Reports

Abnormal P-Wave Delays in The Geysers–Clear Lake Geothermal Area, California

Abstract. *Large teleseismic delays, exceeding 1 second, are found near Mount Hannah in the Clear Lake volcanic field and in the steam-production area at The Geysers. The delays are superimposed on a general delay field of about 0.5 second extending over the volcanic rocks and the steam reservoir. It is postulated that a magma chamber under the surface volcanic rocks with a core of severely molten rock beneath Mount Hannah and a highly fractured steam reservoir probably underlain by partially molten rock at The Geysers are responsible for the observed delays. Both zones extend to depths of 20 kilometers or more.*

The Geysers geothermal power facility, 130 km north of San Francisco, California, is located in part of one of the few known dry-steam geothermal systems in the world. It is situated southwest of the Clear Lake volcanic field in which rocks range in age from 2 × 10^6 to 10,000 years (*1*). Geologic and geophysical evidence suggests that a crustal magma chamber is present under the volcanic field and is probably the heat source responsible for the observed geothermal phenomena in the area (*2–5*). A complex system of faults and fractures is thought to provide paths for deepwater circulation, and the resulting hydrothermal system furnishes the superheated steam that drives The Geysers turbines to produce electricity.

Seismic wave velocities are sensitive to the presence of both magma, hypothesized to be present under the Clear Lake volcanic field, and fractured rock, indicated by the high permeability in the steam reservoir under The Geysers. It is possible to delineate the shape of low-velocity magmatic bodies and to estimate the velocity contrast with respect to the surrounding regional velocity by using seismic waves from distant earthquakes (teleseisms) (*6–8*). We examined teleseismic P waves recorded in The Geysers–Clear Lake geothermal area at 26 stations of the telemetered seismic network operated by the U.S. Geological Survey and at 12 portable stations in the area (*9*). The results are quite unexpected. The seismic waves are delayed over a large area encompassing the geothermal production zone and the volcanic field. Relative delays as large as 1 to 1.5 seconds found at some of the stations indicate a subsurface velocity decrease of 25 percent extending to a depth of 20 km or more. Although a reduction in the velocities of upper crustal material in volcanic and geothermal areas is not surprising, the possibility of an exceptionally large velocity decrease in The Geysers–Clear Lake geothermal area suggests extreme variations in the properties of the underlying material. The implications of such extreme variations, although not clearly understood, are important in assessing the degree of partial melt in the Clear Lake magma system and the characteristics of The Geysers dry-steam reservoir.

Severe changes in wave form occurred in the teleseismic signals recorded at the permanent stations GMK (Mount Konocti), GGL (Glenview), and GSG (Seigler Mountain) located in the Clear Lake volcanic field, station GBO (Black Oaks) located in the steam-production zone (Fig. 1a), and at the portable stations CL05 (located adjacent to GSG in Fig. 1a), CL06, and CL07 (*5*). The signal distortion made it difficult to determine the onset of teleseisms. Our study, therefore, is based on 48 teleseisms for which P-wave arrival times could be read with confidence (*10*). Following standard procedures, we computed (*6*) residuals with respect to Herrin's travel time tables (*11*). In order to correct for source and path errors, we obtained relative residuals by subtracting from each value the residual at a reference station located well outside the anomalous area under investigation. We have used NMW (Mark West Springs) and CL02 as reference stations for the telemetered and portable networks, respectively (Fig. 1a). The teleseisms used are mainly from the northwest, southeast, and southwest azimuths. Taken together, these events provide a cone of seismic rays with an angle to the vertical of about 20°, sampling the crust and upper mantle under each station.

The average relative residuals for each of the three azimuth groups are contoured in Fig. 1, b to d. Because of the variation in data quality from station to station, the averages are based on a maximum of 11 and a minimum of two readings per station per azimuth group. The results for the southwest azimuth (Fig. 1b) show that the delay field is dominated by values greater than 1.5 seconds in the vicinity of GGL in the volcanic field, and greater than 1 second in the vicinity of GBO in the steam-production area. This field is superimposed on a wide zone comprising the volcanic field and production area where the delays are greater than 0.5 second. These results suggest that a broad low-velocity zone may underlie not only the region of Quaternary volcanism but also the Mesozoic Franciscan complex to the west, and that abnormally low velocities may underlie Mount Hannah and the steam-production zone. The lateral extent of the anomalous structure is clearly constrained on the south and west sides as shown by the abrupt change of the residuals to near zero values in these directions. However, owing to inadequate station coverage, the definition of the anomaly to the north and east of Clear Lake is quite uncertain. An examination of azimuthal variations in the delay patterns shows the northwest delays to be less than the southwest delays by 0.7 second at GGL and 0.5 second at GBO (Fig. 1, b and c). Similarly, significant changes in the spatial variation of delays are also observed between the northwest and southeast azimuths (Fig. 1, c and d).

The first step in interpreting the observed delays is to estimate the effect of near-surface structure. Using data from calibration explosions detonated by the

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U.S. Geological Survey, Majer and McEvilly (*12*) and Warren (*13*) have modeled the top 3 km of the crust in The Geysers-Clear Lake area. Their results show that the velocities in the upper layers under the volcanic field and the steam-production zone are not abnormally lower than those in the surrounding rock and hence cannot account for the large teleseismic delays. Moreover, at most stations used in this study, the deviations of the P-wave arrival times from the explosions with respect to travel times predicted by the crustal models are, in general, negligible and indicate that no localized anomalous structures are present immediately under the stations. The exceptions are stations GGL and GSG where the refraction data (according to Warren's model) imply that surface corrections as high as 0.4 second due to shallow low velocities may be required. However, these stations show maximum teleseismic delays of 1.5 and 0.9 second, respectively; these results require the postulation of deeper low-velocity structure to explain a large portion of the teleseismic delays.

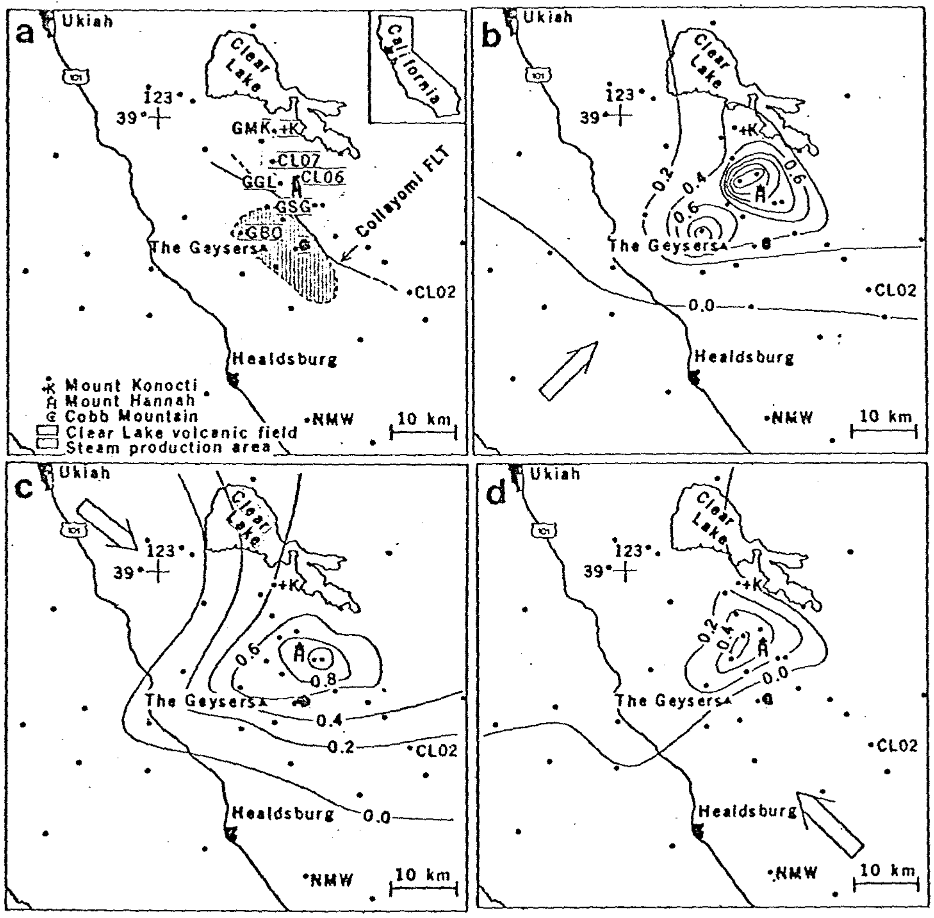

Fig. 1. (a) Station locations (dots) in The Geysers-Clear Lake region. The inferred approximate outlines of the Clear Lake volcanic field (dotted) and the dry-steam (hachured) areas are shown. Relative teleseismic P-wave residual contour maps for (b) southwest events, (c) northwest events, and (d) southeast events are shown. The contour interval is 0.2 second. The arrows in (b to d) represent the direction of approach of teleseismic signals.

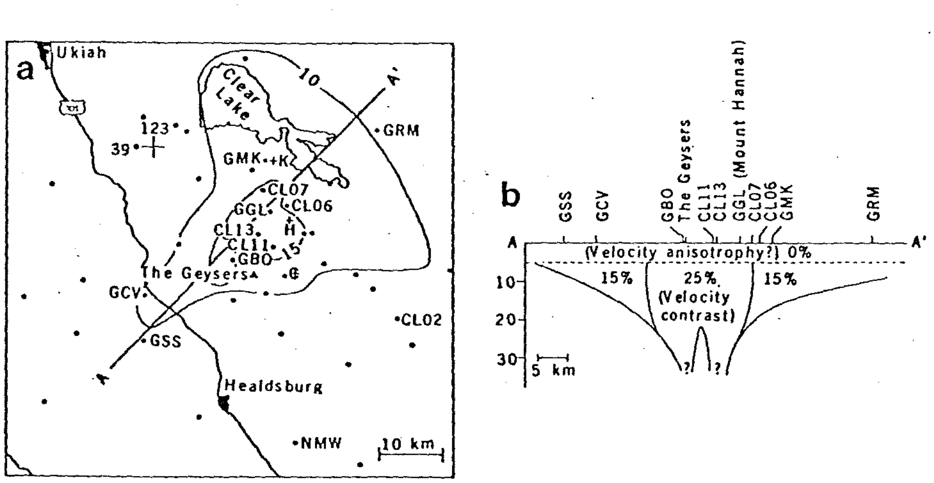

Fig. 2. (a) Calculated depth to the bottom of the anomalous body required to account for the observed delays. The top of the body is assumed to be flat and at a depth of 4 km. The velocity decrease between the 10- and 15-km contours is assumed to be 15 percent and within the 15-km contour (shaded area) to be 25 percent. (b) Conceptual model of the subsurface structure and the percentage of decrease in velocity along the line *A*-*A*' of (a) passing through the production and volcanic zones.

Assuming that the delays are caused by a deep low-velocity body in the crust, we have attempted a simple inversion of the teleseismic data to estimate the dimensions of the body and the velocity contrast inside it relative to the surrounding regional velocity. The procedure used is to compute the length of the anomalous ray path required to cause the observed delays for a given velocity contrast (*6*, *8*). Knowing the anomalous path length, the angle of emergence of the seismic ray, the azimuth of the seismic source, and the depth to the top of the low-velocity region, we can compute the x, y, and z coordinates of the lower surface of the anomalous body.

We have assumed that the top of the body is flat and located at a depth of 4 km. We assume a flat top, although it may not be physically realistic, purely for mathematical convenience. This assumption does not introduce serious errors in the delineation of the anomalous body. In the absence of data from detailed seismic reflection and refraction surveys, we have only indirect evidence to place any constraint on the depth to the top of the body. The assumed depth of 4 km is therefore tentative and based on the paucity of earthquakes below this depth (*14*). The reduction in seismicity can be attributed to several mechanisms, including elevated temperatures causing stable sliding rather than stick slip (*15*), high pore pressures which reduce the effective stress across fault planes, and aseismic slip (creep). However, the simultaneous occurrence of low velocity and low seismicity may also be due to the presence of partially molten or fractured rock incapable of supporting shear stress at shallow depths greater than 4 km in The Geysers-Clear Lake geothermal area. Results of the inversion satisfying the above criteria are shown in Fig. 2, a and b. This model is nonunique and serves only as a conceptual point of view. The model shows a large triangular region comprising the Clear Lake volcanic field and the steam-production zone in which there is an average velocity decrease of about 15 percent with respect to regional velocity. An important feature of the model is a core region beneath Mount Hannah and the steam-production zone where a 25 percent decrease in velocity is required to satisfy the data (shaded area in Fig. 2a). The low-velocity body extends to an average depth of 10 to 15 km, with the core regions extending to 20 km or more. The shape of the low-velocity body is not well defined, and there are thus deficiencies in our modeling procedure.

A reduction of the compressional seismic wave velocity within the earth can be due to a variety of factors (*7*). However, geologic and other geophysical data support our observations and indicate the presence of a magma body under the Clear Lake volcanic field. Chapman (*3*) has suggested the possibility of a magma chamber under Mount Hannah to explain the large gravity low in the region. Isherwood (*4*) inverted gravity and aeromagnetic data to model a magma chamber 10 to 15 km in diameter under Mount Hannah. Hearn *et al.* (*2*) have also shown that geologic and geochronological evidence strongly support the hypothesis that an active magma chamber may be present under the Clear Lake volcanic field. The attenuation of teleseismic body waves (*5*) and the shallow seismicity (*14*) are other geophysical observations that lend support to the magma chamber hypothesis. We propose, therefore, that the low-velocity body under Mount Hannah represents rock in a state of partial melting. Unfortunately, few laboratory data exist to make possible an estimation of the degree of partial melting from seismic data. Even a theoretical model, such as that proposed by Walsh (*16*) in which partial melting occurs in randomly oriented penny-shaped cracks, requires knowledge of both P- and S-wave velocity and attenuation to obtain this estimate.

It is possible that the dry-steam reservoir associated with The Geysers may be responsible for some of the P-wave delays observed in that zone. Laboratory data by Nur and Simmons (*17*) show that the compressional velocity in dry, porous rocks is significantly lower than in the fluid-saturated condition. However, the seismic refraction survey of Majer and McEvilly (*12*) at The Geysers does not show a sufficient velocity anomaly in the top 3 km to account for the observed teleseismic delays. Thus, any delay attributed to the dry-steam field must be occurring at depths greater than 3 km, necessitating that the fracture system extend to about 20 km. Alternatively, the magma chamber postulated to be beneath Mount Hannah may extend beneath The Geysers and together with an overlying fracture system may be responsible for the observed delays. The strong azimuthal variation of delays at stations near The Geysers (Fig. 1) also suggests that an anisotropic velocity distribution in either the fractured dry-steam system or within the magma body may be present. Walsh (*18*) has shown that the compressibility of rocks with cracks is anisotropic. However, since the maximum velocity decrease occurs along a plane perpendicular to the direction of crack orientation and since the teleseismic waves travel at an angle to the vertical of about 20°, a complex fracture model will be required.

A significant feature of our model is a core region in which the velocity decrease may be as high as 25 percent. Data from other areas of Quaternary volcanism such as Yellowstone National Park, Wyoming, and Long Valley, California, show the existence of magma chambers requiring 10 to 15 percent velocity contrast (*7*, *8*). Whether the higher velocity decrease postulated at Mount Hannah means that the magma chamber in this locality is in a higher state of partial melt than that under Yellowstone or Long Valley cannot be determined until shear wave velocity and attenuation data are collected.

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Acid Rain: Neutralization Within the Hubbard Brook Ecosystem and Regional Implications

Abstract. *The neutralization of strong acids from precipitation is largely accomplished (75 percent) in the soil zone by rapid reaction with basic aluminum salts and biologic matter. On a regional basis, acidified and aluminum-rich lakes and streams in New England are confined mainly to low-order watersheds.*

The phenomenon of excess strong acids in contemporary precipitation ("acid rain") over the northeastern United States, and particularly at the Hubbard Brook Experimental Forest, is well documented (*1*). The smallest headwater streams of the Hubbard Brook Experimental Forest directly reflect this input of strong acids in terms of their low *p*H (*2*). In marked contrast, however, the major trunk streams of the northeastern United States are not excessively acidified (*3*); their *p*H is largely dominated by the carbonic acid system, which has been the norm throughout the geologic past. My purpose in this report is to describe and explain the process by which acid rain is transformed into chemically normal stream water. To this end, the chemical character of a small stream, Falls Brook, has been monitored over a 3-year period. Nine sites along this drainage network (Fig. 1) have been sampled on a monthly basis over three annual cycles. Water samples were collected and chemically analyzed by our standard methods (*4*). Mean concentration data, averaged over 37 monthly

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