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Seismic Monitoring at the Geysers Geothermal Field

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SEISMIC MONITORING AT THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

This report summarizes the efforts of LBL to utilize MEQ data in reservoir definition as well as in evaluating its performance. Results of the study indicate that the velocity and attenuation variations correlate with the known geology of the field. At the NW Geysers, high velocity anomalies correspond to metagraywacke and greenstone units while low velocity anomalies seem to be associated with Franciscan melanges. Low Vp/Vs and high attenuation delineate the steam reservoir suggesting undersaturation of the reservoir rocks. Ongoing monitoring of Vp/Vs may be useful in tracking the expansion of the steam zone with time. Spatial and temporal patterns of seismicity exhibit compelling correlation with geothermal exploitation. Clusters of MEQs occur beneath active injection wells and appear to shift with changing injection activities. High resolution MEQ locations hold promise for inferring fluid flow paths, especially in tracking injectate. This study has demonstrated that continuous seismic monitoring may be useful as an active reservoir management tool.

INTRODUCTION

Lawrence Berkeley Laboratory (LBL) scientists and industry partners at The Geysers geothermal field, California have been working together during the last several years to evaluate microearthquake (MEQ) data to study the origin and significance of geothermal seismicity. Seismicity at The Geysers is a common occurrence and there has been many studies concerning the origin and significance of the seismicity. The purpose of the work undertaken by LBL is to apply the MEQ data set for imaging the in situ physical properties such as the seismic velocity and attenuation structures within the reservoir area. Another application that is gaining much attention is monitoring fluid flows during injection activities. To address the above objectives, the MEQ work can be divided into two types of studies. The first is the analysis of the spatial and temporal patterns of seismicity in relation to geothermal activities. The second broad area of study is imaging the reservoir area with the energy created by MEQ activity and inferring the physical properties within the target region. The two types of studies have obvious overlap, and for a complete evaluation and development require high quality data from high-resolution networks with multi-component stations. Currently, LBL maintains two such arrays at The Geysers, as shown in Figure 1. The first array is located at the Central California Power Agency No. 1 (CCPA) steam field at the Northwest (NW) Geysers. The CCPA array is unique in its capability because of a dense station coverage (16 stations covering a 125 km^2 area), high-frequency digital sampling (400 samples/second/channel), and its borehole emplacement. LBL has been working with the Coldwater Creek Operator Corporation (CCOC), now CCPA, in the analysis of the MEQ data set recorded in 1988. Legal and technical complications forced the array to shut down in 1989. However, it was brought back into operation in October 1993. The other array is located at the Southeast (SE) Geysers region within parts of the Calpine, Northern California Power Agency (NCPA) and UNOCAL steam fields. The southeast array consists of 13 high-frequency (480 samples/second/channel) digital three-component stations. The original split-array configuration, consisting of eight LBL and five Lawrence Livermore National Laboratory (LLNL) stations, was not able to provide reliable data on a timely basis. In December 1993, LBL replaced the LLNL stations in order to have all of the data coming to one central point vastly simplifying the data collection and processing. Presented here are the ongoing results of LBL's efforts in the acquisition and analysis of MEQ data from The Geysers geothermal field.

BACKGROUND

The Geysers is a dry-steam geothermal field situated within the central Franciscan Assemblage belt of the northern California Coast Ranges. The Franciscan Assemblage is a complex of metasedimentary rocks consisting mainly of metamorphosed turbidite graywacke with lesser amounts of chert, greenstone, and serpentinized ultramafic rocks (Blake and Jones, 1974; McLaughlin, 1981). The steam reservoir lies within a fractured metagraywacke, and is overlain by either Franciscan greenstone melanges or unfractured metagraywacke in steeply dipping thrust packets that constitute the cap rock (Thompson, 1991). The subsurface structure generally dips to the northeast but is deformed by major NW trending right-lateral faults related to the San Andreas fault system. McNitt et al. (1989) reported that the steam reservoir is bounded on the southwest by the Big Sulfur Creek fault and on the northeast by the contact between the cap rock and the reservoir metagraywacke. Elsewhere, the reservoir boundaries are less sharply defined. A slick pluton (felsite) intruded the base of the metagraywacke contemporaneous with the extrusion of the Clear Lake volcanics northeast of the field. The emplacement of the felsite, which may underlie the whole field, is believed to have altered and hydraulically fractured the brittle metagraywacke, thereby increasing its permeability to host the present geothermal reservoir.

Truesdell et al. (1993) postulate that The Geysers field is tapping heat from a relatively young (0.1 Ma or younger) igneous intrusion based on high heat flow, and evidence of young extrusives such as the basalt flows at the NW Geysers. Walters et al. (1988) described a high-temperature vapor-dominated reservoir (HTR) underlying parts of the NW Geysers region at depths of about 2.5 km. The distinguishing

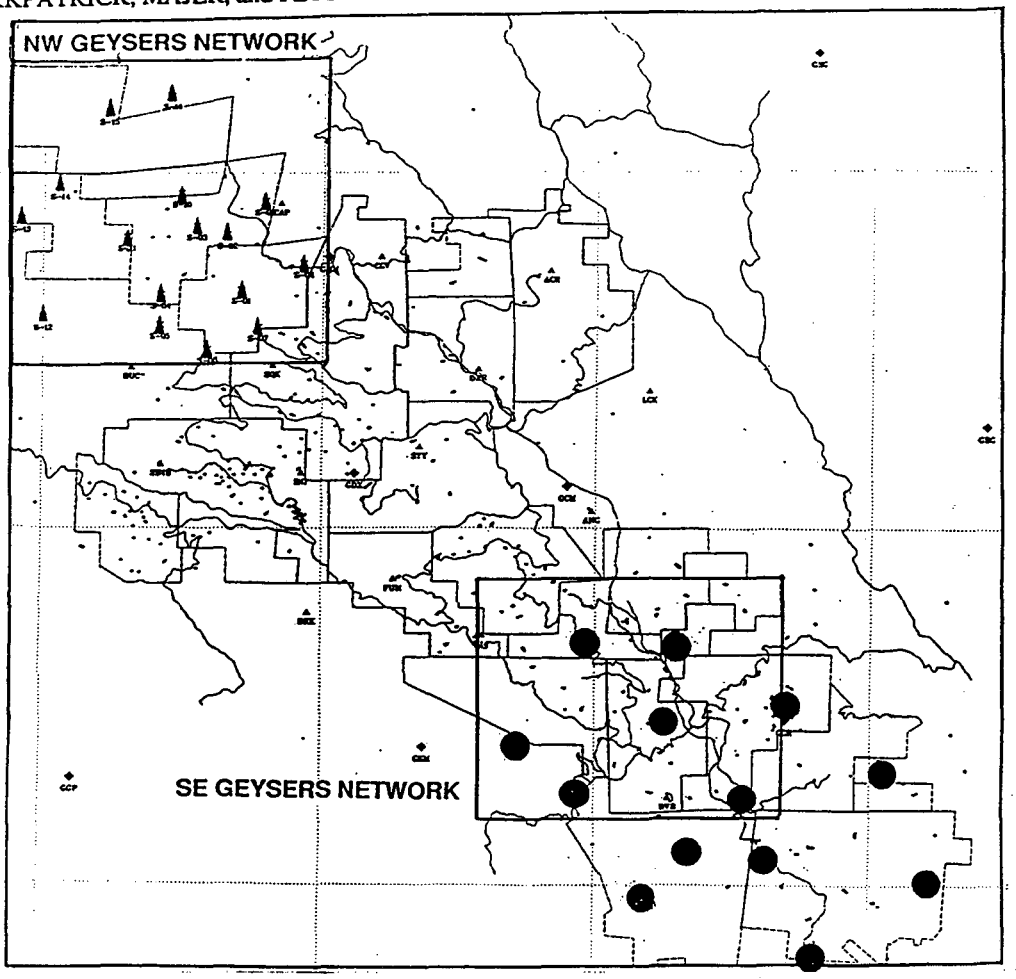

Figure 1. Map showing the locations of the seismic monitoring stations at The Geysers operated by LBL.

reservoir characteristics of the HTR, characterized by higher steam enthalpies, gas concentrations, and reservoir temperatures are attributed to lower recharge and heat loss rates, and less venting compared to the rest of the field.

A number of seismological studies at The Geysers have exploited the high level of seismicity as natural sources for developing structural models of the geothermal reservoir. Eberhart-Phillips (1986) developed a three-dimensional (3-D) P-wave velocity model also found high velocities within the production area and lower velocities on Collayami and Maacama fault zones that bound the known reservoir to the northeast and southwest, respectively. O'Connell and Johnson (1991) conducted a progressive inversion for P- and S-wave velocities and observed Vp/Vs peaks at shallow depths that they interpret as the steam condensation zone. They also found low Vp/Vs within the steam producing horizon, an observation previously reported by Majer and McEvilly (1979), and is consistent with the vapor-dominated nature of the reservoir. More recently, Julian et al. (1993) developed a three-dimensional velocity model for the central Geysers, attributing several high-velocity bodies to the hornfelsic-graywacke aureole above the felsite and to a sliver of high-density melange. In a study correlating P wave velocity and attenuation structure, Zucca et al. (1994) reported a high P-wave velocity associated with the felsite body and low velocity in the steam 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 NW Geysers and the SE Geysers.

Northwest Geysers

In March 1990, LBL, in cooperation with CCOC, now CCPA, undertook the collection, archiving, and interpretation of the approximately 5000 MEQs recorded in 1988 during the first year of production and injection activities. Monitoring stopped in 1989 and was reactivated in October 1993. To date, over 1600 MEQs have been located. The MEQ data set from the CCPA array provides a test case to monitor the changes in reservoir properties between the two time periods in response to continued production of the field. 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 activities. Figure 2 presents in map view and a west-east cross section of the relocated events recorded at the NW

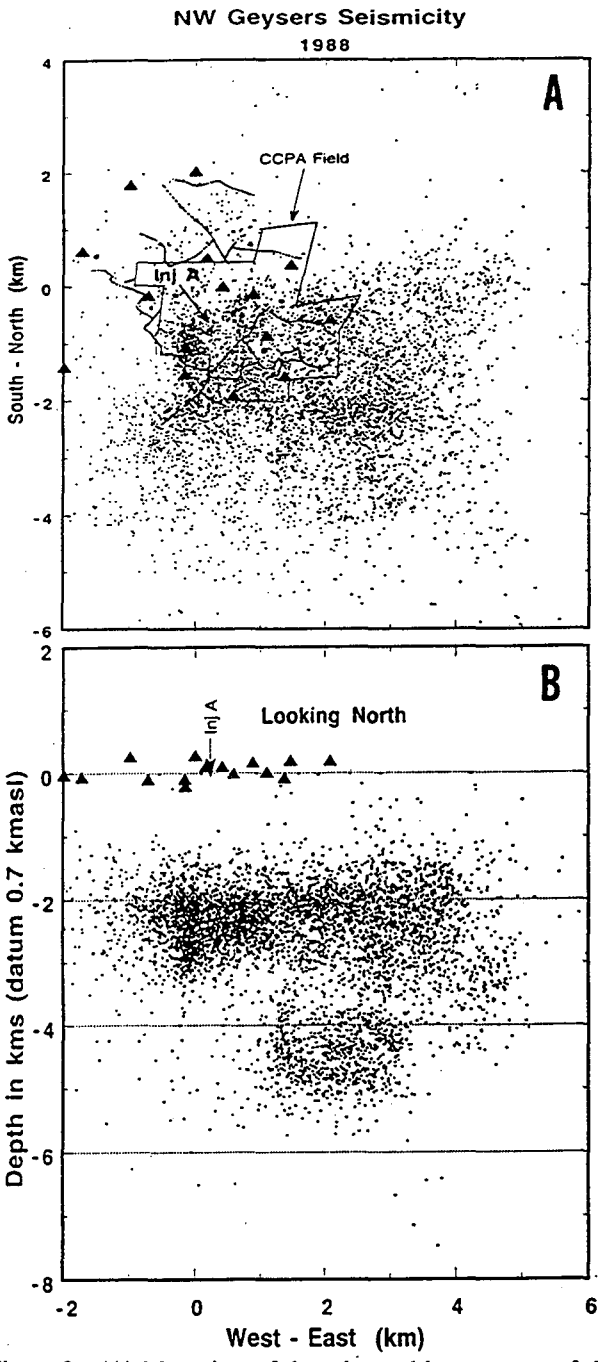

Figure 2. (A) Map view of the relocated hypocenters of the events recorded in 1988 at the NW Geysers region. Local origin is centered at 38°50.55'N, 122°49.64'W. Triangles mark seismometer locations. Mapped fault traces are also shown. (B) West-east cross section across the region with all events projected.

Geysers in 1988. MEQs 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 two 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 2b). The shallow seismicity gets deeper to the north consistent with the greater depth of the steam reservoir in that direction. A cluster of MEQs with focal depths between 2 and 3 km is located beneath the injection well A, as shown in Figure 2. Injector A was the only active injection well at that time. In an expanded view of the MEQ cluster around injector A, Figure 3 clearly shows the strong spatial correlation of the seismicity around the bottom of injector A and extending several hundred meters beneath the well. The MEQ distribution seems to define a vertical planar structure striking roughly north-south.

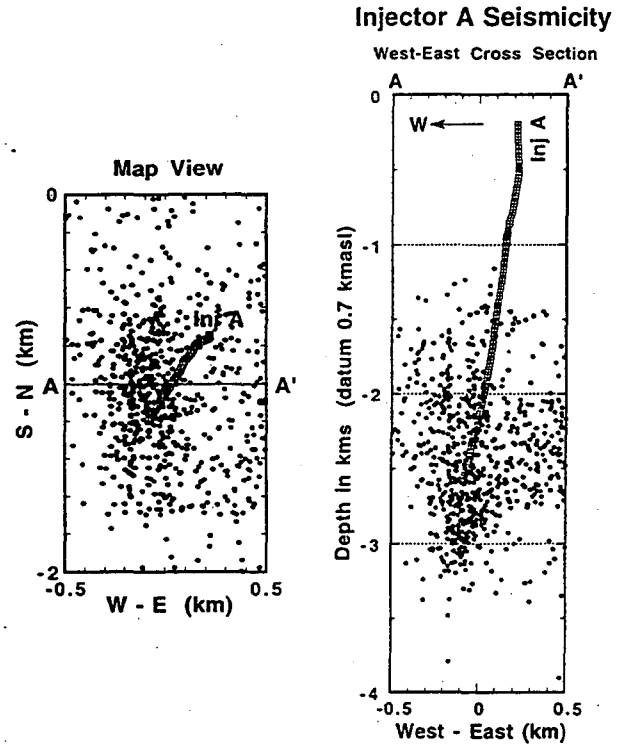

Figure 3. Map view and west-east cross section showing the locations of MEQs around injector A. The MEQ distribution seems to define a vertical planar structure striking roughly north-south. Datum plane is 0.7 kmasl.

In terms of temporal correlation, Figure 4 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 5 presents a comparison between injector A'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.

Plots of the MEQs recorded recently are presented in Figure 6. Present background seismicity generally mimics the distribution of MEQs recorded in 1988 even as the field has been in sustained production for five years. MEQs are concentrated within the CCPA steam field extending to the south and east while MEQs are still relatively scarce north and west of the field. As in 1988, the focal depths occur mainly at

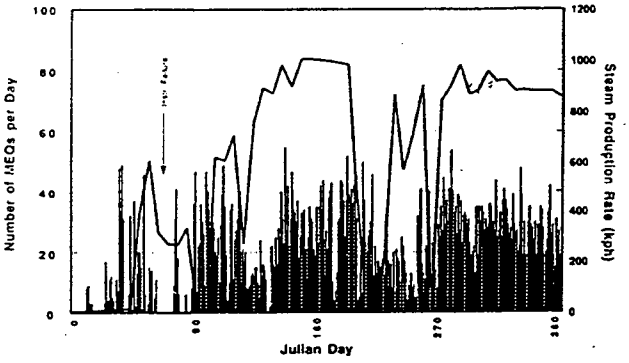

Figure 4. Comparison between the seismicity rate within the CCPA steam field and the field-wide steam production rate. Seismicity more than doubled with the start of sustained production.

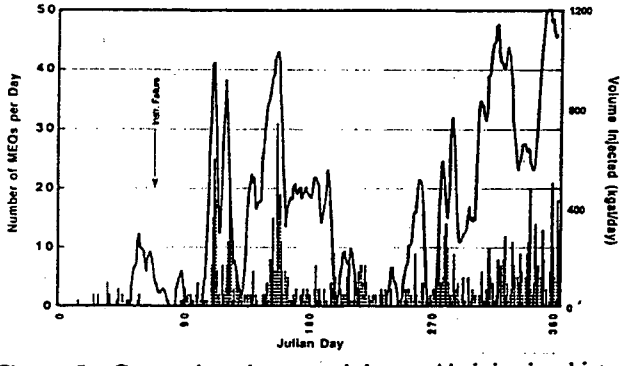

Figure 5. Comparison between injector A's injection history and seismicity rate nearby. Note the good correlation between peaks in seismic activity and injection rate.

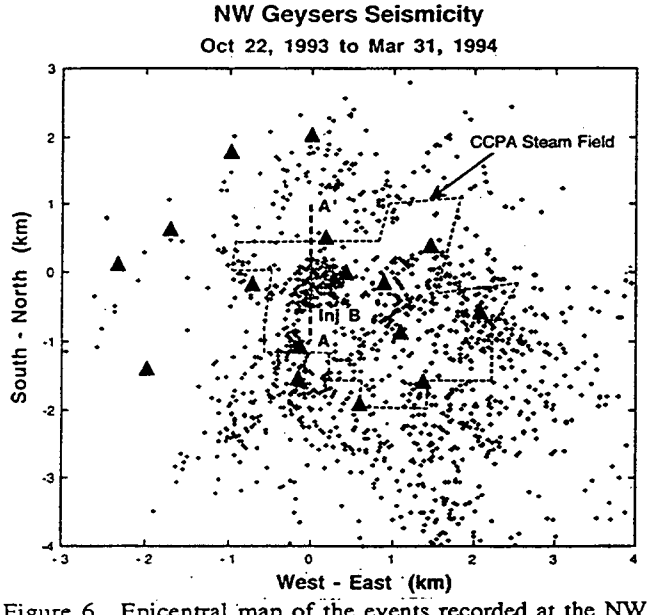

Figure 6. Epicentral map of the events recorded at the NW Geysers region from October 1993 to March 1994. MEQ distribution generally follows the seismicity patterns in 1988. Note the shift in MEQ activity from beneath injector A to beneath injector B (see Figure 2a)

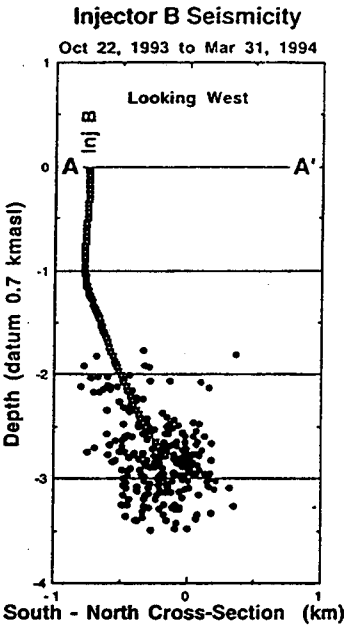

Figure 7. North-south cross section showing the locations of MEQs around injector B. MEQs cluster around the bottom of the injection well and extending several hundred meters below. Datum plane is 0.7 kmasl.

two depths: a broad shallow seismicity between 1 and 3 km depth, and a deeper cluster between 3.5 and 5 km depth towards the southeastern edge of the field. The extent of seismicity probably maps the region that is hydraulically affected by both steam withdrawal and reinjection. The main difference in the seismicity pattern between the two time periods is the shift in MEQ activity from beneath injector A to about 1 km northeast beneath injector B. Since the start of the present monitoring, reinjection has shifted to injector B. Figure 7 shows the seismic activity around injector B. MEQs cluster around the bottom of injector B extending to a depth of 3 km. Current pressure data from injector B suggest that injection does have an effect on the saturation of the formation and fluid is invading the zones around the well (Pers Comm., M. Walters, Russian River Energy Corp.). At present, there is not enough data to establish any temporal relationship between injection at injector B and seismicity nearby. Continuous coverage has only been achieved starting in February 1994.

Southeast Geysers

Several operators in the SE Geysers region (Calpine, NCPA, and UNOCAL) have undertaken a cooperative effort to understand more fully the mechanisms associated with reinjection activities. The objectives of the SE MEQ study are to demonstrate the utility of high resolution, multi-component, MEQ data 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 NW Geysers study.

The work in the SE Geysers to date has concentrated on collecting data for location and occurrence studies. This upgrade of the southeastern array has enabled the collection and processing of the data to occur in a timely and efficient manner. In cooperation with UNOCAL, we identify and extract the common events that occurred in the SE Geysers area. P- and S-wave arrival times and first motion polarities are then hand-picked for these events. Much of the effort has been focused on developing a correct 3-D velocity model to

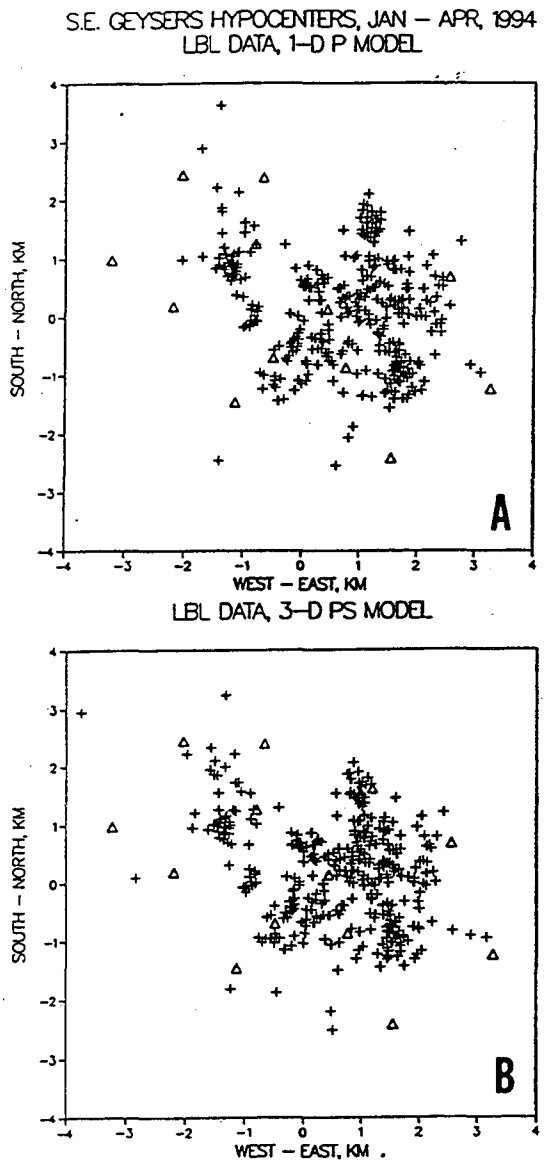

Figure 8. Map view of hypocentral locations in the SE Geysers. Local origin is at coordinates 38°43.66' N, 122°45.72' W. (A) 1-D P-wave velocity model. (B) 3-D P- and S- wave velocity model. Note the tighter spatial clustering of events and the general westward shift in locations in (B).

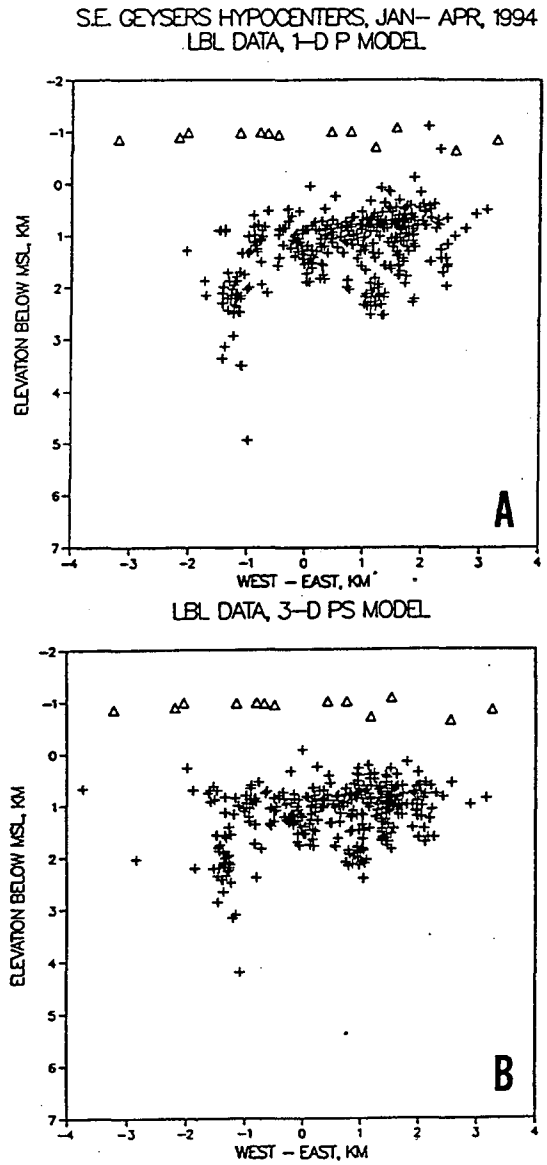

Figure 9. West-east cross section showing the focal depths of MEQs in the SE Geysers. (A) 1-D P-wave velocity model. (A) 3-D P- and S- wave velocity model. Note the tighter spatial clustering of events, the general westward shift in locations, and the reduction of scatter in elevation in (B).

improve the MEQ locations. As a first step, we used 142 events recorded in January and February 1994 to invert for a 1-D P-wave velocity model. The resulting velocity model was then used to locate the events from January to April 1994. Out of the 425 MEQs located, we selected 300 high-quality events for the inversion of 3-D P- and S- wave velocity structures, using a modified version of Thurber's method (Michelini and McEvilly, 1991). The final velocity model was then used to relocate the 425 events.

Figures 8 and 9 present a comparison between the hypocenters relocated using the 1-D and the 3-D velocity models, respectively. The 3-D velocity model resulted in more tightly clustered groups of events, less scatter in focal depths, and generally located approximately 50 to 500 meters (160 to 1600 feet) west of those obtained with the 1-D model. The locations of the events seem to suggest association with geothermal activities as evidenced by their clustering around active production and injection wells. However a definitive relationship has not been established at this point.

In addition to investigating seismicity patterns, we used the MEQs as energy sources to develop subsurface images of the reservoir area, focusing on modeling the 3-D velocity and attenuation structures beneath the target region. A set of about 500 high-quality events distributed evenly through-out the field and with a minimum of 10 P-wave arrivals were selected for the inversion study. The selected events have impulsive first arrivals and distinct S phases that were determined only on the horizontal components. We estimate the picking accuracy to be 2.5 ms for P-wave and 10 ms for S-wave arrival times, respectively.

We solved the joint problem for 3-D velocity distribution and hypocenter locations using the progressive inversion scheme proposed by Thurber (1983) and modified by Michelini and McEvilly (1991) for cubic spline interpolation. The Thurber method of progressive inversion estimates the earthquake relocations and velocity variations by minimizing travel-time residuals using damped least-squares. Because the problem is non-linear, solutions are found by linearizing the problem and solving iteratively until the residuals fall below a predefined acceptable value. The target region was divided into a 3-D rectangular grid with velocities assigned to each grid point. Based on the results of the synthetic tests, we adopted a grid spacing of 1 km (x 6 nodes) horizontally and 1 km (x5 nodes) vertically centered on the region of interest. The starting P-wave velocity model is derived from the one-dimensional velocity model obtained by O'Connell and Johnson (1991). We obtained the corresponding S-wave model assuming a Vp/Vs ratio of 1.73.

The differential attenuation structure was obtained for the NW Geysers from the P- and S-wave amplitude spectral ratios. We constructed spectral ratios by dividing each spectrum with a reference spectrum from each observing station. The reference spectrum was derived from the average spectrum of all events that were recorded in that station. We then estimated the differential attenuation operator from the slopes of the spectral ratios. We limited our frequency bandwidth below 60 Hz where we assume that source contribution is negligible. The velocity models and the ray paths for all events are known from the previous velocity inversion. The inversion for the differential attenuation structure was carried out using a modification of the progressive inversion scheme of Thurber (1983).

Results and Interpretation

The observed velocity and attenuation structures at the NW Geysers correlate well with mapped geologic units (Nielson et al., 1991). Figures 10, 11 and 12 present the resulting P-wave, Vp/Vs and P-wave differential attenuation models, respectively, with the model resolution superimposed as intensity to indicate regions of low resolution. Horizontal slices at three depths through the 3-D velocity volume are presented for each case. Depths are referenced to a datum plane 0.7 km above sea level (kmasl), the average elevation of the region. High velocities to the north and east of the field seem to be associated with greenstone and metagraywacke units. In particular, the prominent high velocity east of the field also coincides with low attenuation values (high Q). High Vp/Vs values also characterize this region. We identify this shallow zone as a thin condensation zone above the producing horizon. Lower velocities and higher attenuation (low Q) west of the field at shallow depths correlate with Franciscan melange units. Low P-wave anomalies and higher attenuation (low Q) underlie the southern region between 2 and 3 km depth. Low Vp/Vs values also characterize this region

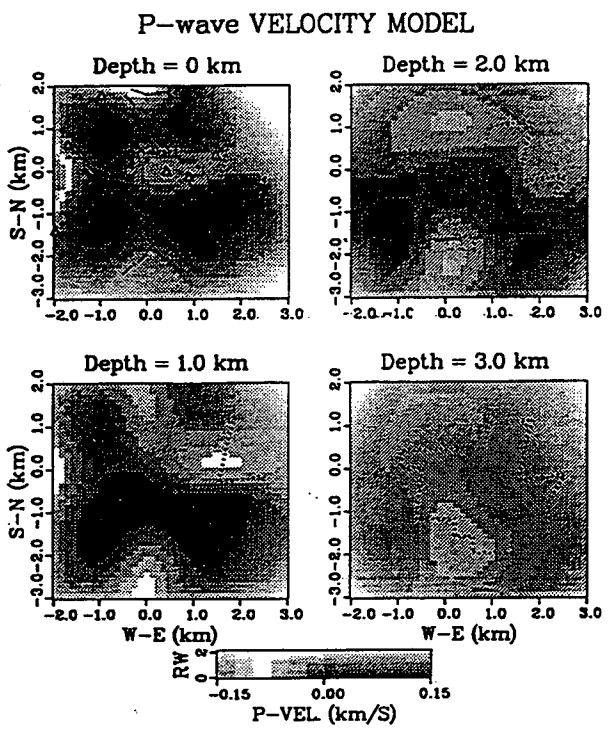

Figure 10. Horizontal cross sections of the final P-wave velocity model taken at three depths. Datum plane is at 0.7 kmasl. Shades denote velocity variations, while intensity indicates model resolution.

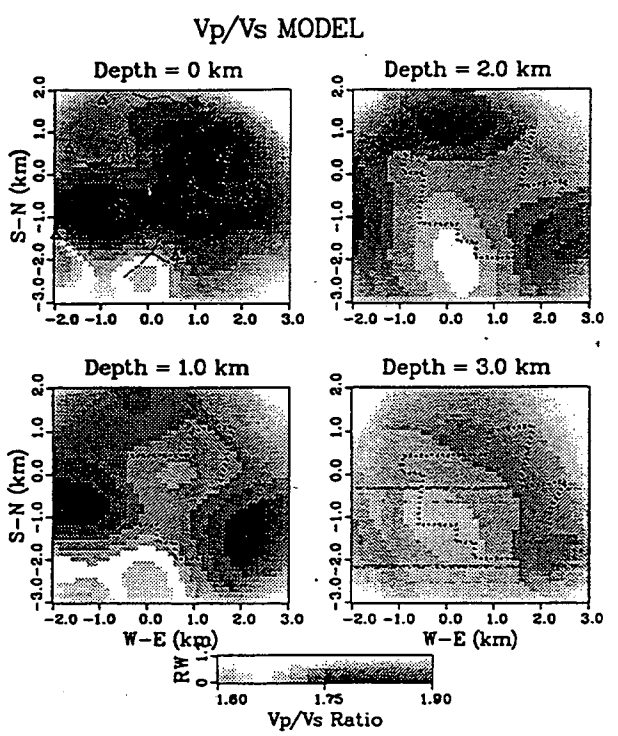

Figure 11. Horizontal cross sections of the Vp/Vs structure taken at three depths. Datum plane is at 0.7 kmasl. Shades denote Vp/Vs variations, while intensity indicates model resolution.

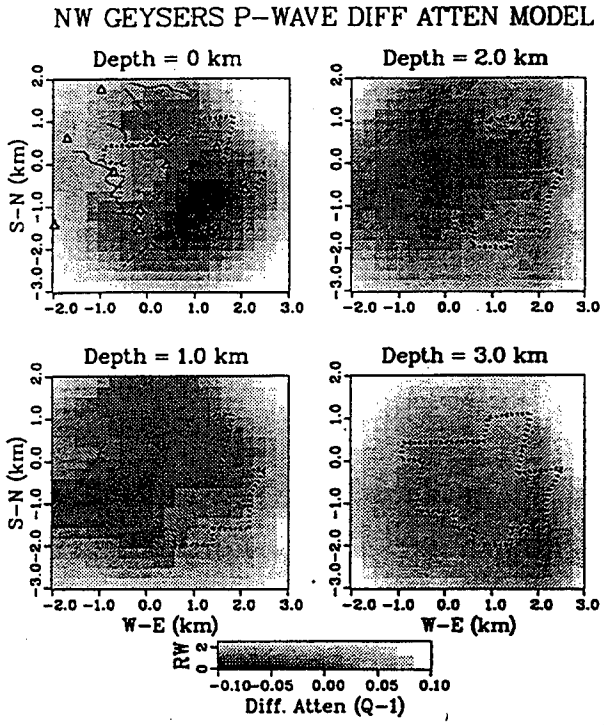

Figure 12. Horizontal cross sections of the final P-wave attenuation model taken at three depths. Datum plane is at 0.7 kmasl. Shades denote differential Q^{-1} variations, while intensity indicates model resolution.

suggesting undersaturation of the reservoir rocks. Most of the steam entries also occur within this region and probably delineate the steam reservoir. These anomalies may be explained by high rock temperatures and the presence of gases. Walters et al. (1988) described a high temperature vapor-dominated reservoir (HTR) characterized by higher steam enthalpies, gas concentrations and reservoir temperatures compared to the "typical" Geysers reservoir underlying the southern sections of the field at depths of about 2.5 km

The 3-D P- and S-wave velocity models we have obtained for the SE Geysers are considered preliminary. An analysis of model resolution has not been performed; therefore the model is not presented in detail here. Also, the spatial coverage throughout the field is not as complete as the NW Geysers, so the resolution near the edges of the model suffers. The gross features of the model indicate an area of higher-than average P- and S- velocities in the western half of the region, and lower-than-average P- and S- wave velocities in the eastern half. A clear pattern of variations in the Vp/Vs ratios, which may be interpreted in terms of degree of reservoir saturation, has not emerged. We hope that the additional data will provide more complete coverage of the SE Geysers area.

SUMMARY AND CONCLUSIONS

The results of the study have demonstrated the importance of MEQ data in reservoir definition. At the NW Geysers, velocity and attenuation variations correlate with the known geology of the field. High velocity anomalies correspond to mapped sections of metagraywacke and greenstone while low velocity anomalies seem to be associated with Franciscan melange units. Low Vp/Vs and high attenuation delineate the steam reservoir between depths of 1 and 3 km suggesting undersaturation of the reservoir rocks. Continuous monitoring of Vp/Vs may be useful in tracking the expansion of the steam zone with time. Spatial and temporal patterns of seismicity exhibit compelling correlation with geothermal exploitation. Clusters of MEQs occur beneath active injection wells and appear to shift with changing injection activities. High resolution MEQ locations hold promise for inferring fluid flow paths, especially in tracking injectate. In addition, injection seismicity is superimposed on a more general pattern of shallow seismicity presumably related to such factors as "natural" seismicity and effects of steam withdrawal. 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.

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