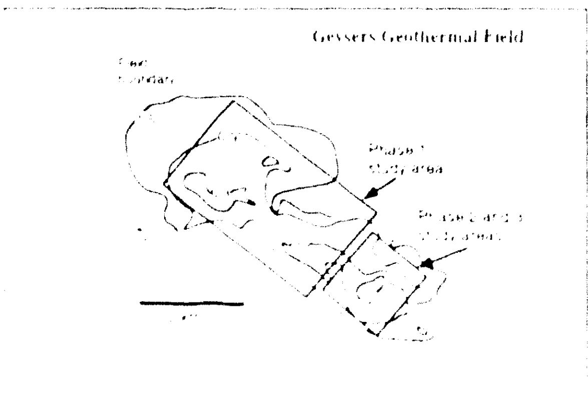


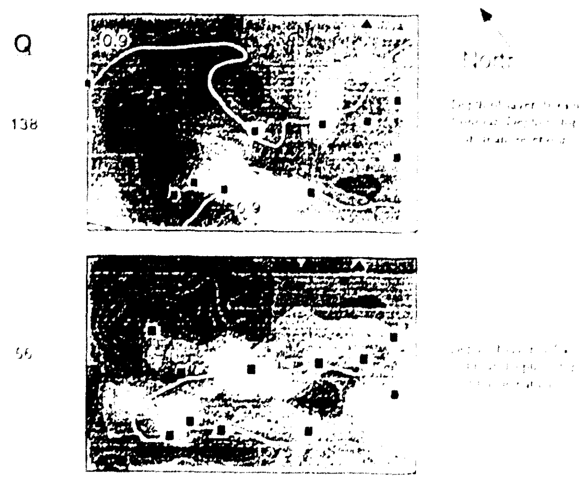
suggest that the saturation is in the 30 to 70% range while saturation at the top of the reservoir could go up or down and still agree with the lab results for Q alone obtained by Ito et al. (1979). A drop in saturation at the top of the reservoir below about 30% seems the most likely since the velocity is lower in the reservoir compared to the country rocks indicating a drop in saturation compared to the country rocks.

For phase 1, we have calculated the velocity and attenuation structure of the Geysers region using local earthquakes. Our data for the inversion consist of P wave arrival times and pulse widths which we used to compute three dimensional compressional wave velocity structure and one dimensional compressional wave attenuation structure. Our velocity structure correlates well with the surface geology and published studies on the structure of the reservoir. The reservoir appears to exhibit low velocity with the surrounding country rock. The Q decreases with depth which we infer to indicate partial saturation (30 to 70%) at depth with drier conditions near the top of the reservoir. We plan to apply a similar analysis to the data we are currently collecting at for phases 2 and 3 of our work.

Summary and Conclusions

The work to date indicates that MEQ data can, and are being used to infer the flow of injectate within the reservoir area. Recent results of the imaging indicates that the attenuation and Vp/Vs results possibly could be used to infer fluid saturation. Several unique high resolution data sets have been obtained and plans are being made to monitor several new injection projects in the near future. Cooperation with industry has yielded results that have guided and focused the work in an effective fashion. Without this cooperation the work would not have been possible.





Acknowledgment

This work was performed at Lawrence Berkeley Laboratory and Lawrence Livermore National Laboratory and was supported under the Geothermal Technology Division and the Assistant Secretary for Conservation and Renewable Energy of the U.S. Department of Energy under contract DE-AC03-76SF0098 and W-7405-ENG-48. We would also like to thank the operators of The Geysers field, Calpine, CCPA, NCPA, and Unocal for their cooperation, and in particular Mark Walters, Bill Smith, Mitch Stark, and Joe Beal for their interaction.

References

Allis, R.G., 1982, Mechanism of induced seismicity at The Geysers geothermal reservoir, California. *Geophys. Res. Lett., 9,* pp 629.

Bufe, C.G., S.M. Marks, F.W. Lester, R.S. Ludwin, and M.C. Stickney, 1981, Seismicity of the Geysers-Clear Lake region, *U.S. Geol. Surv. Prof. Pap., 1141,* pp 129.

Denlinger, R.P., and C.G. Bufe, 1981, Reservoir conditions related to induced seismicity at The Geysers steam reservoir, northern California, *Bull. Seismol. Soc. Am., 72*(4), pp 1317.

Eberhart-Phillips, D., and Oppenheimer, D.H., 1984, Induced seismicity in The Geysers geothermal area, California *J. Geophys. Res., 89,* pp 1191.

S. L. Enedy, Smith, J.L., Yarter R.E., Jones, S.M., and Cavote, P.E., 1993, Impact of injection on reservoir performance in the NCPA steam field at The Geysers, Presented at the 1993 Stanford Geothermal Workshop, Stanford, California.

Evans, J.R., and Zucca, J.J., 1988, Active High-Resolution Tomography of compressional-wave velocity and attenuation structure at Medicine Lake Volcano Northern California Cascade Range, *J. Geophys. Res., 93, 15,* pp 15,016.

Griggs, D.T., Turner, F.J., and Heard, H.C., 1960, Deformation of Rocks at 500° to 800° . *Geological Soc. Am. Mem. 79,* 39.

Hamilton, R. M., and Muffler, L. J. P., 1972, Microearthquake at The Geysers Geothermal area, California, *J. Geophys. Res., 77,* pp 2081.

Handin, J., 1966, Strength and Ductility, in Handbook of Physical Constants, S.P. Clark, Jr., (ed.) *Geol. Soc. Amer. Memoir, 97* pp 238.

Ito, H., J. DeVilbiss, and A. Nur, 1979, Compressional and shear waves in saturated rock during water-steam transition. *J. Geophys. Res. 84,* pp 4731.

Industry Consortium 1989, Geysers, 'Top of Reservoir Map' and 'Top of Felsite Map', both maps compiled through the cooperative efforts of UNOCAL, Freeport-McMoRan Geysers Geothermal, Northern California Power Association, GEO, Santa Fe Minerals Inc., and the Department of Water Resources of the state of California, presented at the Geothermal Resources Council Annual Meeting, 1 - 4 Oct., Santa Rosa, CA.

Lange, A. L., and Westphal, W. H., 1969, Microearthquakes near The Geysers, Sonoma County, California, *J. Geophy. Res., 74,* pp 4377.

Ludwin, R.S. and C.G. Bufe, 1980, Continued seismic monitoring of The Geysers, California, geothermal area, *U.S. Geol. Surv. Open File Rep., 80-1060,* 50 pp.

Ludwin, R.S., Cagnetti, V., and Bufe, C.G., 1982, Comparison of seismicity in The Geysers geothermal area with the surrounding region, *Bull. Seism. Soc. Am., 72,* pp 863.

Majer, E. L. and T. V. McEvilly, 1979, Seismological investigations of the geysers geothermal field. *Geophysics 44,* pp 246.

Majer, E.L., 1978, Seismological Investigation in Geothermal Regions, Ph.D. thesis, University of California, Berkeley, LBL Report 7054.

Marks, S.M., Ludwin, R.S., Louie, K.B. and Bufe, C.G., 1978, Seismic monitoring at The Geysers geothermal field, California, *U.S. Geol. Surv. Open File Rep., 78-798,* 26 pp.

McGarr, A., 1976, Seismic moments and volume changes, *J. Geophys. Res., 81,* pp 1487.

McNally, K.C., 1976, Spatial, Temporal, and Mechanistic Character in Earthquake Occurrence, A Segment of the San Andreas Fault in Central California. Ph.D. Thesis, University of California, Berkeley.

Michelini, A., 1991. Fault zone structure determined through the analysis of earthquake arrival times (Ph.D. Thesis), University of California, Berkeley.

Oppenheimer, D.H., 1986, Extensional tectonics at The Geysers geothermal area, California, *J. Geophys. Res., 91,* pp 11463.

Peppin, W.A., and Bufe, C.G., 1980, Induced(?) versus natural earthquakes: Search for a seismic discriminant, *Bull. Seismol. Soc. Am. 70*(1), pp 269.

Spencer, E.W., 1969, *Introduction to the Structure of the Earth,* New York, McGraw-Hill.

Stark, M. A., 1990. Imaging injected water in The Geysers reservoir using microearthquake data. *GRC Transactions, v. 14,* pp 1697.

Stark, C.L., and Majer, E.L., 1989, Seismicity of the Southeastern Geysers. LBL-26679, 109 pp.

Stesky, R.M., 1977, Rock Friction - Effect of Confining Pressure. *Proc. of Conference II, Experimental Studies of Rock Friction with Application to Earthquake Prediction.* U.S. Geological Survey, p. 331.

Thurber, C.H., 1983. Earthquake locations and three- dimensional crustal structure in the Coyote Lake area, Central California, *J. Geophys. Res., v. 88,* p. 8226.

Zucca, J. J., and J. R. Evans, 1991, Active high-resolution compressional-wave attenuation tomography at Newberry volcano, central California, *J. Geophys. Res., 97,* pp 11, 047.

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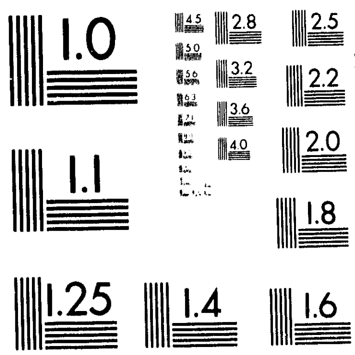
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Seismic Monitoring at The Geysers

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Introduction

During the last several years Lawrence Berkeley Laboratory (LBL) and Lawrence Livermore National Laboratory (LLNL) have been working with industry partners at The Geysers geothermal field to evaluate and develop methods for applying the results of microearthquake (MEQ) monitoring. It is a well know fact that seismicity at The Geysers is a common occurrence, however, there have been many studies and papers written on the origin and significance of the seismicity. The attitude toward MEQ data ranges from being nothing more than an curious artifact of the production activities, to being a critical tool in evaluating the reservoir performance. The purpose of the work undertaken by LBL and LLNL is to evaluate the utility, as well as the methods and procedures used in of MEQ monitoring, recommend the most cost effective implementation of the methods, and if possible link physical processes and parameters to the generation of MEQ activity.

One of the most promising uses of MEQ monitoring that has been proposed is monitoring the flow of fluids during injection activities. Another proposed use has been to define active fault and fracture patterns that could be possible targets for in-fill drilling. A more recent use has been to use the microearthquakes as sources to image the physical properties within the reservoir area. The success of all of these proposed uses, as well as any other, will depend upon the resolution obtained and the understanding of the physical and chemical processes causing the MEQ activity. The use, or misuse, of MEQ data is critically dependent upon the quality and resolution of the data. In this sense The Geysers offers an excellent and unique test case due to the diversity of MEQ studies carried out at The Geysers and the supporting geological, geophysical, hydrological, and geochemical information potentially available.

To address the objectives above the MEQ work can be categorized into two types of studies. The first type is the direct analysis of the spatial and temporal distribution of MEQ activity and studying the nature of the source function relative to the physical or chemical processes causing the seismicity. The second broad area of study is imaging the reservoir/geothermal areas with the energy created by the MEQ activity and inferring the physical and/or chemical properties within the zone of imaging. The two types of studies have obvious overlap, and for a complete evaluation and development require high quality data from arrays of multicomponent stations. Much of the effort to date at The Geysers by both DOE and the producers has concentrated establishing a high quality data base. It is only within the last several years that this data base is being fully evaluated for the proper and cost effective use of MEQ activity. Presented here are the results to date of DOE's effort in the acquisition and analysis of the MEQ data.

Background

One of the earliest published reports on MEQ's at The Geysers was done by Langue and Westphal in 1969. In this paper, it was reported that the recorded seismicity was shallow (≤ 5 km) and at a rate of 4 events per day. In 1972, Hamilton and Muffler observed activity of similar amounts, with the activity localized in the production area. At this time, the power generation was 82 MW. As time passed and the steam production rate increased, the MEQ activity also increased. By September of 1976, with a power generation of 550 MW, the activity rate had increased to 25 to 30 events per day (Majer, 1978). In these early studies, the magnitudes and detection thresholds were not well defined but magnitude zero seemed to be the lower detection threshold of these surveys. By 1984, when the production had increased to 1000 MW, it had become quite clear that there was a direct relationship between production and seismicity. Since the early work on microseismicity at the Geysers, a number of authors have reported the empirical link between production activities and seismicity (Marks, et al, 1978; Ludwin and Bufe, 1980; Peppin and Bufe, 1980; Bufe, et al, 1981; Allis, 1982; Denlinger and Bufe, 1982; Ludwin, et al, 1982; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986; Stark and Majer, 1989) just to name a few. Oppenheimer, (1986) quite clearly showed the that the location of earthquakes with $M \geq 1.2$ for the periods 1976-1984 spatially correlated with the growth in the number of power plants. Most of these authors agree that the seismicity is not associated with any dominant through going fault system. The activity seemed to occur somewhat at random and appeared to be clustered in the production region. Most of the events recorded in these studies were strike-slip and normal in nature (Oppenheimer 1986), but also exhibited some thrust activity at shallow depths. Again, as noted on the early surveys, the seismicity was very shallow, and almost all less than 5 km in depth below the surface.

The arrays that were used in locating the above-mentioned events were mostly analog recording with low frequency (< 50 hz) response. Also, the stations spacings were on the order of several kilometers at best, thus yielding location error of ± 1 km to $\pm .5$ km, in general. In the last several years, however, several arrays with high frequency digital borehole 3-component recording have been installed at The Geysers, (Figure 1). One such array is in the Northwest Geysers, which was installed by Geothermal Energy Operators (GEO), and now owned by the Central California Power Association (CCPA) and is operated by the Russian River Energy Company. Its intended purpose is to monitor MEQ activity associated with production activities. The CCPA array is unique in its capability because of the dense station coverage (16 stations), high frequency digital sampling on three components (400 samples/second/channel), and its boreholes sensors. The data from this array make it ideal for evaluating MEQ monitoring techniques. In addition to CCPA array, Unocal operates an analog array in the central and southeast Geysers region. The

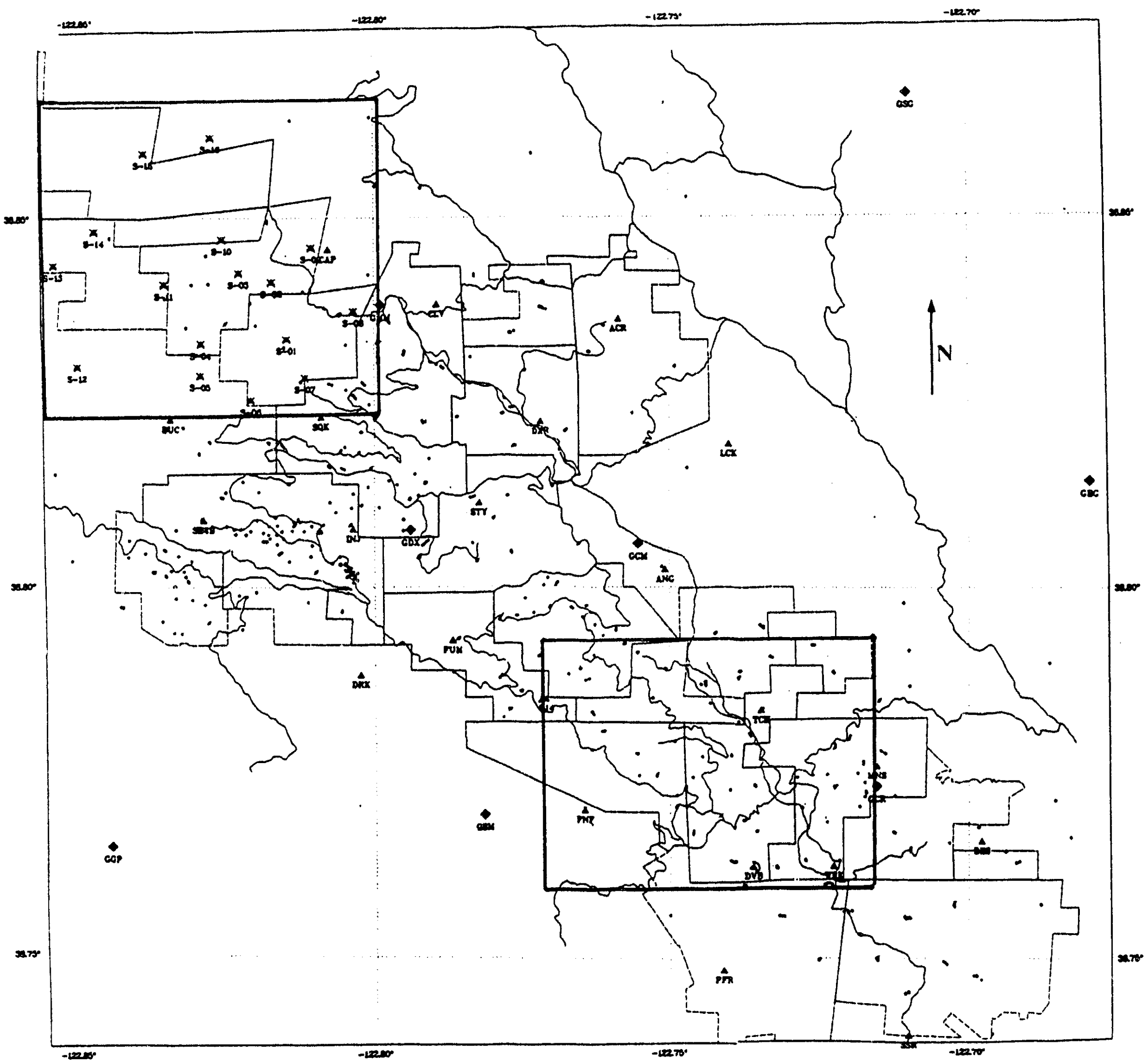


Figure 1. The locations of the seismic monotoring stations in The Geysers area. The northwest and southeast Geysers microearthquake arrays being used in this study are highlighted. Also shown are some of the USGS stations used in previous studies. Note the density of the stations used in this study to the station spacing used in the studies using the USGS stations.

Unocal southeast array has been augmented by equipment from LBL and LLNL with 13 high frequency (480 samples/second/channel) digital three component stations. The CCPA array and the southeast array have been the source of the majority of the data for the results reported here. These arrays are routinely collecting microearthquakes down to magnitude -1. With this improved capability the goal is to be able to improve on early studies and hopefully determine a more precise relation between production activities and seismicity. Overall the objectives of the MEQ work are:

(1) Demonstrate the utility of high resolution, multicomponent, microearthquake data (MEQ) for:

(a) Locating high permeability paths in the reservoir.

(b) Aid in the location of in-fill well drilling.

(c) Monitor effect of condensate injection in real time.

(2) Develop 3-D model of reservoir.

(a) P- and S-wave velocity and amplitude structure.

(b) Poissons ratio model.

(c) 3-D structural model using MEQ locations for inferring flow paths.

To fully understand the relation between microearthquakes and a geothermal environment, many different factors must be considered. A crucial question to answer is: does such a phenomenon as a "geothermal earthquake" exist? If so, a useful exploration and/or monitoring tool would be provided. On a fundamental level, the basic mechanism of an earthquake is a sudden loss of cohesion or strength of a material. The factors controlling failure are: rock type, confining pressure, temperature, amount and manner of directed stress, solubility of the material, time and rate of strain (Spencer, 1969). Although all these factors are closely interrelated, an obvious characteristic to examine in geothermal regions is the temperature. Though not always consistent, the effect of increasing temperature is to lower the brittle-ductile transition pressure, (Griggs, Turner, and Heard, 1960). Increasing temperature may also tend to decrease the rate of microearthquakes (McNally, 1976). However, only at temperatures in excess of 400°C does this effect begin to dominate. At these temperatures, the motion on a fault becomes stable gliding rather than a series of discrete, rapid slips or "stick-slip" (Stesky, 1977). Therefore, in a region that is anomalously hot, microearthquakes may be expected to be absent or to exist only at shallower depths. An increase in temperature also tends to increase the fault angle with respect to the principal stress direction (Handin, 1966). In a region that is under relatively uniform stress, a hot area may be indicated by anomalous fault plane solutions compared to the cooler surrounding areas. In the Geysers, one mechanism in particular that may be causing MEQ activity is the conversion of a seismic slip to seismic slip due to an increase in coefficient of friction due to exsolved silica into fracture surfaces (Allis, 1982).

Increased temperature may also have an indirect effect by influencing the content of the pores. If the temperature is high enough, steam, rather than water, may be present. A common failure criteria is the Coulomb relation, the total shearing resistance offered by an isotropic material to failure, is proportional to the effective normal stress , the difference between the actual normal stress , and the pore pressure . If the pores contain steam, which is highly compressible, is small; thus is larger than in an adjacent area where the pores are filled with water and is large. Therefore, would be expected to be higher in a steam filled region, thus resulting in fewer earthquakes compared to an adjacent region. This assumes, of course, that all other parameters remain constant, which is not the case. Injection, or withdrawal of fluids may also affect the normal stress, thus either decreasing or increasing the threshold of failure, respectively.

In a convective geothermal system, the temperature gradients in the zone of convection are not as large as the temperature gradients on the edges of the reservoir. If the reservoir is a vapor dominated resource, pore pressure may also remain relatively constant within the steam zone, especially compared to a hydrostatic gradient. However, the pressure differential between the outside and inside of the reservoir would vary considerably from the top to the bottom. These pressure differentials may be evident in the stress drops or available stresses for an earthquake. If there is a systematic variation in the magnitude of microearthquakes with depth, or in relation to steam zones, such a differential pressure effect may be responsible.

Another parameter most likely to be affected by geothermal activity would be the rock type. The high temperatures and hydrothermal activity undoubtedly alter the rocks within the reservoir. A possible mechanical effect is to weaken the rocks in certain regions and possibly strengthen the rocks in certain regions and possibly strengthen the rocks where the hydrothermal solution cools and deposits its dissolved solids. Along with hydrothermal activity, such factors as differential expansion due to larger temperature gradients, weakening from dehydration erosion, and hydrolytic weakening of quartz may all lower the failure criteria of the material, thus encouraging seismicity.

Unfortunately, geothermal reservoirs are not describable in steady-state terms, especially if the resource is being exploited. Continual fluid movement, phase-changes, and heat transfer will change the state of the reservoir. If microearthquake activity is related closely to these processes, then the seismicity will also be in continual state of flux. Microearthquake activity may indicate the balance between the withdrawal of fluids and the recharge of fluids from the surrounding water supply. Volumetric changes occur when the fluid is withdrawn, and, because of finite permeability, the recharge is not instantaneous. McGarr (1976) has shown that for volume changes due to mining operations, there is a close relationship between the volumetric moment due to seismic failure and the amount of rock removed. Although rock is not being removed in the geothermal case (other than the amount by dissolution), compaction would be expected to occur with possible failure consistent with the direction of the maximum principal stress. If more fluid is being withdrawn than replaced by ground water recharge or reinjection, an increase in microearthquake activity could be expected. Also, as this occurs and pore pressure drops a steam zone may develop if ample heat is available. Therefore, rather than an exploratory tool, microearthquake monitoring may prove useful for determining areas of recharge and depletion within a producing reservoir.

Microearthquake Location and Occurrence Studies

As stated earlier the two broad areas of investigation have been in the characterization of the MEQ activity (space and time) and in the use of the MEQ activity for imaging the subsurface. Presented in this section are the results of the location and occurrence work in the northwest Geysers and the southeast Geysers. The data from this work has come from the CCPA network and the Unocal network augmented LBL/LLNL stations in the southeast Geysers.

Northwest Geysers

In March of 1990 LBL, in conjunction with the Coldwater Creek Operator Company (CCOC), (Now CCPA) undertook the collection, analysis processing, and interpretation of the microearthquake (MEQ) data from the 16 station, digital, 3 component, high frequency CCOC array in place at the northwest Geysers geothermal field. To date the processing has concentrated only on data collected prior to full production and injection in the NW Geysers and for approximately after one year full production and injection activities started (1988). (This involved detailed analysis and processing of approximately 5000 events.) During this time the injection occurred at two different sites, Prati 8 and 9, but with the main injection at Prati 8. The array has been out of operation due to legal and technical complications, however, it is anticipated that the array will be brought back into operation in 1993 to begin background monitoring prior to new injection activities.

Several previous studies have concluded that the high seismicity in The Geysers region is related to geothermal development (Eberhart-Phillips and Oppenheimer, 1984; Stark, 1990). Results of the present study indicate further that seismicity rate is related to production and injection and that reservoir property changes due to exploitation may be detected. Figure 2 presents in plan view the relocated hypocenters of the events around the CCPA area. Microearthquakes are concentrated within the CCPA field extending south and east into the older sections of the producing field. Seismicity is low to the north and west in the direction where the field is undeveloped. Seismicity occurs in two distinct 2 zones: a broad, shallow zone between 1 and 3 km depth, presumably related to the production zone, and a deeper cluster between 3.5 and 5 km depth just beyond the southeast edge of the field, (see Figure 3). A cluster of microearthquakes with focal depths between 2 and 3 km is located beneath the injector

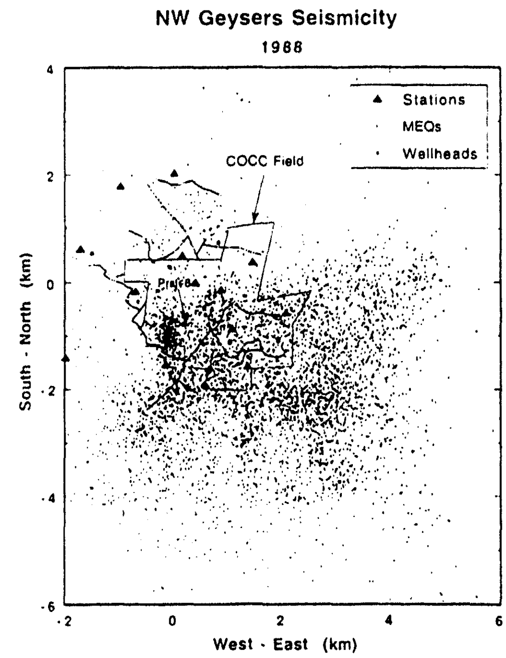


Figure 2. Map view showing the locations of microearthquakes during 1988 in the CCPA geothermal field. Microearthquakes are concentrated within the central part of the field extending south and east. Seismicity is low to the north where the field is not being produced.

well Prati-8, as shown in Figure 3. The microearthquake distribution seems to define a vertical planar structure striking roughly north-south. Figure 4 is an expanded view of the seismicity around Prati 8. As can be seen there is a strong spatial correlation of the seismicity to zone around the bottom of Prati 8 and extending several hundred meters beneath the well. Current pressure data from Prati 9 suggest that injection does have an effect on the saturation of the formation an fluid is invading the zones around the well. (Pers Comm, M. Walters, Russian River Energy Corp) If this also occurred around Prati 8 then the seismicity may indeed be an indication of the zone of invasion of the fluid.

In terms of temporal correlation, Figure 5 presents a comparison between the seismicity rate within the CCPA area and the field-wide steam production rate. Beginning at Julian day 90, 1988, seismicity increased significantly to approximately 20 events per day, more than double the pre-production seismicity rate. High seismicity was sustained during the course of steam production except during a short lull between Julian days 225 and 270 when production rate decreased temporarily. Figure 6 presents a comparison between Prati 8's injection history and seismicity rate nearby. Note the good correlation between peaks in seismic activity and injection rate. Seismicity increased with the start of sustained injection, and peaks in seismicity occurred during periods of maximum injection. Spatial and temporal correlation between injection activity and seismicity provide compelling evidence for induced seismicity around Prati 8.

In addition to investigating the characteristics of the microearthquakes themselves, the temporal changes in the velocity structure and seismicity patterns in response to geothermal activity are also being investigated. Particular attention has focused on the changes in the Vp/Vs structure because of its sensitivity to fluid

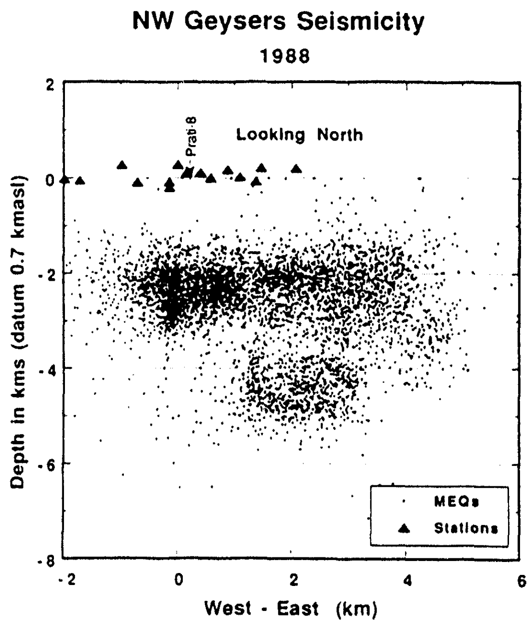


Figure 3. Cross section (East to West) of seismicity through the northwest Geysers. Note the two distinct zones of seismicity, shallow in the production zone and deep below the production zone. Note the clustering of events beneath the injector Prati 8. Datum plane is 0.7 kmasl.

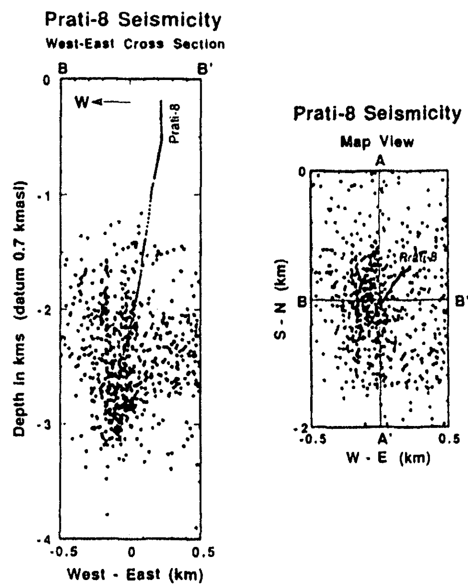


Figure 4. Expanded and cross sectional view, and map view of microearthquake locations around the injector Prati 8. The microearthquake distribution seems to define a vertical plane striking N-S. Datum plane is 0.7 kmasl.

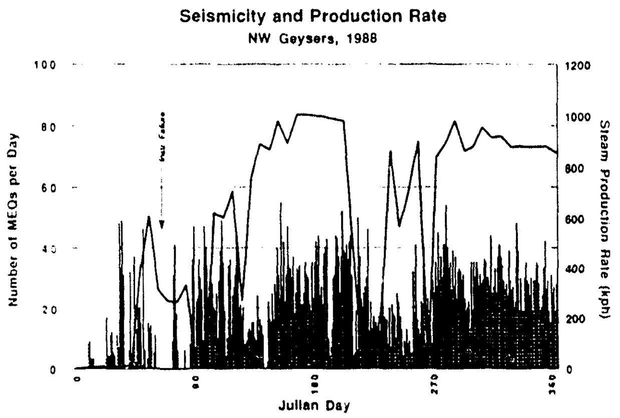


Figure 5. Comparison between the seismicity rate within the CCPA area and field-wide steam production rate. Seismicity more than doubled with the start of sustained production.

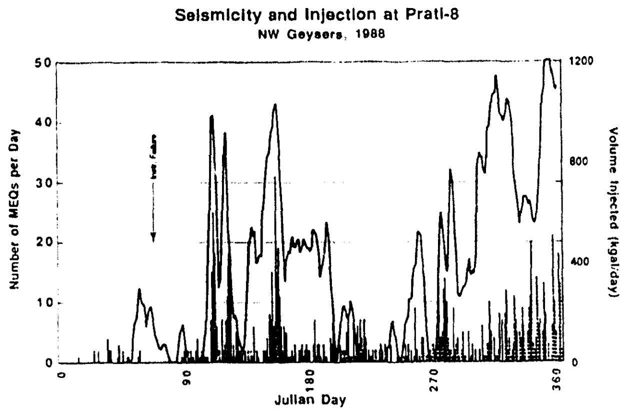


Figure 6. Comparison between injection history of Prati 8 and seismicity rate nearby. Note the good correlation between peaks in seismic activity and injection rate.

saturation changes expected in a geothermal region. The data set consists of carefully hand-picked P- and S-wave arrival times recorded by the 16- element borehole network. From the 5000 events recorded in 1988, 300 high-quality events distributed evenly through-out the field were selected for each of the time periods for the joint hypocenter-velocity inversion. The region was parameterized into a 3-D rectangular grid with velocities assigned to each nodal point. The grid contains 294 nodes spaced at 1 km horizontally, and 0.5 km vertically. The joint problem for 3-D velocity structure and hypocenter locations is solved using the progressive inversion scheme proposed by Thurber (1983) with cubic spline interpolation (Michelini, 1991).

No substantial change in the Vp/Vs structure was evident during the monitoring period. One possible reason is that one year may not be sufficient time to detect appreciable changes in reservoir properties. However, note in Figure 7 the high Vp/Vs ratio at the location of Prati 8, again possibly indicating an invaded zone around the bottom of Prati 8. The production zone is marked by a low Vp/Vs ratio between depths of 1 and 4 km, suggesting undersaturation of the reservoir rocks in response to continued steam withdrawal. The zones to the northwest indicate that the structure in this area may be controlled by a southwest to northeast cross cutting structure, possibly separating the high temperature reservoir from the main reservoir body to the southeast.

The results of the work to date in the northwest Geysers study have shown that the velocity structure and the seismicity pattern in the northwest Geysers area seem to be related to geothermal exploitation. The low Vp/Vs ratio within the producing zone is consistent with continued depletion of reservoir rocks as the field is produced. Ongoing monitoring of Vp/Vs maybe useful in tracking the expansion of the steam zone, or as seen in high Vp/Vs ratios around Prati 8, the tracking of injectate with time. Spatial and temporal correlation between seismicity and geothermal activity provide compelling evidence for induced seismicity. High resolution microearthquake locations hold promise for inferring fluid flow paths, especially in tracking injectate. Processing of the data has revealed a strong correlation between injection and seismicity. However, in addition it can be said that the injection seismicity is superimposed on a more general pattern of seismicity related to such factors as "natural" seismicity and effects of withdrawal. At this point in time we have a good characterization of the seismicity patterns in this area and their relationship to various reservoir parameters. In 1993 the NW Geysers Array will be brought back into operation (the legal and technical problems have been overcome) in order to collect background data for future injection experiments.

Southeast Geysers

In addition to the work in the northwest Geysers several operators (Calpine, NCPA, and Unocal) in the southeast Geysers region have undertaken a cooperative effort to more fully understand the mechanisms associated with reinjection activities. To date, MEQ rates and location have shown a good correlation with injection activities (Stark, 1990). UNOCAL is presently operating an analog array of MEQ stations in the injection region. Although this array has been very useful, precision location of events dictates digital acquisition at higher frequency contents using three component data. The work in the northwest Geysers has demonstrated the utility of multicomponent, high-frequency, digital data. During the last year LBL (8 stations) and LLNL (5 stations) installed a high frequency array in the SE Geysers to apply this technology to an injection experiment. It has become obvious that the split array operation is not providing reliable data on a timely basis, however, LBL is now in the process of buying 5 stations to replace the LLNL stations in order to have all of the data coming to one central point. This would streamline the data collection and processing. The data rates (seismicity) are not as high as in other areas of the field (150 to 200 events per month) so it is reasonable expect that with the split array problem solved the data processing could be done on a more timely basis than now. The objectives of the southeast MEQ study is to demonstrate the utility of high resolution, multicomponent, microearthquake data (MEQ) for understanding the effect of condensate injection. The study has been underway for a year and is not as far along in data processing as the northwest Geysers study. The work in the southeast Geysers to date has concentrated on collecting data for location and occurrence studies as well as for imaging the injection activities. With high frequency data it is also hoped that one can correlate source mechanisms (size, slip, moment, etc.) with injection activities and available stress information, as well as monitor changes in the above parameters as a function of time.

Shown in Figure 8a is the station distribution in the southeast Geysers. Also shown in Figure 8a are the locations of 610 high quality (recorded on 5 or more stations) events during the time

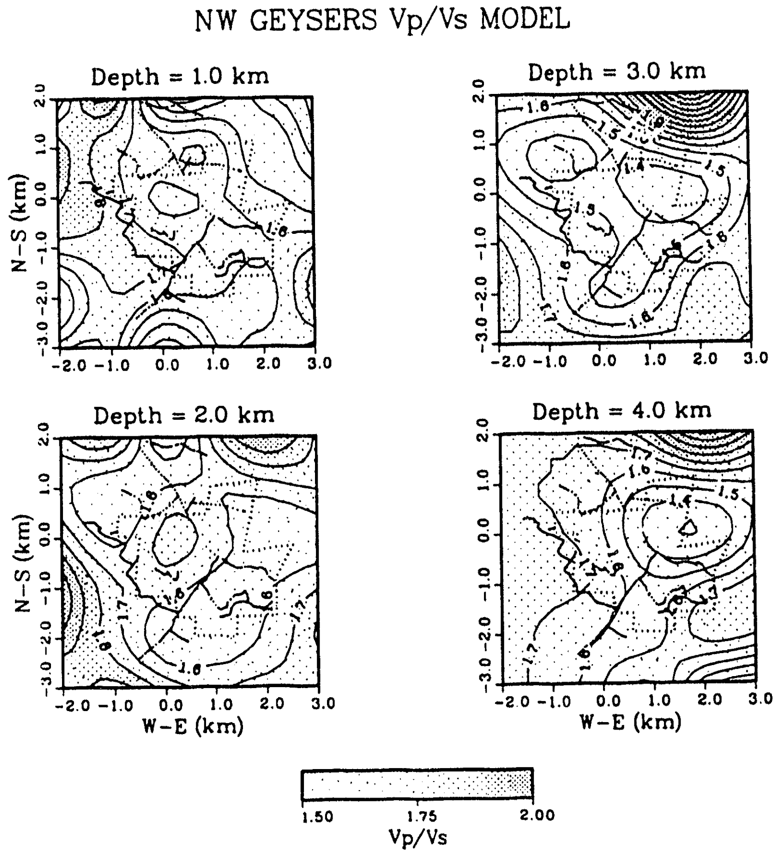


Figure 7. The Vp/Vs model of the CCPA field derived from inverting the 1988 MEQ data. Each square is a horizontal slice through the model at different depths.

period of January to September 1992. Figure 8a shows an East-West cross section projected onto a plane running through the origin (0) on Figure 8b. Figure 9 shows the reservoir pressure in isobars as of 1988, and the location of some of the MEQ stations used in this study. Also shown in Figure 9 are the locations of the wells NCPA is using for injection and the traces of the wells projected to the surface. As observed by Enedy et al. (1993) the events cluster around the injection wells. In depth, the events also cluster around the wells and less so beneath the wells, unlike the northwest Geysers. Also, as Enedy et al. (1993) showed the events do not locate within the felsite, but above it. The locations also show a good correlation to the zone of injectate, as inferred from deuterium analysis, (Enedy et al., 1993).

The locations shown in Figure 8 were derived using the same methods as developed for the analysis in the northwest Geysers, using a 3-D velocity model. In the case of the southeast Geysers the rate of activity is lower so only 231 events were used for the inversion to obtain the 3-D velocity model. Also, the spatial coverage throughout the field is not as complete as the northwest Geysers, so the resolution near the edges of the model suffers. Figure 10 is a horizontal slice of the velocity model at 1.0 kilometers below the datum. The model was derived from the joint inversion of 231 events. Also, plotted on this figure are the 610 events located with this model. As seen in the northwest Geysers there is a strong degree of lateral heterogeneity reflected in the velocity model. Correlation with the geologic structure has not been done at this time.

Seismic Imaging for Saturation Conditions

In-situ knowledge of saturation conditions at the Geysers is important for understanding the role of fluid injection in resource replenishment and to prospect for new drill sites. LLNL is engaged in a three phase project to infer these properties from seismic imaging data. Phase 1 of the project is complete and the results are reported here. The objective is to compute seismic compressional-wave velocity and attenuation images in terms of the geologic structure and fluid saturation. Data are still being collected as part of the southeast Geysers study to provide information on the injection experiments. Later phases of the work will concentrate on applying the methods to specific zones within the field, and expanding the analysis to include such parameters as amplitudes from spectral ratios and spectral matching.

Fluid saturation conditions of the matrix rock of a reservoir have traditionally been estimated from core samples. However, the data obtained in this manner tend to have a large uncertainty since the fluid in the pores tends to flash to steam due to the drop in pressure bringing the sample to the surface. If saturation data could be reliably obtained in-situ this information could be used to manage production and understand the role of injection. We are attempting to use seismic imaging to determine fluid saturation. Compressional wave velocities are sensitive to both lithology and saturation conditions so it has been traditionally difficult to separate the two effects. Our method is to include compressional wave attenuation in the analysis to try remove the effect of lithology.

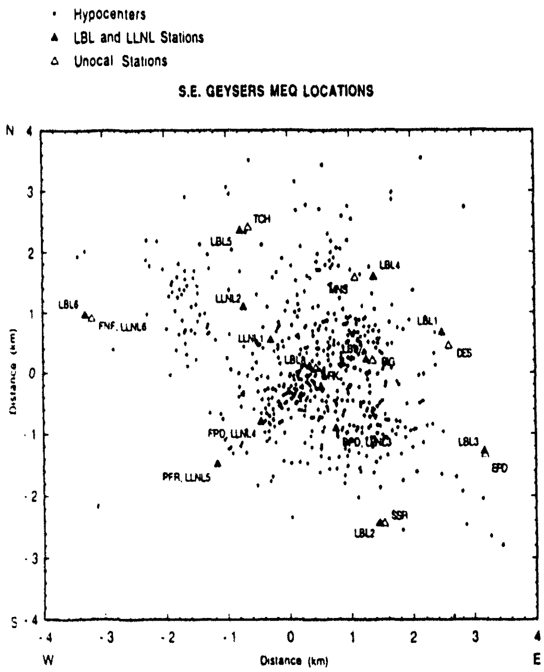


Figure 8a. The station locations and a plan view of the 610 high quality events located in the southeast Geysers during January to September, 1992 using a refined 3-D velocity model.

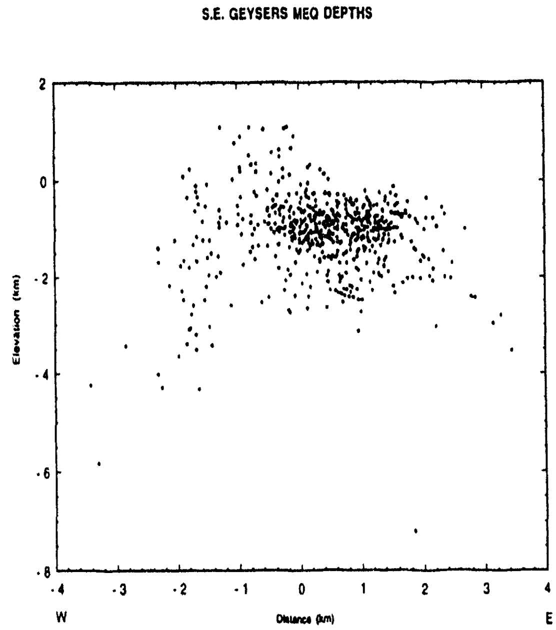


Figure 8b. An East-West cross section of Figure 8a.

Figure 11 shows the location of the study areas with respect to the boundaries of the known steam reservoir. The LLNL project consists of three phases. Phase 1 has a large target area and was an attempt to get more or less field-wide definition of saturation conditions. The data consist of approximately 300 earthquakes that are of magnitude 1.2 and distributed in depth between sea level and 2.5 km. The data were collected by the UNOCAL-NEC-Thermal (U-N-T) partnership. Phases 2 and 3 are smaller scale studies focused on specific fluid injection experiments. At the time of the writing of this paper (April 1993), the collection of the phase 2 data set is almost complete , but the analysis has not yet started. The collection of the phase 3 data is planned to begin in the Spring of 1993. Both of these projects are cooperative with the Lawrence Berkeley Laboratory as part of the southeast Geysers experiment. We base our interpretation of the velocity and attenuation data on the laboratory results of Ito et al. (1979) who carried out velocity and attenuation measurements on Berea sandstone samples at elevated temperatures and varying degrees of saturation to approximate reservoir conditions. Their measurements show that P- velocity increases with saturation but that Q (seismic quality factor = change in energy/energy per cycle) decreases. In addition, Q falls dramatically when the rocks are partially saturated. These laboratory results were for frequencies near 10,000 Hz, raising the question of their applicability to field measurements at lower frequencies. However, results from Evans and Zucca (1988) and Zucca and Evans (1992) show that P-wave attenuation and seismic velocity structure contain complimentary information at Medicine Lake and Newberry volcanoes, and may be used to predict the location of geothermal drilling targets. They found that regions with low and normal-to-high P-wave velocity are suggestive of boiling water, in areas independently identified as good geothermal prospects by other means.

Method and Data

Compressional-wave (i.e. P-wave) arrivals are used in the analysis. A first arrival is picked to measure the P-wave arrival time and the elapsed time between this arrival and the first zero crossing to measure the pulse width. The P-wave travel times and pulse widths are related to the velocity and attenuation, and related through an empirically determined constant. Integration is carried out along the ray path. Velocity is held constant during the calculation of the attenuation structure. To compute velocity and attenuation structure, we used the Thurber inversion method (Thurber, 1983) as modified by Eberhart-Phillips (personal communication, 1989) to compute a three- dimensional model of velocity. We modified the algorithm to compute attenuation structure recognizing the similar nature of the two parameters. U-N-T provided us with waveforms and hand-picked first arrivals (Debbie Turner, Unocal Inc., personal communication, 1990). Because of the abundance of data, we selected the best events to further process and obtain P-arrival times and pulse widths. We used only arrivals with at least 10:1 signal-to-noise ratio of the first pulse observed at 8 or more stations. We examined each pulse by eye for evidence of multipathing. The first arrival pick was also examined by eye to see if further adjustment was necessary. The estimated error in the arrival time reading is less than +0.01 s (one sided error). The measurement error in the first zero crossing is small compared to the error in the first arrival pick.

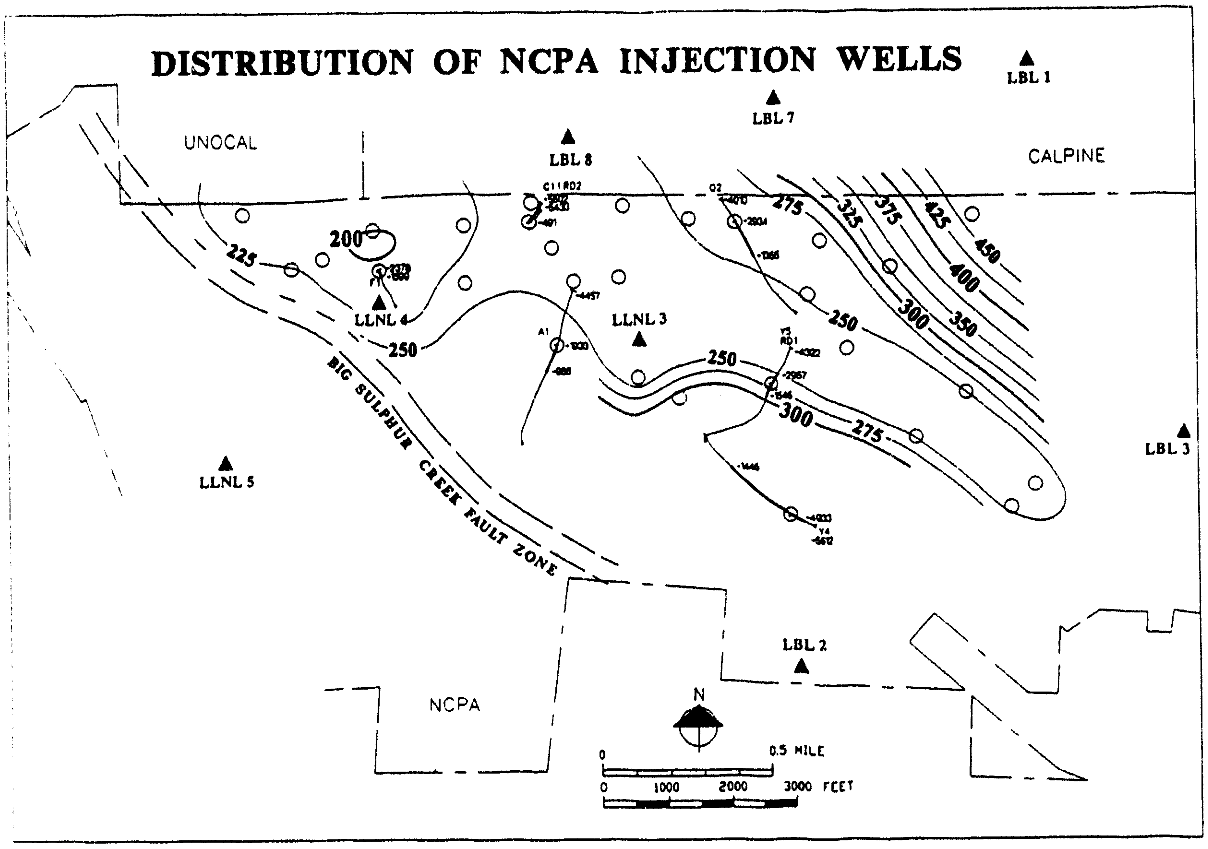


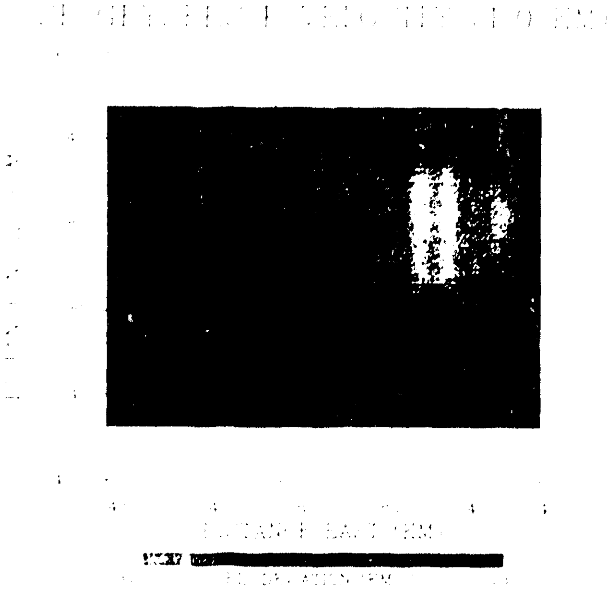
Figure 9. A map showing the distribution of seismic stations and the distribution of the NCPA injection wells. Also shown are the isobars of the reservoir pressures.(this figure was provide by NCPA)

Inversion Results

The three-dimensional inversion for velocity resulted in a 75% weighted variance reduction over the one-dimensional starting model. The velocity inversion results are shown in Figure 12. The results are displayed as horizontal slices through the three-dimensional velocity volume. Although the model extends from the surface to a depth of almost 4 km, we present only the two layers at 0.9 and 1.5 km depth for the sake of brevity. In general, the velocity increases with depth. The central portion of the model tends to have the highest relative velocities down to at least the 0.9 km depth level. At the deepest level shown at 1.5 km depth, the lower (i.e. south) part the image has the highest overall velocities. For the attenuation inversion, we were only able to achieve significant data variance reduction with the one-dimensional model. The 1D model had a starting data variance of 0.000309 s and a final data variance of 0.000073 s after calculation of the source term and variations. This is a net variance reduction of 76%, however most of this is due to solving for, the source contribution to the pulse width. Only about 15% of the variance reduction is due to the structure. The results are shown adjacent to the velocity results in Figure 12.

Interpretation

We find that the velocity structure correlates with known mapped geologic units and the location of reservoir. In Figure 12, the layer at 0.9 km depth shows low velocity correlated with the reservoir. The next layer down is at 1.5 km depth and shows the felsite intrusion associated with a blotchy series of high velocity anomalies. Although the felsite and the indurated graywacke reservoir rocks should have roughly equivalent velocity, the felsite is likely to be less fractured and could exhibit slightly higher velocity. The weak velocity contrast could explain the blotchy nature of its signature in the velocity image. The high Q in the upper part of the reservoir is consistent with the earlier results of Majer and McEvilly (1979) who also found relatively high Q in this region. The low Q in the lower part of the reservoir

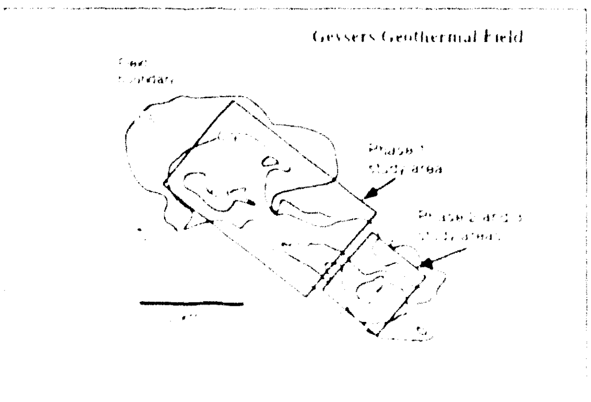


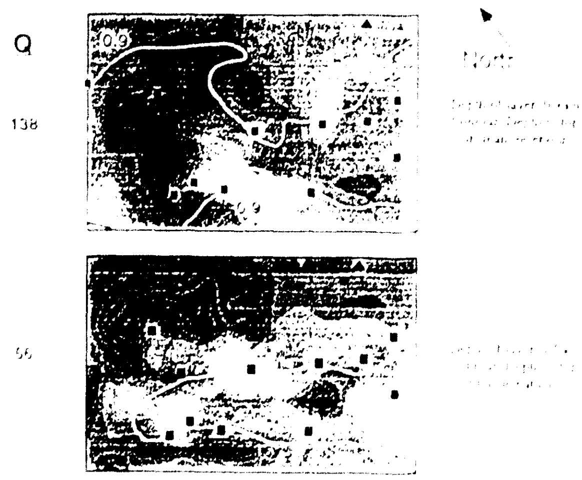
[illegible] that the saturation is in the 30 to 70% range while saturation at the top of the reservoir could go up or down and still agree with the lab results for Q alone obtained by Ito et al. (1979). A drop in saturation at the top of the reservoir below about 30% seems the most likely since the velocity is lower in the reservoir compared to the country rocks indicating a drop in saturation compared to the country rocks.

For phase 1, we have calculated the velocity and attenuation structure of the Geysers region using local earthquakes. Our data for the inversion consist of P wave arrival times and pulse widths which we used to compute three dimensional compressional wave velocity structure and one dimensional compressional wave attenuation structure. Our velocity structure correlates well with the surface geology and published studies on the structure of the reservoir. The reservoir appears to exhibit low velocity with the surrounding country rock. The Q decreases with depth which we infer to indicate partial saturation (30 to 70%) at depth with drier conditions near the top of the reservoir. We plan to apply a similar analysis to the data we are currently collecting at for phases 2 and 3 of our work.

Summary and Conclusions

The work to date indicates that MEQ data can, and are being used to infer the flow of injectate within the reservoir area. Recent results of the imaging indicates that the attenuation and Vp/Vs results possibly could be used to infer fluid saturation. Several unique high resolution data sets have been obtained and plans are being made to monitor several new injection projects in the near future. Cooperation with industry has yielded results that have guided and focused the work in an effective fashion. Without this cooperation the work would not have been possible.





Acknowledgment

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References

Allis, R.G., 1982, Mechanism of induced seismicity at The Geysers geothermal reservoir, California. *Geophys. Res. Lett.*, *9*, pp 629.

Bufe, C.G., S.M. Marks, F.W. Lester, R.S. Ludwin, and M.C. Stickney, 1981, Seismicity of the Geysers-Clear Lake region, *U.S. Geol. Surv. Prof. Pap.*, *1141*, pp 129.

Denlinger, R.P., and C.G. Bufe, 1981, Reservoir conditions related to induced seismicity at The Geysers steam reservoir, northern California, *Bull. Seismol. Soc. Am.*, *72*(4), pp 1317.

Eberhart-Phillips, D., and Oppenheimer, D.H., 1984, Induced seismicity in The Geysers geothermal area, California *J. Geophys. Res.*, *89*, pp 1191.

S. L. Enedy, Smith, J.L., Yarter R.E., Jones, S.M., and Cavote, P.E., 1993, Impact of injection on reservoir performance in the NCPA steam field at The Geysers, Presented at the 1993 Stanford Geothermal Workshop, Stanford, California.

Evans, J.R., and Zucca, J.J., 1988, Active High-Resolution Tomography of compressional-wave velocity and attenuation structure at Medicine Lake Volcano Northern California Cascade Range, *J. Geophys. Res.*, *93*, *15*, pp 15,016.

Griggs, D.T., Turner, F.J., and Heard, H.C., 1960, Deformation of Rocks at 500° to 800° . *Geological Soc. Am. Mem. 79*, 39.

Hamilton, R. M., and Muffler, L. J. P., 1972, Microearthquake at The Geysers Geothermal area, California, *J. Geophys. Res.*, *77*, pp 2081.

Handin, J., 1966, Strength and Ductility, in Handbook of Physical Constants, S.P. Clark, Jr., (ed.) *Geol. Soc. Amer. Memoir, 97* pp 238.

Ito, H., J. DeVilbiss, and A. Nur, 1979, Compressional and shear waves in saturated rock during water-steam transition. *J. Geophys. Res. 84*, pp 4731.

Industry Consortium 1989, Geysers, 'Top of Reservoir Map' and 'Top of Felsite Map', both maps compiled through the cooperative efforts of UNOCAL, Freeport-McMoRan Geysers Geothermal, Northern California Power Association, GEO, Santa Fe Minerals Inc., and the Department of Water Resources of the state of California, presented at the Geothermal Resources Council Annual Meeting, 1 - 4 Oct., Santa Rosa, CA.

Lange, A. L., and Westphal, W. H., 1969, Microearthquakes near The Geysers, Sonoma County, California, *J. Geophy. Res.*, *74*, pp 4377.

Ludwin, R.S. and C.G. Bufe, 1980, Continued seismic monitoring of The Geysers, California, geothermal area, *U.S. Geol. Surv. Open File Rep.*, *80-1060*, 50 pp.

Ludwin, R.S., Cagnetti, V., and Bufe, C.G., 1982, Comparison of seismicity in The Geysers geothermal area with the surrounding region, *Bull. Seism. Soc. Am.*, *72*, pp 863.

Majer, E. L. and T. V. McEvilly, 1979, Seismological investigations of the geysers geothermal field. *Geophysics 44*, pp 246.

Majer, E.L., 1978, Seismological Investigation in Geothermal Regions, Ph.D. thesis, University of California, Berkeley, LBL Report 7054.

Marks, S.M., Ludwin, R.S., Louie, K.B. and Bufe, C.G., 1978, Seismic monitoring at The Geysers geothermal field, California, *U.S. Geol. Surv. Open File Rep.*, *78-798*, 26 pp.

McGarr, A., 1976, Seismic moments and volume changes, *J. Geophys. Res.*, *81*, pp 1487.

McNally, K.C., 1976, Spatial, Temporal, and Mechanistic Character in Earthquake Occurrence, A Segment of the San Andreas Fault in Central California. Ph.D. Thesis, University of California, Berkeley.

Michelini, A., 1991. Fault zone structure determined through the analysis of earthquake arrival times (Ph.D. Thesis), University of California, Berkeley.

Oppenheimer, D.H., 1986, Extensional tectonics at The Geysers geothermal area, California, *J. Geophys. Res.*, *91*, pp 11463.

Peppin, W.A., and Bufe, C.G., 1980, Induced(?) versus natural earthquakes: Search for a seismic discriminant, *Bull. Seismol. Soc. Am. 70*(1), pp 269.

Spencer, E.W., 1969, *Introduction to the Structure of the Earth*, New York, McGraw-Hill.

Stark, M. A., 1990. Imaging injected water in The Geysers reservoir using microearthquake data. *GRC Transactions, v. 14*, pp 1697.

Stark, C.L., and Majer, E.L., 1989, Seismicity of the Southeastern Geysers. LBL-26679, 109 pp.

Stesky, R.M., 1977, Rock Friction - Effect of Confining Pressure. *Proc. of Conference II, Experimental Studies of Rock Friction with Application to Earthquake Prediction.* U.S. Geological Survey, p. 331.

Thurber, C.H., 1983. Earthquake locations and three- dimensional crustal structure in the Coyote Lake area, Central California, *J. Geophys. Res.*, *v. 88*, p. 8226.

Zucca, J. J., and J. R. Evans, 1991, Active high-resolution compressional-wave attenuation tomography at Newberry volcano, central California, *J. Geophys. Res.*, *97*, pp 11, 047.

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