NO. 8 JOURNAL OF GEOPHYSICAL RESEARCH MARCH 10, 1976

25

Application of the Self-Potential Method to Geothermal Exploration in Long Valley, California

LENNART A. ANDERSON AND GORDON R. JOHNSON

U.S. Geological Survey, Denver, Colorado 80225

A self-potential survey made in the Long Valley caldera produced an anomaly derived from a dipolar source superimposed on potentials negative in polarity in relation to the area outside the caldera. The dipolar anomaly, consisting of negative and positive components differing amplitude by approximately 1 V, is centered over a resurgent dome in the west central part of the caldera. The exact nature of the potential source is unknown; however, electrofiltration processes caused by movement of heated groundwater that gives rise to streaming potentials are thought to be the principal cause of the dipolar anomaly. Diffusion potentials resulting from concentration differences between rising volcanic water and descending meteoric water may be responsible for the negative potentials measured within the caldera. Potential increases as high as 1100 mV were observed across the perimeter of the caldera.

INTRODUCTION

The mapping of natural electrical potentials within the Long Valley caldera, located in the east central part of California (Figure 1), constitutes an attempt to utilize the self-potential method in the detection and delineation of thermal sources within a known geothermal area. The use of the self-potential method in geothermal exploration was most unorthodox in that an absolute correlation between anomalous surface potentials and thermal sources at depth had not been established. However, higher than normal background potentials in geothermal areas have been reported by *White et al.* [1964] and *Corwin* [1973], and a single profile obtained across the Mud Volcano area in Yellowstone National Park produced a positive anomaly of about 40–50 mV which was unmistakably caused by phenomena related to thermal activity [*Zohdy et al.*, 1973]. On the basis of the possible utility of the self-potential method in geothermal exploration as suggested in these reports it was considered of practical interest to carry out a self-potential survey in Long Valley, where other geophysical data were available for interpretational support.

FIELD PROCEDURE

Self-potential measurements were made with copper–copper sulfate nonpolarizing electrodes spaced 300 ft (91.5 m) apart and a high-impedance millivoltmeter. Because of the large area to be surveyed, potential gradients were measured along a traverse, and individual readings added successively to construct a profile of potentials relative to a base station established at the junction of old U.S. Highway 395 and Mammoth Lakes Road (Figure 1). All self-potential data were subjected to a low-pass filtering process to remove short-wavelength potential variations generated by near-surface effects. Figure 2 shows an example of profile data in the three forms of measured, compiled, and filtered data obtained along traverse A-A′ (Figure 1).

Data initially were collected on a long closed loop traverse; where it was possible, subsequent traverses were tied to the original traverse at two points. Closure offsets were distributed linearly along the profile to compensate for accumulative errors. Errors in individual readings were minimized by selecting electrodes which produced less than 1 mV in a side-by-side arrangement and by reversing the relative position of the electrodes for alternate readings in order to counteract electrode potential imbalance if it should occur during the course of the day. Assuring contact with the moist overburden was a particular problem in Long Valley because of the insulating properties of the large quantities of pumice within the surface material. The contact problem was overcome by watering the area of electrode emplacement, but this procedure often produced potentials in the vicinity of the electrodes because of salinity gradients and the downward filtration of the introduced water. In time an equilibrium level was reached; however, in many instances fluctuations of the self-potential field decreased the accuracy of the measurement, and thus a probable source of much of the profile closure error was produced.

Typically, traverses completed on the same day or on successive days closed with very little error. For example, the initial loop, a 26-mi (42 km) traverse starting south of Casa Diablo Hot Springs and circling to the east and south, was completed within 3 days and closed with an error of 55 mV.

SURVEY RESULTS

The contoured self-potential data shown in Figure 3 produced some unexpected and rather spectacular results. The most obvious and impressive features on the map are the positive and negative anomalies overlying the south and north parts of the Cenozoic volcanic rock, respectively. Each anomaly exceeds 400 mV, so that there is a minimum net potential difference approaching 900 mV across a distance of about 5 km. The nearly equal amplitude of each anomaly suggests that a common source was responsible for generating the anomalies, and on the basis of the gradient between peak values it may be inferred that the source is deeply buried.

In the part of the caldera west of U.S. Highway 395, self-potentials continue to decrease. Profile data, insufficient to permit contouring, indicate that the potentials fall to at least −800 mV. The potential field in the southern part of the caldera is rather uniform, but to the north and northwest the self-potentials increase as the caldera perimeter is approached.

SOURCE MECHANISMS

In designating the negative and positive anomalies located over the volcanic rock as the most significant features on the map it is assumed that the anomalies are produced by effects associated with thermal activity at depth. Thus far no follow-up studies have been done using borehole investigations to confirm the results of the self-potential survey; therefore very

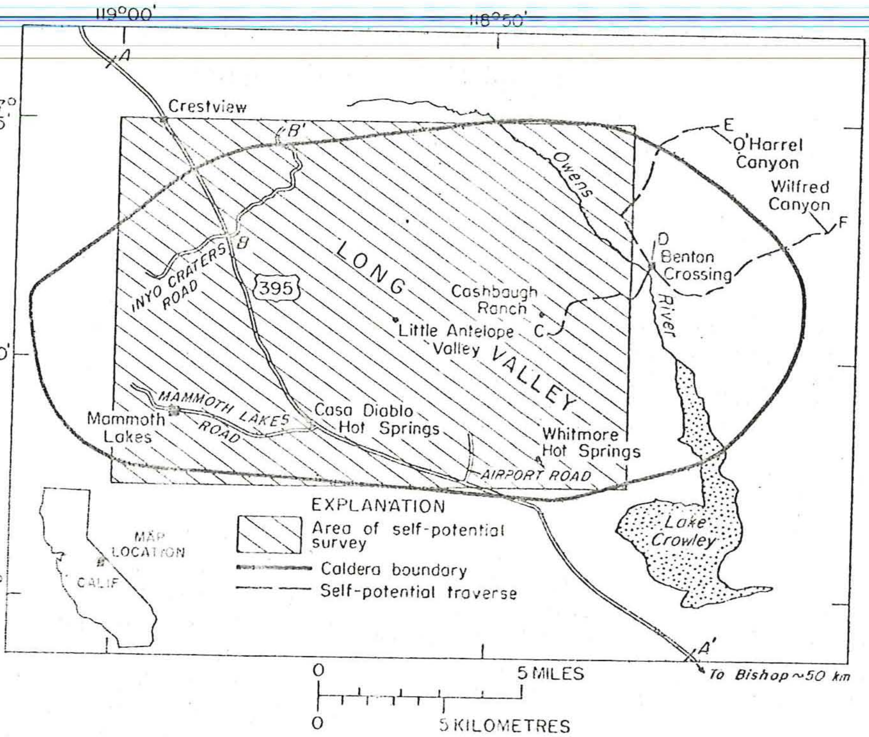

Fig. 1. Index map showing survey locations, Long Valley, Mono County, California.

little information exists from which a source mechanism can be positively identified. However, extensive previous work on self-potential phenomena provides enough information to permit speculation on possible processes involved in generating self-potential anomalies in geothermal fields. A paper by *Nourbehecht* [1963] is of particular interest in that it sets forth those internal conditions necessary to produce electrical signals at the earth's surface. The stated conditions are not repeated herein.

Many mechanisms may conceivably generate natural electromotive forces and thereby contribute to the total observed anomaly. However, the fact that the negative and positive anomalies have similar amplitudes and occur in a relatively uniform geologic environment suggests a singular predominating mechanism. It is thought that this mechanism is related to the heat-triggered movement of water in a convective cell. The potentials are believed to be generated by electrofiltration processes, the result being an effect called 'streaming potential.'

The electromotive force generated by streaming potentials is primarily controlled by fluid pressure for a given set of rock conditions. According to *Dakhnov* [1962], streaming potentials are caused by the preferential adsorption of one ion species on the grain surfaces comprising the pore walls. Be-

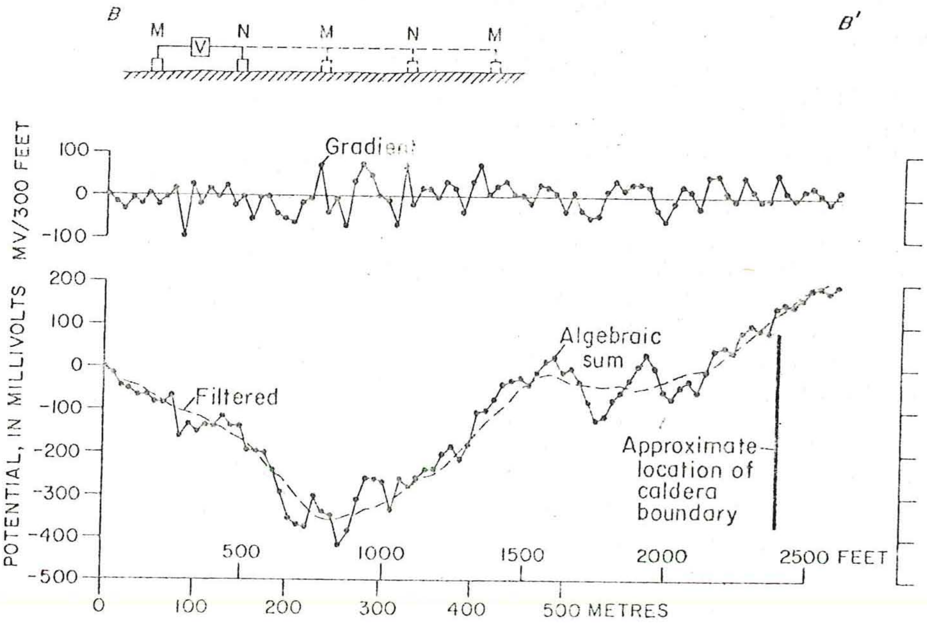

Fig. 2. Self-potential profile A-A' data as measured, compiled, and filtered prior to contouring.

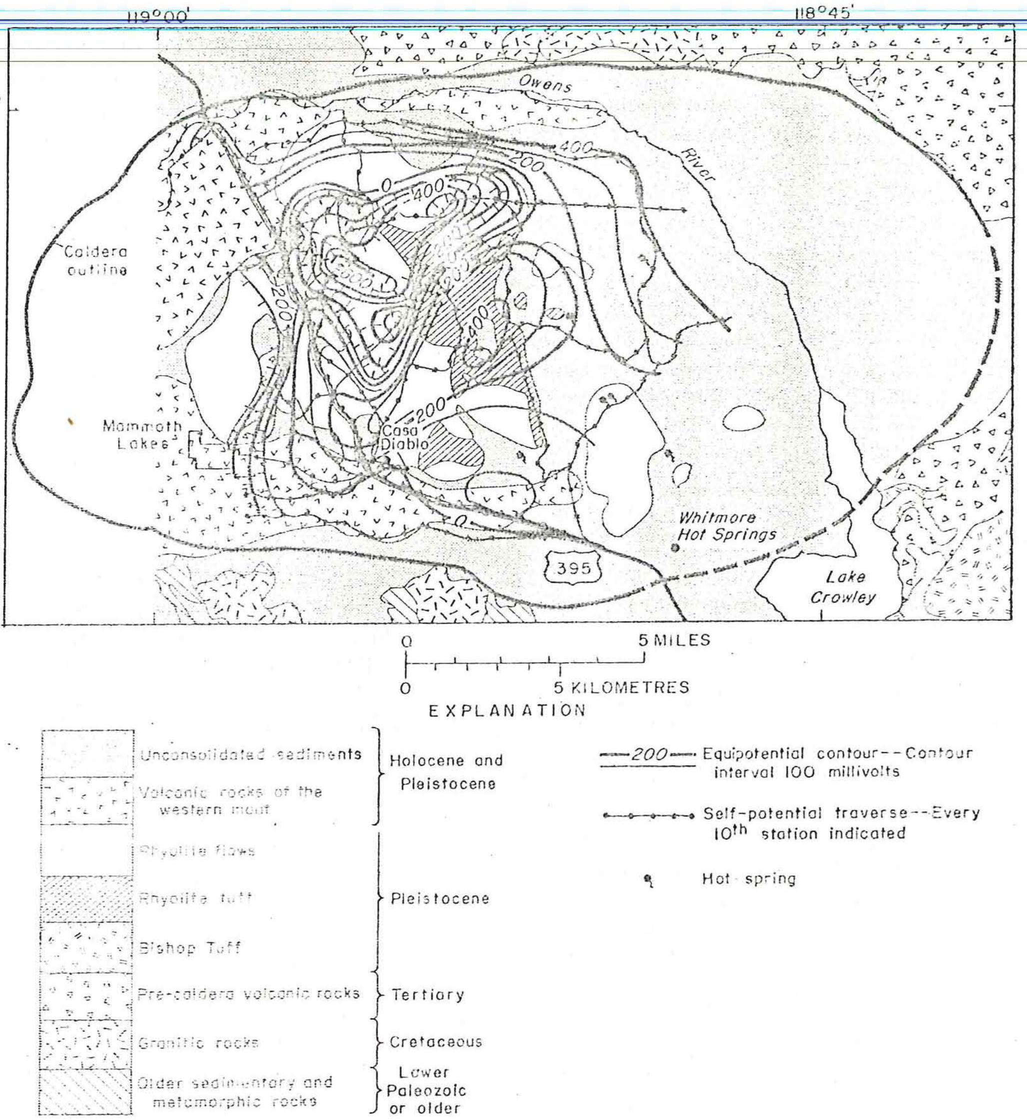

Fig. 3. Self-potential and generalized geologic map of the west central part of Long Valley, Mono County, California. Geology generalized from *Bailey et al.* [1976].

cause the adsorbed ions are all of the same polarity, the free liquid in the center of the pore spaces is enriched in ions of opposite charge. In the presence of a differential pressure across the rock formation the pore waters will move so as to produce a net charge separation along the line of water movement. In most rock systems, anions are adsorbed; therefore the pore waters carry a surplus of cations, and a positive potential is set up in the direction of flow. Some clays and carbonate rocks in basic solutions will produce the opposite effect.

Streaming potentials are dependent upon factors best described by the equation

$$E_s = \epsilon\zeta\Delta P/\xi[\sigma + \sigma_s(2/r)] \qquad (1)$$

where ΔP is the pressure difference across the rock formation, r is the crack width or pore radius of the rock, σ_s is the surface conductance of the diffuse layer within the pore spaces, and ϵ, ζ, σ, and ξ are the dielectric constant, zeta potential, conductivity, and viscosity of the pore water, respectively. Potential is that which exists across the fixed charges at the pore walls and those charges within the mobile layers of liquid. The properties ϵ, ξ, and σ are always positive; therefore the polarity of a surface anomaly arising from streaming potentials will be dependent upon the direction of water flow and the zeta potential.

Typically, (1) is expressed as a ratio of $E_s/\Delta P$, which is an equilibrium statement implying that the charge separation caused by fluid movement will be counteracted by electrostatic forces so as to reach an asymptotic value for a given set of rock conditions. As the pressure increases, the streaming potential will increase proportionately.

Phenomenologically, one can envision a deeply buried thermal source heating the groundwater so as to cause an upward migration of the water. Upward-moving water generally produces positive potentials at the surface; therefore we may attribute the positive anomaly over the Quaternary rhyolite to ascending groundwaters. In the event that the movement of water is impeded by a cap rock of low permeability, the heated water either travels through fracture systems to the surface, where it forms hot springs, or following some loss of heat, cycles downward if no escape is possible. Descending waters will generate a negative potential at the surface, and this mechanism may be responsible for the negative anomaly over the northern part of the Quaternary rhyolite. A similar negative counterpart is not developed south of the positive anomaly because, as is shown in Figure 3, the heated waters have found escape routes to the surface through the hot springs along the east and south flanks of the rhyolite; the relatively high potentials observed south and southeast of the positive anomaly are thereby sustained. The escaping water must certainly be replenished if the hot water convection cell is to be maintained. Groundwater recharge areas conceivably exist at several locations within the caldera; however, surficial evidence suggests that the principal source of fresh water is from surface flow off the Sierra highlands into the western part of the caldera. The downward percolation of meteoric water through rocks which are primarily basalt may be responsible for generating the high negative potentials observed in the western part of the survey areas.

Electrochemical effects may be responsible, at least in part, for the anomalies over the volcanic rock. On the basis of data provided by *Lewis* [1974] we know that springwaters north of the anomalous area are low in dissolved solids. If this fresh water can find access to a permeable layer within the volcanic sequence and thus come in contact with the saline thermal waters, then mechanisms for generating significant surface potentials will be activated. The first of these mechanisms involves processes by which diffusion potentials are produced. Diffusion potentials are developed across a liquid junction when two solutions of differing salinities are in direct contact. Ions from the more concentrated solution migrate into the dilute solution at a rate dependent upon the mobility of the ions involved. The more mobile ions are typically of one polarity; therefore a separation of charge will develop across the solution boundary, the result being a net current flow. Temperature differences between solutions will increase ion mobility, the effect being thereby enhanced, and the presence of clays within the rock may do the same.

The second of these mechanisms that take place at the interfacing of unlike solutions produces oxidation-reduction potentials if certain conditions are met. According to *Sato and Mooney* [1960] a difference in the Eh or redox potential of the solutions in contact must exist in order to provide the driving source for the transfer of electrons from one solution to the other. The electron transfer also requires the presence of a conductive body across the solution boundary and an electron mobility rate which exceeds the mobility of the upward-moving positive ions in the surrounding solution. To attribute the observed Long Valley anomalies to an oxidation-reduction process, the fresh water must contain free oxygen to create an oxidizing environment, and in like manner, the thermal waters must provide a reducing environment. Data from *Lewis* [1974] show that there may be sufficient dissolved iron in the thermal waters to satisfy the latter condition; however, the vehicle for electron transfer is still lacking. A paper by *Willey et al.* [1974] indicates that dissolved sulfides exist in relative abundance within the groundwaters of Long Valley. If these sulfides are deposited in disseminated form in the zone of groundwater mixing, then a mechanism for electron flow will exist [*Sato and Mooney,* 1960]. In the Mud Volcano area in Yellowstone National Park, core samples extracted from a borehole indicated the presence of disseminated pyrite deposited by thermal waters in the near-surface layer. Pyrite was found at a depth of 50 ft (15.2 m), and it increased in abundance down to the bottom of the hole at 347 ft (105.8 m) [*Zohdy et al.,* 1973].

Pyrite deposition is not uncommon in areas of thermal activity, nor are reducing agents uncommon in thermal waters. The main concern, however, is whether sufficient free oxygen can be maintained within the infiltrating groundwaters to provide an oxidizing environment at the necessary redox potential to generate the observed surface potentials. Free oxygen is generally depleted rapidly, particularly in the presence of dissolved organic materials.

Nourbehecht [1963] in his study of diffusion and electrokinetic source mechanisms calculated the upper limit of potential amplitude measurable at the surface for each effect. Maximum surface potential for the diffusion process is given as 100 mV; the streaming potential mechanism has a calculated capability of producing anomalies of 'several hundred millivolts.' *Sato and Mooney* [1960] indicated that half-cell potentials relating to oxidation-reduction effects usually range in amplitude from 400 to 500 mV, although much higher potentials have been observed in the field.

A number of other naturally occurring phenomena may conceivably act to produce measurable self-potentials at the surface. However, for the known possible processes there are so many variables involved that all necessary conditions will rarely be met.

PROFILE DATA

Because individual traverses did not normally extend beyond the caldera boundaries, the contoured data do not adequately define the self-potential gradients observed in the vicinity of the caldera walls. Contours in the northern part of Figure 3 indicate an increase in potential as the edge of the caldera is approached; this effect, however, can better be seen in profile form.

Profile data obtained along traverse A-A′ (Figure 1), as shown in Figure 4, were relatively smooth and therefore were not filtered in the usual manner. Instead, every 10th data point was plotted, a somewhat angular appearance to the profile thus being imparted. The traverse extended beyond the physical limits of the caldera as inferred from gravity data [*Pakiser et al.,* 1964]. The character of the profile indicates that the self-potentials within the caldera are substantially lower than or negative with respect to those potentials generated outside the caldera. On approaching the northern wall of the caldera the

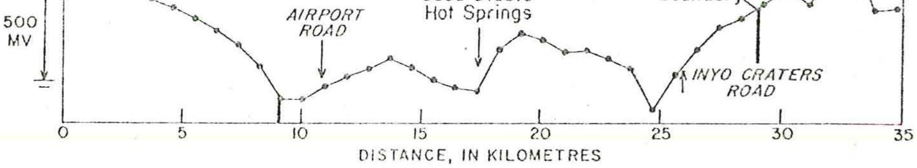

Fig. 4. Self-potential profile obtained along a north-south trending traverse following U.S. Highway 395.

potentials increase, but beyond the wall the potentials show signs of decreasing. The fact that self-potentials do decrease outside the caldera suggests that the high potentials are caused by effects localized near the caldera edge. A decrease in self-potential was not observed south of the caldera boundary; however, unlike the other caldera walls the southern wall is not physically apparent. Indeed, the gravity data obtained in the southern part of the caldera have a lower gradient than data from elsewhere along the caldera perimeter. This fact suggests that the southern caldera wall may consist of a series of fault blocks rather than a single offset, a structural characteristic which would tend to broaden those effects that may be attributed to a source near the edge of the caldera.

Profiles (C-D, D-E, D-F) obtained in the eastern part of the caldera (Figure 5) (see Figure 1 for location) show a gradual and virtually uninterrupted increase in potentials from their starting point to the wall of the caldera, where the potentials level off and eventually begin to decrease outside the caldera. The potential rise on each profile is substantial; the potential increased by more than 1100 mV along the traverse leading through Wilfred Canyon and nearly 1000 mV on the O'Harrel Canyon traverse.

The cause of the potential increase near the caldera boundary is unknown, but possibly, a combination of the mechanisms previously discussed may be responsible for the observed effect. It was first thought that the potential gain could be attributed to outward-flowing current that increased in density within the surface layer as a result of a lateral increase in resistivity encountered at the caldera edge. To test this supposition, a two-dimensional model was formulated with the use of a buried current source and a vertical contact separating media of differing resistivities.

Image theory was used to derive equations for calculating potentials on each side of the contact. For a current source located within the medium of resistivity ρ_1 the equations are

$$V_1 = \frac{\rho_1 I}{2\pi}\left\{\frac{1}{[(k-a)^2+d^2]^{1/2}} + \frac{k}{[(x-a)^2+d^2]^{1/2}}\right\} \quad (2)$$

$$V_2 = \frac{\rho_1 I}{2\pi}(1+k)\left\{\frac{1}{[(x-a)^2+d^2]^{1/2}}\right\} \quad (3)$$

where V_1 and V_2 are potentials measured over ρ_1 and ρ_2 material, respectively; d, the depth of burial to a point current source; a, the distance from the source to the vertical contact; I, the current strength; and k, the reflection coefficient equal to $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$. By using these equations, profiles of potential field distribution can be compiled from any number of randomly positioned current sources of either polarity.

To simulate the potential effects observed at the edge of the caldera, it was necessary to provide for a horizontal offset in the relative locations of current sources. Figure 6 shows profiles calculated for the indicated dipolar current source arrangement by using first a medium of uniform resistivity and second a resistivity contrast, where ρ_2 is 10 times larger than ρ_1. From the shape of the curves it is seen that no lateral resistivity changes are required in order to produce the observed edge effects. However, a resistivity increase representing the caldera walls will serve to enhance the relative increase in potential as measured from a point within the caldera. These calculations suggest that a source mechanism that produces potentials positive in polarity exists near the perimeter of the caldera.

The nature of the various mechanisms which may possibly combine to create the anomalous potentials associated with the caldera perimeter is, of course, speculative. Perhaps the surface potentials within the caldera are relatively low as a result of diffusion and oxidation-reduction processes occurring at the junction of meteoric and thermal waters. These electrochemical effects would most often result in a negative potential at the surface. In addition, it may be supposed that thermal waters flow upward along a relatively permeable path created around the perimeter of the caldera during the time of subsidence. The upward-migrating waters would generate streaming potentials positive in polarity, the observed edge effect thus being produced. To our knowledge there are no hot springs along the borders of the caldera; therefore if the streaming potential concept is valid, the thermal waters are either returned to the depths nearer the center of the caldera, the relatively low inner-surface potentials thereby being enhanced, or they simply merge with meteoric groundwaters within the alluvium.

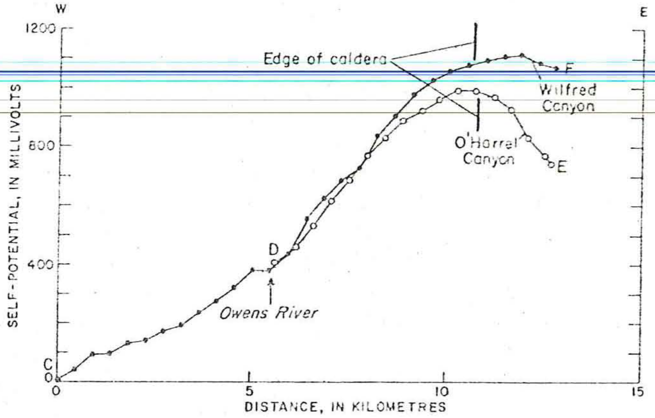

Fig. 5. Self-potential profiles along the eastern caldera traverses, Long Valley, Mono County, California.

Summary and Conclusions

Field observation and theory both indicate that anomalous self-potentials may be expected in geothermal areas. Previous reported attempts to utilize the self-potential method in geothermal exploration produced ambiguous results, probably because these earlier surveys were generally limited to areas of

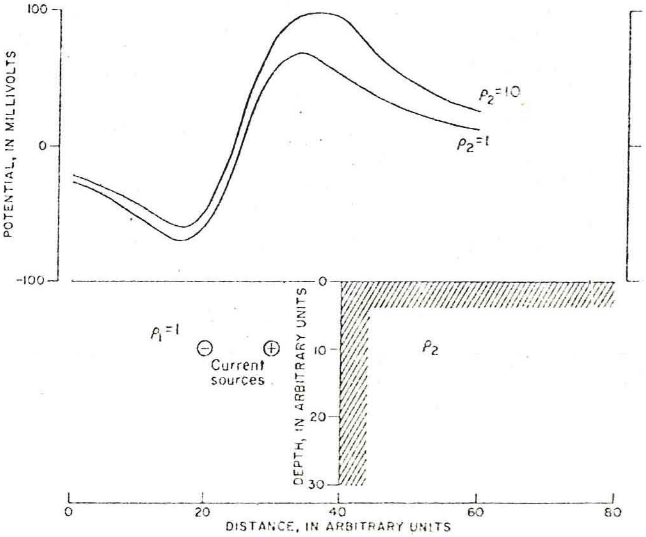

Fig. 6. Theoretical profiles calculated for a buried dipolar source in homogeneous media and for a source near a vertical contact dividing media of differing resistivities.

hot spring activity. In Long Valley we chose to extend our survey to cover a major part of the caldera and, by data filtering, to remove the effects of near-surface potentials from those potentials emanating from sources at depth. We acknowledge, however, that potentials from near-surface effects, particularly in hot spring areas, can be substantial and can thereby evoke undeserved attention.

The Long Valley self-potential survey yielded a number of interesting results. As an example, potentials associated with the perimeter of the caldera are very much higher than those associated with the central area of the caldera. Whether this phenomenon is unique to Long Valley or whether it can be observed in other calderas is a question yet to be answered. However, the effect was found to be generally symmetrical about the mapped edge of the caldera, and the possibility that an external source mechanism causes the perimeter potentials was thereby precluded.

The dipolar anomaly overlying the Quaternary volcanic rock in the west central part of the caldera is the most significant feature of this self-potential survey in terms of thermal potential. The positive anomaly covers the southern part of a resurgent dome and is ringed to the south and southeast by hot springs. No similar surface manifestation is affiliated with the negative anomaly to the north. Although several source mechanisms may combine to produce the dipolar anomaly, we believe that electrokinetic phenomena, primarily in the form of streaming potentials, principally cause the observed surface potentials. The resistivity of the pore waters within the thermal zone is typically very low; however, low-resistivity pore water moving through a thick section of rock over a very broad area may be magnified into potentials of considerable magnitude.

The depth to the current source is unknown primarily because the manner in which surface potentials are produced is very complex [*Nourbehecht*, 1963]. However, it is believed that the large-scale anomalies are caused by sources at depth. The deep lobes of the negative anomaly, particularly the westernmost one and its associated positive anomaly immediately south, may indicate the presence of a secondary hot water convection cell within the major water system or an unidentified source mechanism at an intermediate depth.

The results of other geophysical surveys do not correlate well with the findings of the self-potential survey. Perhaps the thermal zone beneath the volcanic rock is too deep to be detected by controlled source methods, or perhaps the emphases of the other surveys were on other aspects or areas.

The total field resistivity map presented in the paper by *Stanley et al.* [1976] does show the area of the positive self-potential anomaly to be less resistive than the rock associated with the negative anomaly. This resistivity difference, however, may be attributed to clay alteration within the volcanic rock caused by the upward migration of thermal waters rather than to effects of the hot water convection cell itself.

We are reasonably confident that the self-potential method will find application to geothermal exploration, although the fundamental relationship between them has yet to be completely understood. Despite the fact that source mechanisms have not been specifically defined, there is sufficient theoretical evidence to support the notion that high-amplitude potentials can be systematically mapped at the surface. In Long Valley we have demonstrated that anomalies covering many square miles can be defined and separated from short-wavelength potentials originating from shallow sources. Although field procedures may need to be refined in order to make measurements with greater reliability, the self-potential method as a reconnaissance technique is relatively simple to apply and may prove to have the advantage of sensing the dynamic aspects of a thermal system at depths greater than those possible with most controlled source methods.

REFERENCES

Bailey, R. A., G. B. Dalrymple, and M. A. Lanphere, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California, *J. Geophys. Res.*, *81*, 725–744, 1976.

Corwin, R. F., Offshore application of self-potential prospecting, Ph.D. thesis, Univ. of Calif., Berkeley, 1973.

Dakhnov, V. N., Geophysical well-logging—The application of geophysical methods; electrical well-loggings, *Colo. Sch. Mines Quart.*, Engl. Transl., *57*(2), 445 pp., 1962.

Lewis, R. E., Data on wells, springs, and thermal springs in Long Valley, Mono County, California, open file report, 52 pp., U.S. Geol. Surv., Menlo Park, Calif., 1974.

Nourbehecht, B., Irreversible thermodynamics in homogeneous media and its application to certain geoelectric problems, Ph.D. thesis, Mass. Inst. of Technol., Cambridge, 1963.

Pakiser, L. C., M. F. Kane, and W. H. Jackson, Structural geology and volcanism of Owens Valley region, California—A geophysical study, *U.S. Geol. Surv. Prof. Pap. 438*, 68 pp., 1964.

Sato, M., and H. M. Mooney, The electrochemical mechanism of sulfide self-potentials, *Geophysics*, *25*(1), 226–249, 1960.

Stanley, W. D., D. B. Jackson, and A. A. R. Zohdy, Deep electrical studies in the Long Valley caldera, Mono and Inyo Counties, California, *J. Geophys. Res.*, *81*, 810–820, 1976.

White, D. E., G. A. Thompson, and C. H. Sandberg, Rocks, structure, and geologic history of Steamboat Springs thermal area, Washoe County, Nevada, *U.S. Geol. Surv. Prof. Pap. 458-B*, B1–B63, 1964.

Willey, L. M., J. R. O'Neil, and J. B. Rapp, Chemistry of thermal waters in Long Valley, Mono County, California, open file report, 19 pp., U. S. Geol. Surv., Menlo Park, Calif., 1974.

Zohdy, A. A. R., L. A. Anderson, and L. J. P. Muffler, Resistivity, self-potential, and induced-polarization surveys of a vapor-dominated geothermal system, *Geophysics*, *38*(6), 1130–1144, 1973.

(Received January 27, 1975;
revised December 4, 1975;
accepted December 15, 1975.)