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Seismic Imaging for Saturation Conditions at The Geysers, California

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SEISMIC IMAGING FOR SATURATION CONDITIONS AT THE GEYSERS, CALIFORNIA

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ABSTRACT

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. We are engaged in a three phase project to infer these properties from seismic imaging data. Phase 1 of the project is complete and we report on those results here. We are still collecting data on the other phases at the time of writing of this paper.Our method is to compute seismic compressional-wave velocity and attenuation images in terms of the geologic structure and fluid saturation. Our data consist of seismograms recorded from local earthquakes. Using compressional-wave arrival times, we invert for earthquake location, origin time, and velocity along a three-dimensional grid. In phase 1, to compute attenuation we used the initial pulse width of the compressional-wave. In the later phases, we intend to include attenuation parameters measured from spectral ratios and spectral matching. We find that the velocity structure correlates with known mapped geologic units, including a velocity high that is correlated with a felsite body at depth that is known from drilling. The dry steam reservoir, which is also known from drilling, is mostly correlated with low velocity. The Q (*i.e.* the inverse of attenuation) increases with depth from the surface to the top of the dry steam reservoir and decreases with depth within the reservoir. The decrease of Q with depth indicates that the saturation of the reservoir rock increases with depth.

INTRODUCTION

Liquid saturation conditions of the matrix rock of vapor-dominated geothermal reservoirs have traditionally been estimated from core samples. However, the data obtained in this manner tend to have a large uncertainty since the liquid 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 degree of 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. Attenuation is the property of a material to dissipate the energy of a wave and is defined in the frequency domain as:

$$A(\omega) = A_0(\omega)e^{\frac{-\omega R}{VQ}}$$

where $A(\omega)$ is the Fourier amplitude, R is the wave travel distance, V is the seismic velocity, and Q is the quality quotient. Attenuation is proportional to Q^{-1}.

Figure 1 shows the location of the study areas with respect to the boundaries of the known steam reservoir. Our 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. Our 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.

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 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 complementary 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 Q 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

We use compressional-wave (*i.e.* P-wave) arrivals in our analysis. We pick the first arrival to measure the P-wave arrival time and the elapsed time between this arrival and the first zero crossing (figure 2) to measure the pulse width. The P-wave travel times and pulse widths are related to the velocity and attenuation, respectively, through the following relationships:

$$t = t_0 + \int_{ray} \frac{ds}{V(r)}$$

$$\tau = \tau_0 + C \int_{ray} \frac{ds}{V_0(r)Q(r)}$$

where t and τ are the P-wave arrival time and pulse width, respectively, t_0 and τ_0 are the origin time and the initial pulse width, respectively, and V and $1/Q$ are the velocity and attenuation structure. C is an empirically determined constant. Integration is carried out along the ray path. V is subscripted in the second equation to indicate that it 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 equations.

U-N-T provided us with waveforms and hand-picked first arrivals (Debbie Turner, 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.

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 3. 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 four layers at -0.3, 0.3, 0.9 and 1.5 km depth below sea level for which there is adequate resolution—0.4 and above for the layers shown.

In general, non-linear inversions depend on their starting models. A good way to mitigate this effect is to base the starting model as much as possible on previous knowledge of the structure. To develop our starting model, we combined the results of previous seismic studies in the region (Majer *et al.*, 1988; O'Connell and Johnson, 1991; Eberhart-Phillips, 1986) to modify where necessary the one-dimensional model that U-N-T (M. Stark, personal communication, 1990) uses to locate microearthquakes in the region.

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^2 and a final data variance of 0.000073 s^2 after calculation of the source term and Q variations. This is a net variance reduction of 76%, however most of this is due to solving for τ_0, the source contribution to the pulse width. Only about 15% of the

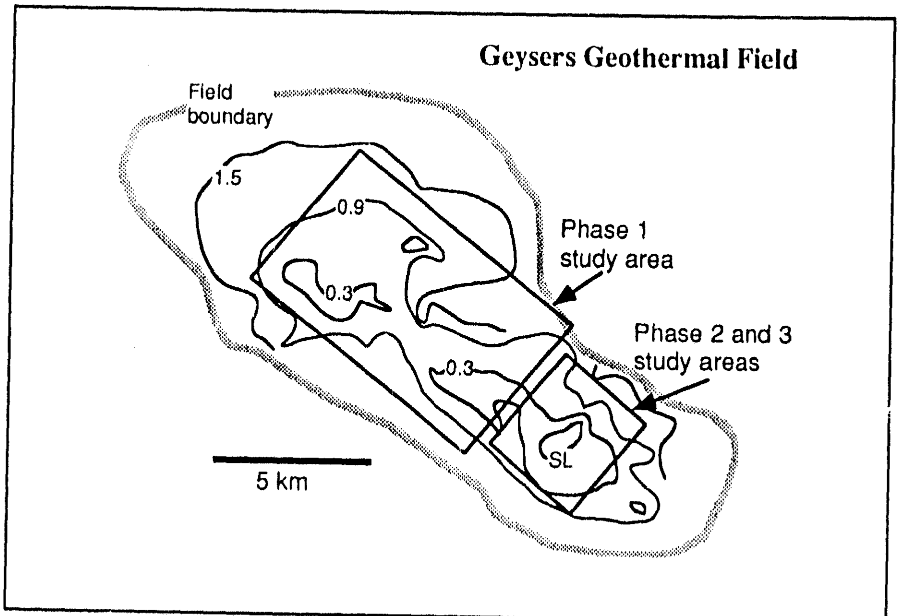

Figure 1. Location map of the study areas. Base map is the the depth to the dry steam reservoir (Industry Consortium, 1989). Datum in sea level, contours are in kilometers below the datum.

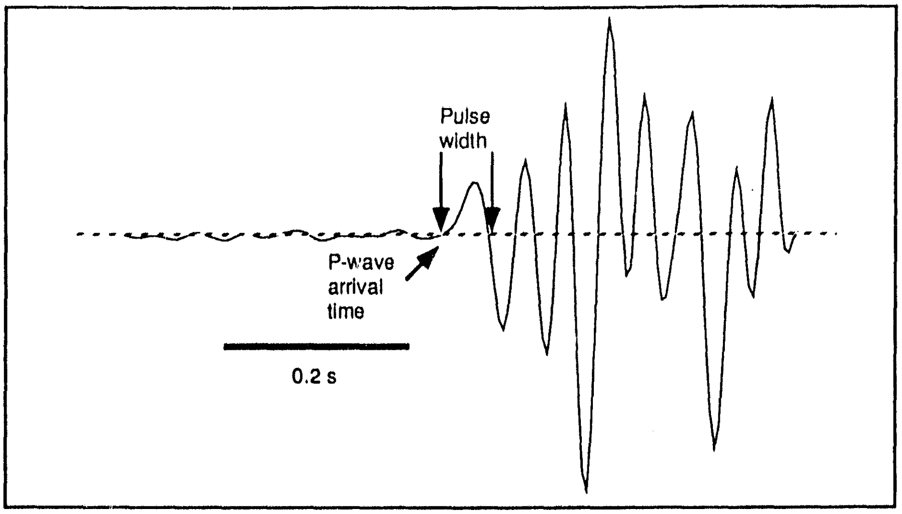

Figure 2. Example of data showing arrival time and pulse width measurements. P-wave arrival time is measured at the first break and pulse width is the elapsed time between the zero crossing and the first break.

variance reduction is due to the structure. The Q results are shown adjacent to the velocity results in figure 3. Our results are limited to 1D most likely because of the pulse-width data being very noisy, rather than the absence of lateral variations in Q structure. Higher digitization-rate data, such as is being collected in phases 2 and 3 of our project, should reduce the pulse-width data noise.

INTERPRETATION

We find that the velocity structure correlates with known mapped geologic units and the location of reservoir. Our uppermost layer (layer 1 at –0.3 km depth) is completely above the reservoir and should be influenced mostly by the surface geology. McLaughlin (1981) has published a geologic map of the region which we have generalized for our target volume in figure 3. Our observed high-velocity body in the center of this layer correlates at its south end with the ultramafic stringer and continues to the northeast, which implies a dip to the north of the body which agrees with McLaughlin's map and cross section. The apparent pinchout of the high-velocity body to the southeast is probably the result of the loss of resolution in that corner of the model.

The layer at 0.3 km depth intersects the reservoir at three cupolas. The northern cupola is clearly associated with low velocity and the other two are less so. The layer at 0.9 km depth clearly 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. These results agree with the less well resolved results of Eberhart-Phillips (1986) who found lowered velocities within the reservoir compared to the surrounding rock.

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 suggests 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.

CONCLUSIONS

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 within the reservoir 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 of analysis to the data we are currently collecting at for phases 2 and 3 of our work.

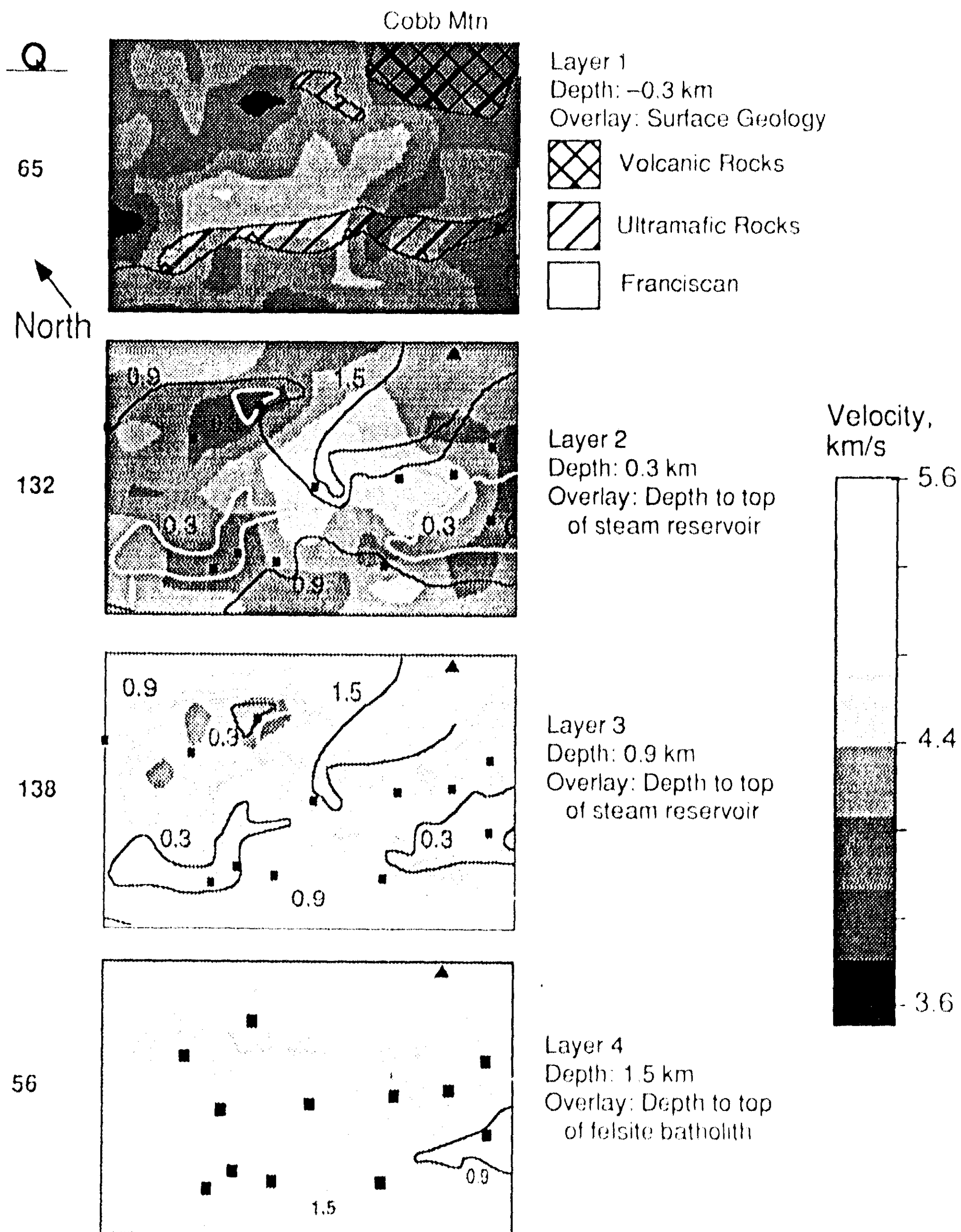

Figure 3

Horizontal Slices through the Geysers reservoir. The image shows P-wave velocity variations from the 1D starting model. Dark indicates low velocity and light indicates high velocity. The Q for the layer is printed to the left of the image. Solid squares indicate locations of power plants. The wire contour shows the intersection of the image plane with the structure shown in the overlay.

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