PROCEEDINGS, Fourteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 1989
SGP-TR-122

SELF-POTENTIAL ANOMALY CHANGES AT THE EAST MESA AND CERRO PRIETO GEOTHERMAL FIELDS

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ABSTRACT

Repetitive self-potential (SP) surveys recently completed over two producing geothermal fields, Cerro Prieto and East Mesa, ten years after the original surveys gave us an unprecedented opportunity to see whether SP changes over the fields are related to pressure gradients associated with massive fluid movements; i.e., production, injection and natural recharge. A strong correlation between SP and production was observed at Cerro Prieto where the anomaly position has shifted eastward, and where we were able to model the new anomaly on the basis of actual production rates and the hydrogeology. On the other hand, we were unable to explain the East Mesa anomalies on the basis of what we presently know about production rates and the hydrogeology of that system. The SP voltages over the East Mesa area are smaller, and non-geothermal sources effects are more apparent. We suspect, as well, that electrochemical (diffusional) potentials are caused by fault-guided leakage of thermal fluids in the shallow clay caprock.

INTRODUCTION

Most geothermal fields are reported to have an associated self-potential (SP) anomaly of tens to over several hundred millivolts (Corwin and Hoover, 1979). Although the interpretation of these voltages has proved difficult in the past due to the multiplicity of causes (e.g., electrokinetic, thermoelectric, and chemical diffusion effects), lack of laboratory and field data, and the lack of interpretative techniques, recent advances indicate that the main mechanism is related to the electrokinetic effect. That is, these so-called streaming potentials are generated by subsurface flows of water, both natural and induced by geothermal fluid extraction and injection activities (Ishido et al., 1983; Ishido et al., 1987). SP measurements made near individual geothermal production and injection wells being tested show that changes of 5 to 10 mV occur as the wells are subjected to short-term flow and injection tests (Ishido et al., 1983; Sill, 1983a). Although these voltages are close to the typical SP noise level of ± 5 mV, the voltage anomalies over a large multi-well geothermal field would be many times larger.

An unprecedented opportunity to study production-related SP effects occurred recently when we obtained SP data sets over two producing geothermal fields; East Mesa and Cerro Prieto. SP surveys had been run over both fields ten years earlier (Corwin et al., 1978; Corwin et al., 1981), and thus it was also hoped that the repeat surveys would show changes correlative to changes in production activities. East Mesa and Cerro Prieto are a fortunate choice of fields for comparative studies because they share a few common geological features, yet have had markedly different production histories. Both reservoirs occur in nearly horizontal deltaic sediments of the Salton Trough and both systems have been under increasing development and exploitation between the survey years. On the other hand, there exist many significant differences in the physical parameters of the systems, chemistry of their brines, and their production rates and histories.

DATA ACQUISITION PROCEDURES

Attempts were made to resurvey the two fields in the same fashion as the original surveys, but this was impossible to do for reasons discussed in this section. For the most part surveys could be rerun along the same lines and with the same type of equipment; copper-copper sulfate electrodes and a 10 Mohm impedance digital multimeter. Because of geothermal activities some survey line had to be relocated, other lines were extended to expand the surveys into newer production areas. Telluric noise monitoring was carried out during surveys to check for periods of anomalously strong noise.

With minor exceptions both East Mesa surveys were carried out using the fixed reference technique in which one electrode remains fixed at a base and is connected to the multimeter via a very long wire. In this mode of operation, multiple base stations were required (14 for the 1987 survey), and loop errors were distributed to help minimize cumulative errors. In 1987, a 100-m station separation was used. These data are higher in resolution and better in quality than the 1978 data for which a 200-m station separation was used.

Data acquisition techniques used at Cerro Prieto consisted of both the fixed reference and the less desirable "leapfrog" technique in which both electrodes move in an alternating fashion along the survey line. The 1978 Cerro Prieto survey was conducted almost entirely using the reference electrode technique and station separations of 100 to 350 m. Due to the increased cultural activity and loss of easy access to some areas, the 1988 survey was done entirely using the leapfrog method with a 100-m measuring dipole (Rodríguez, 1988). The leapfrog mode is highly susceptible to cumulative random errors along a line. Errors at line crossing points were distributed around loops to help minimize this problem.

The corrected voltages were all then smoothed by means of a 5-point moving average to help remove small voltage perturbations due to various noise sources, that is telluric noise, man-made electrical noise, and background geologic noise due to point-to-point variations in soil moisture and chemistry. This is a low-pass filtering operation which preserves the long spatial wavelengths in the data, but which changes individual readings up to 20-30 mV. The smoothed data sets were then hand contoured. Both new SP contour maps display more detail than the original maps. This is due to the closer station spacing used in the two recent surveys, and additional (fill-in) survey lines. Such differences make direct comparisons of the results difficult. Another consideration when comparing repeat surveys, particularly those at Cerro Prieto, is the difference in background voltage levels. This difference may be due simply to the choice of reference station.

CERRO PRIETO RESULTS

The initial SP survey was conducted in late 1977 and early 1978 when production was limited to the shallow α reservoir. At that time approximately 12 wells were producing 750 tonnes/hr (≈250 L/s) from a reservoir region 1.0 to 1.4 km below the surface. Steam separated at the wellheads was delivered to the original 75 MWe plant (Units I and II of the CPI plant). The SP contours (Fig. 1) showed a dipolar anomaly, peak-to-peak voltage of 160 mV, whose axis trended N-S and was centered over the original production area (Corwin et al., 1978; Fitterman and Corwin, 1982). The dipolar anomaly may be explained in terms of fluid recharge by waters ascending through the sandy gap of the otherwise impermeable O Shale unit (Halfman et al., 1986a).

The second SP survey was carried out by Jorge Rodríguez Bahena of CFE in March 1988. At that time the installed electric generating capacity had increased to 620 MWe with the expansion of the CPI plant and the addition of two new 220 MWe plants (CPII and CPIII), that went on line in 1986-1987. Most steam for the three plants was provided by brine from deeper reservoir regions (primarily the β reservoir) located east of the original production area (Halfman et al., 1986a; 1986b). Brine reinjection has been insignificant. Not unexpectedly, the 1988 survey (Fig. 2) reveals that the SP anomaly has changed. Among the more significant changes are the following:

(1) the dipolar anomaly is less clear,

(2) the steepest SP gradients have shifted eastward a distance of over 2 km to a position that appears to correlate with the surface projection of the Fault H zone (Halfman et al., 1986b),

(3) the voltage amplitude variations have increased up to 20% along some lines.

INTERPRETATION OF THE CERRO PRIETO DATA

To determine whether the 1988 SP data are, in fact, production related, we attempted to numerically model the SP using known production data for the month of the surveys, the hydrogeologic-lithofacies model for the system, and the subsurface geophysical parameters, either measured directly (electrical resistivity and temperature) or inferred from reservoir models (permeability). Thus far, we have focussed our attention on a single northwest-southeast trending profile, Line E–E′, for which there is a lithofacies cross-section and a recently updated model of geothermal fluid flow (Halfman et al., 1986b). In addition, the profile is roughly normal to the steepest SP gradients, and it crosses an area of significant geothermal production. Figure 3 shows the simplified lithofacies section, with the interpreted geothermal fluid flow patterns, and the geothermal production intervals. Northwest of Fault H production is from 2.2 km, the upthrown side of the β reservoir in Sand unit Z. Southeast of the Fault H production comes mainly from a depth of 2.6 to 2.8 km in the downthrown Sand Z unit. Temperatures in the β reservoir are 320-350°C. Less is known about the deeper γ reservoir (unit K) and so it has been excluded from this study.

To calculate the surface SP along profile E–E′ we used a program SPXCPL written by Sill and Killpack (1982) and modified for easier use at LBL. A complete discussion of the basis for these calculations is beyond the scope of this paper (see for example Nourbehecht, 1963; Sill, 1983b), so it shall suffice to say

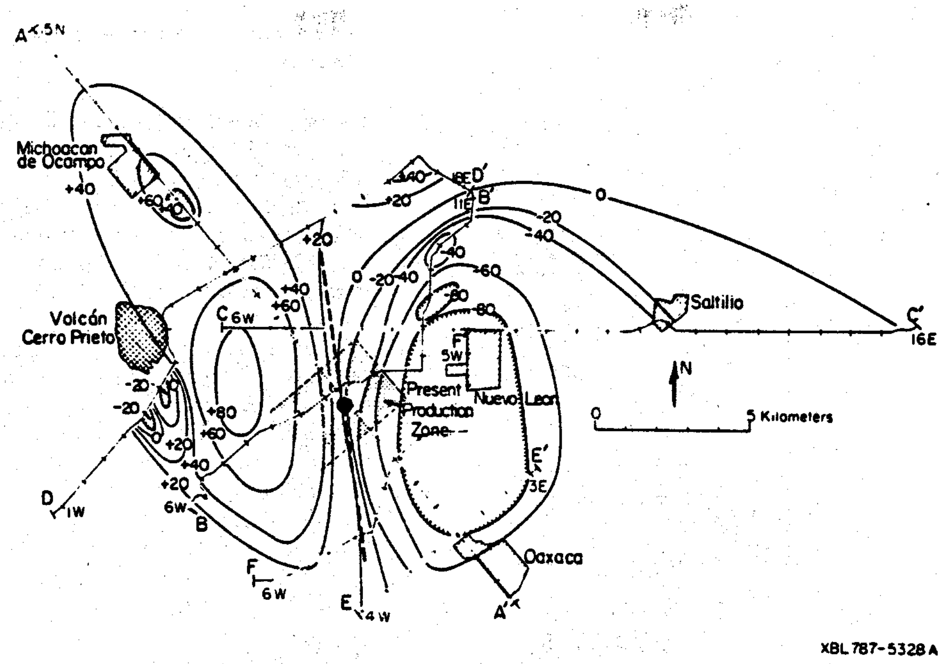

Fig. 1. The 1977-78 Cerro Prieto SP contour map.

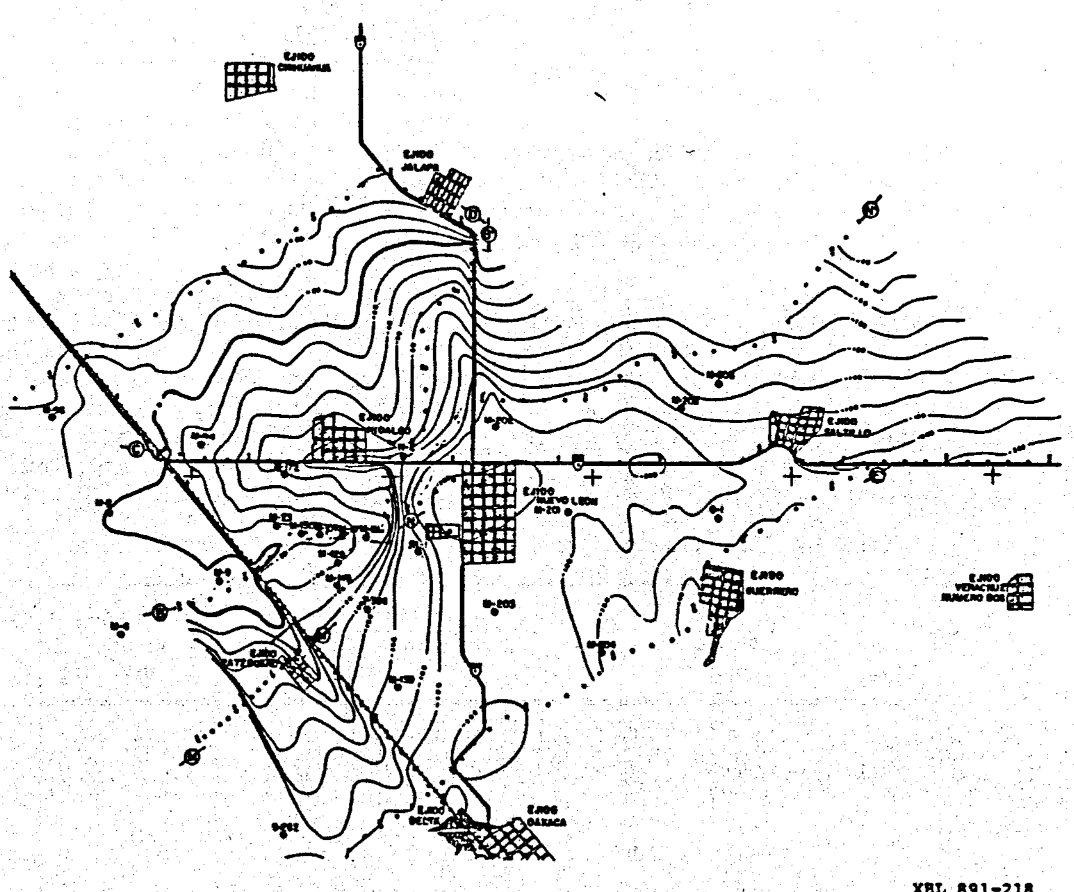

Fig. 2. The 1988 Cerro Prieto SP contour map.

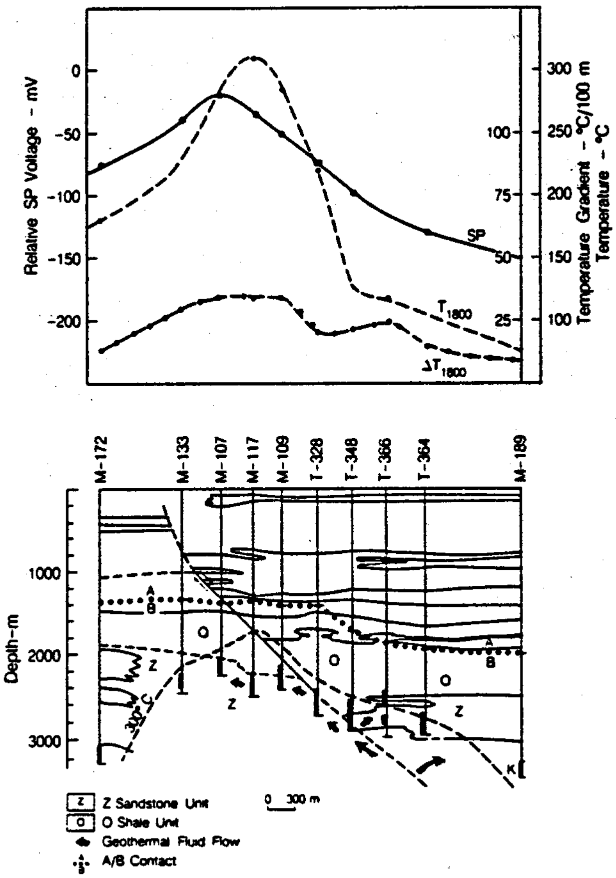

Fig. 3. Simplified lithofacies section for the north-south Line E–E′ (after Halfman et al., 1986b). Also shown is the SP voltage profile plotted against the subsurface temperature and temperature gradient at 1800 m depth.

that SPXCPL solves separately for the electric potentials in the earth subject to a distribution of pressure (flow or electrokinetic) sources and thermal (thermoelectric) sources. SPXCPL solves the 2-D coupled flow problem by explicitly modeling both the primary flow (fluid flux, heat flux) and the induced secondary electric potentials that arise from the primary flows (Onsager, 1931).

Figure 4 shows the flow model constructed and used, and Table 1A lists the parameters for the model. The two large negative flow sources (II and IV) account for actual well production from the upthrown and downthrown sides of the β reservoir, respectively, during March 1988. The positive flow sources simulate recharge effects.

We were able to obtain a reasonable fit to the observed SP anomaly after relatively few iterations (Fig. 5). Electrical resistivity values are reasonably well constrained by surface and wellbore surveys and so these were not varied. Unit permeabilities had to be reduced by about half the values used by Halfman et al. (1986a), and the values for the electrokinetic coupling coefficient, a critical parameter in the modeling exercise, were taken from tables of representative values for sands and shales.

We found that the location and magnitude of recharge sources is essential for fitting the SP anomaly. The SP low in the southeast part of the survey area requires both shallow lateral fluid flow in Unit 2 and deeper lateral recharge in the Z Sand unit from the southeast. The fit improved after we eliminated recharge source I, simulating deep Z Sand recharge from the northwest. The fit improved more after we eliminated source V which simulates deep vertical recharge to the β reservoir. This came as a bit of a surprise because it contradicts the hydrogeologic model showing a deep source of fluid ascending the H fault (Halfman et al., 1986b) and feeding both the β and γ reservoirs. It must be pointed out that the SP is not conclusive evidence for the presence or absence of recharge. First, the SP calculations are highly model specific and nonunique. Second, the final model is also highly dependent on the choice of profile to be fitted and data accuracy along that profile. However, these numerical tests clearly point out the sensitivity of SP surface voltages to recharge sources.

Table 1A. Unit Parameters for Cerro Prieto SP Model: Pressure Sources

Unit	Geologic Designation	Electrical Resistivity (ohm-m)	Permeability (md)	Electrokinetic Coupling Coeff. (mV/atm)
1		2	10	5
2		20	50	20
3		6	10	5
4		0.5	50	50
5	Shale O	6	0.5	5
6	Sand Z	3	50	100
7		10	5	5

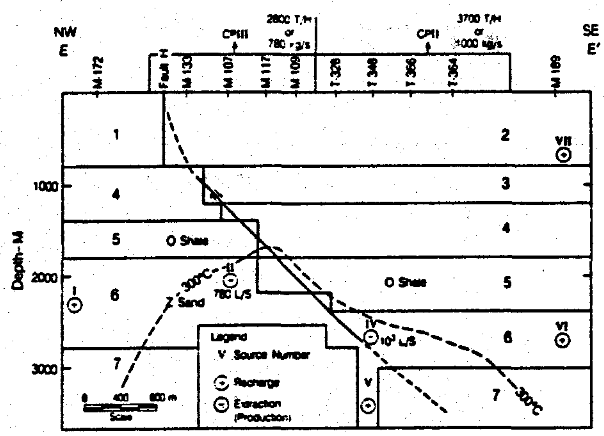

Fig. 4. Two-dimensional hydrologic flow model used to model SP effects at Cerro Prieto.

To see how much the SP data was affected by thermoelectric currents, we next calculated the voltages due to a distribution of thermal sources. A reasonable fit to the subsurface temperature distribution was obtained by using 70 sources, each 0.25 x 10^6 Watts, in the region outlined in Figure 6, and the rock thermal parameters shown in Table 1B. Although a closer fit to subsurface temperatures could have been achieved, modeling was terminated when it became apparent that the peak thermoelectric voltage at the surface is less than 4 mV, and less than the noise level of the field data.

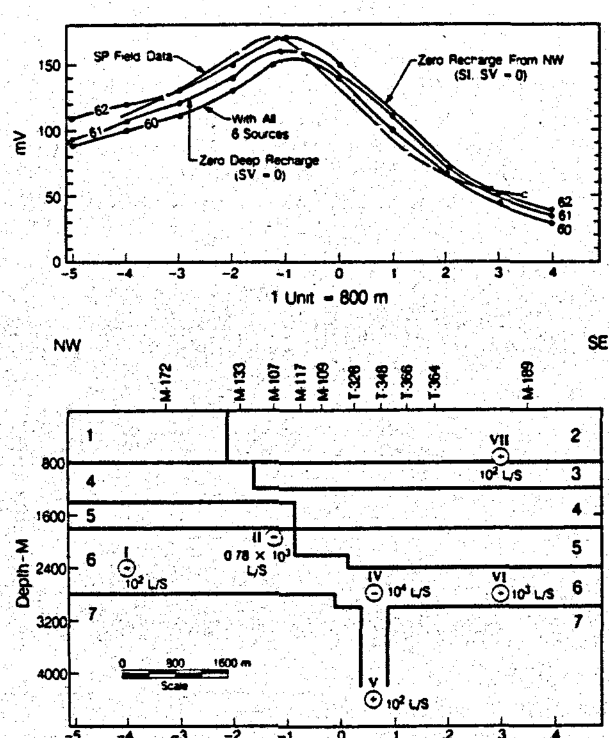

Fig. 5. Numerical model results for different cases of recharge (60, 61 and 62 refer to the data file numbers). Horizontal distance resolution is 200 m.

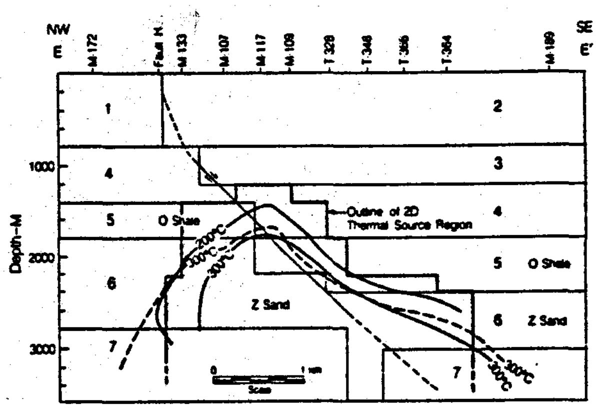

Fig. 6. Two-dimensional thermal model for Cerro Prieto used to calculate thermoelectric SP voltages. Seventy point sources, 0.25 x 10^6W each were used, but produce only a broad negative anomaly of < 4 mV (peak). The solid isotherm lines are calculated, the dashed line is measured.

EAST MESA RESULTS

The 1978 East Mesa SP survey (Fig. 7) was conducted after several wells had been drilled and tested by Republic Geothermal, U.S. Bureau of Reclamation (Burec), and Magma Power Company, but prior to large-scale, continuous geothermal production. A broad dipolar anomaly (90 mV peak-to-peak) was modeled by using charge separations along three steeply dipping pairs of planes; two that run northwesterly through Section 6 (T. 16 S., R. 17 E.), roughly between the Burec and Republic wells (Corwin et al., 1981). Because these planes were found to correlate with the traces of known or suspected faults, Corwin et al. (1981) concluded that conditions along faults were causing the SP voltages. However, known subsurface temperature and pressure gradient and estimated electrokinetic and thermoelectric coupling coefficients for the rocks all seemed far too low to account for the anomaly amplitude. They suggested that another mechanism might be generating the source currents.

Aside from enhanced resolution, the 1987 data appear relatively unaltered and unaffected by production activities (Fig. 8). Because of the higher data density, the 1987 data set has a much richer and more complex pattern of 10 to 30 mV (after smoothing) highs and lows, but the relations between discrete SP variations and production activities are subtle. During the first two weeks of December 1987 when the second survey was made, two binary power plants were in operation and a third was being prepared for start-up. Production wells in Section 7 were delivering approximately 200 L/s to the 10 MWe (gross) Magma plant. To the north, another 11 production wells, most in the southern part of Section 30, were producing approximately 500 L/s for the Ormesa I (30 MW

Table 1B. Unit Parameters for Cerro Prieto SP Model: Thermal Sources

Unit	Geologic Designation	Electrical Resistivity (ohm·m)	Thermal Conductivity (W/m·°C)	Thermoelectric Coupling Coeff. (mV/°C)
1		2	2	0.05
2		20	2	0.10
3		6	2	0.30
4		0.5	2	0.10
5	Shale O	6	1.8	0.30
6	Sand Z	3	2	0.10
7		10	2.5	1.00

gross) plant. Another seven production wells in Sections 5 and 6 were in the last stages of testing prior to the start-up of the Ormesa II (20 MW gross) plant. Geothermal fluids are produced from depths of 1.2 to 2.1 km and are injected into offset wells at depths of 0.9 to 1.5 km.

In view of the amount of fluid produced and injected (the pressure sources), the SP amplitude variations are small. A few of the discrete anomalies seem to be non-geothermal in origin. For example, a new 50 mV low around well 18-28 is probably due to oxidizing well casing, and the persistent 20 mV low at the west end of Line D may be due to a pump motor along the East Highline Canal. Small highs adjacent to the East Highline Canal may be due to fluid leakage. Other small discrete anomalies do seem to correlate with geothermal activities. In particular, notice that a the original 60 mV high in the southwest corner of the survey area has become a complex pattern of 30 mV highs to 20 mV lows. The E-W trending low running through Sections 7 and 8 correlates with injection wells 46-7, 46-7B, and 84-7, while the adjacent high on the south correlates with production wells 48-7, 48-7A, 48-7B and 88-7. This correlation is illustrated in Figure 9 which shows the smoothed SP data for Line A, a south-to-north profile, passing through several wells, including production well 88-7 and injection well 84-7, 700 m apart.

The observed SP anomaly could be fitted in only a very rough way to this production-injection doublet. A pair of 300 L/s sources at 800 m depth yielded the

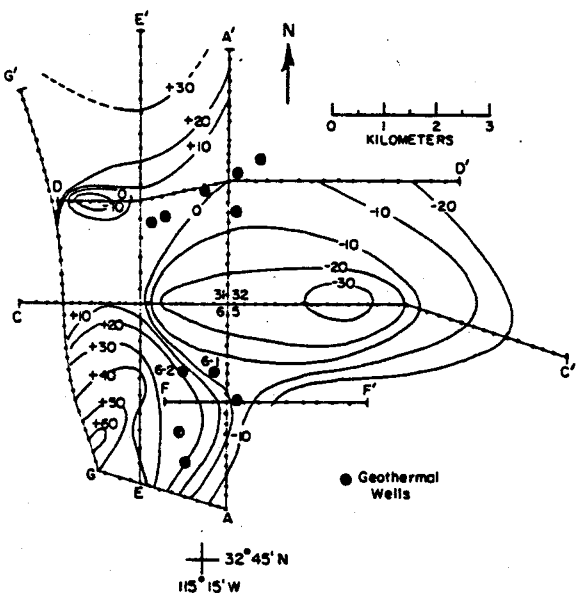

Fig. 7. The 1978 East Mesa SP contour map.

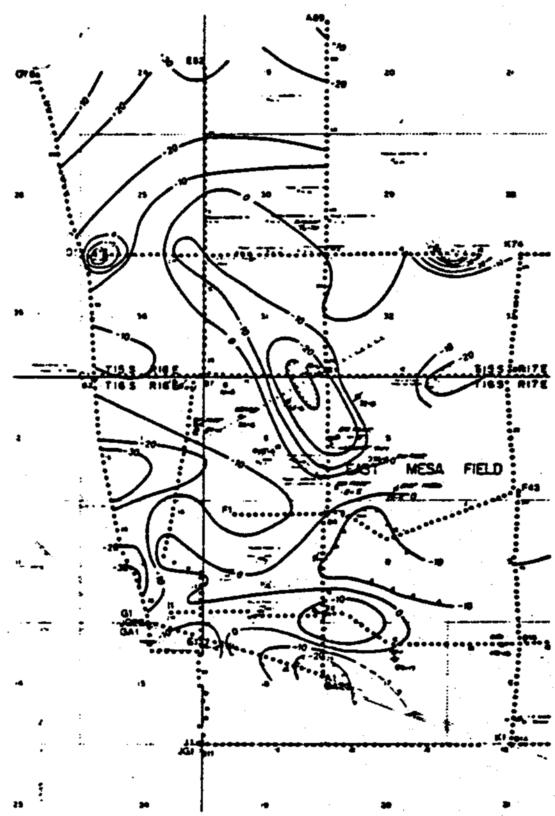

Fig. 8. The 1987 East Mesa SP contour map.

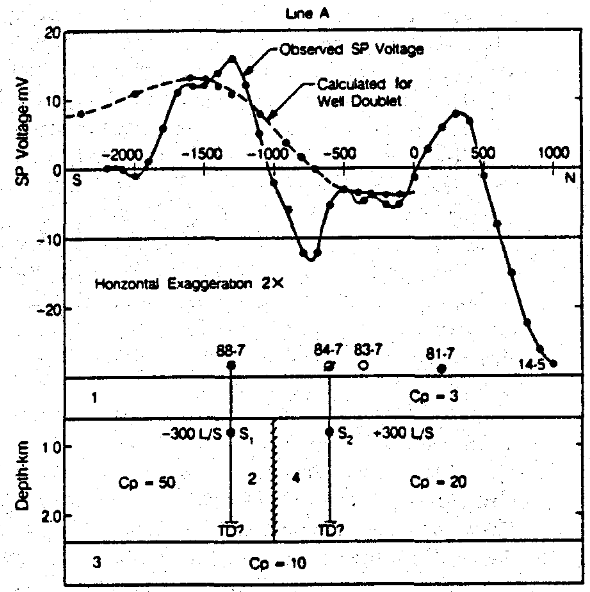

Fig. 9. SP model for the south end of East Mesa Line A (north-south).

observed voltages. Model parameters are listed in Table 2A and 2B. To get the asymmetry in the SP curve one can alter source strengths and source depths. Alternatively, as shown in Figure 9, we can also introduce a boundary between the two wells across which zone the electrokinetic cross-coupling changes. A fault boundary in this area has been indicated by offsets in the clay caprock thickness and from interference tests. The amplitude of the calculated dipolar anomaly seems to match the field data for the assumed pressure source strengths, but the steep gradients in the observed SP curve shape indicate shallower source currents. We cannot match the steep gradients unless we bring both pressure sources closer to the surface and, at the same time, reduce the thickness of the clay caprock layer, layer 1. As there is no justification for this model, we are led to conclude that the data cannot be explained by a well doublet alone. Moreover, as we learned later, actual source depths are deeper and source I is only about 30 L/s (T. Hinrichs and J. Tennison, personal communications, 1989). Thus, the true doublet anomaly should have a very small peak amplitude and a broader dipolar voltage form.

Comparing the general appearances of both data sets again, we also see that the broad dipole negative of the 1978 data has been replaced by a narrow northwest-trending 30 mV low. This interesting feature also correlates with one of the normal faults (down-to-the-west) inferred from drill hole data and the heat flow anomaly (T. Hinrichs, personal commun., 1986). A cross-section normal to anomaly strike and through several ORMAT wells is shown in Figure 10. The gradients of the observed SP anomaly indicate a source at a depth of around 600 m, the approximate depth of the contact between the low permeability clay cap and the underlying reservoir rocks (Riney et al., 1979; Goyal and Kassoy, 1981). However, calculations reveal that neither a thermal nor a pressure source at this depth can explain the anomaly. A thermal source at or below the contact, and which produces the appropriate subsurface temperatures yields only a small (≈1 mV) positive SP. A pressure

Table 2A. Unit Parameters for East Mesa SP Models: Pressure Sources

Unit	Geologic Designation	Electrical Resistivity* (ohm-m)	Permeability** (md)	Electrokinetic Coupling Coeff. (mV/atm)
1	Clay Cap	4.5	1	3
2	Reservoir Rocks	2.0	100	50
3	Deeper Sediments	5.0	5	10
4	Reservoir Rocks	2.0	100	20

Table 2B. Unit Parameters for East Mesa SP Models: Thermal Sources

Unit	Geologic Designation	Electrical Resistivity (ohm-m)	Thermal** Conductivity (W/m·°C)	Thermoelectric Coupling Coeff. (mV/°C)
1	Clay Cap	4.5	1.44	0.3
2	Reservoir Rocks	2.0	2.06	0.1

*Meidav and Furgerson, 1971
**Goyal and Kassoy, 1981; Riney et al., 1979

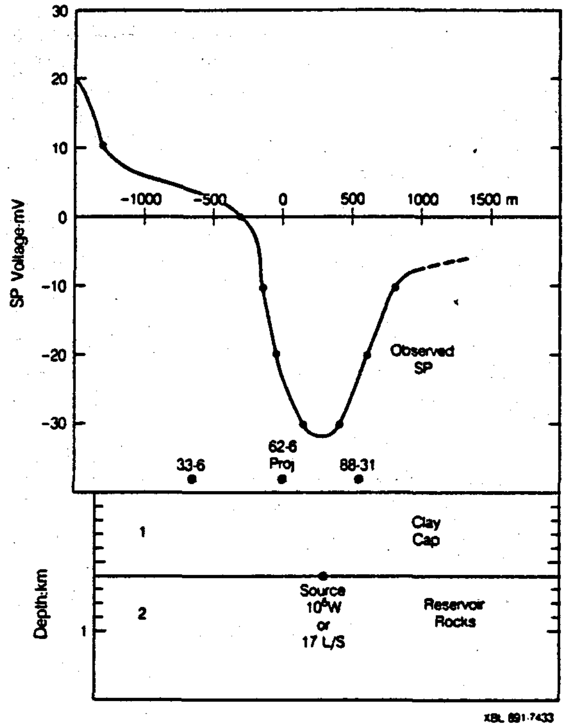

Fig. 10. SP model for a section though the -30 mV anomaly at East Mesa.

source with of magnitude 17 L/s, as calculated by Goyal and Kassoy (1981) to get the right energy balance for the hydrothermal system, gives the proper (negative) voltage, but generates only a weak SP effect of about 1 mV at the surface. Either our model and model parameters are in error, or as Corwin et al. (1981) concluded, a more significant SP mechanism exists. It has been suggested that fluid leakage into the clay cap may be creating an electrochemical potential.

CONCLUSIONS

SP resurveys over the East Mesa and Cerro Prieto geothermal fields show a number of differences from surveys made 10 years earlier. Part of the differences can be attributable to better data quality and higher data density of the recent surveys. However, it seems particularly evident that the shift in the Cerro Prieto anomaly can be explained by production-recharge differences. At the time of the initial survey in 1978 production for the CPI plant came from the shallow α reservoir with thermal fluid recharge ascending a "sandy gap" in the otherwise impermeable Shale O unit. At the time of the resurvey in 1988, production has been greatly expanded to the east with most fluids produced from the deeper β reservoir and thermal recharge guided, in part, by the Fault H. A numerical model for electrokinetic SP currents fits the 1988 production data and the current hydrogeologic model reasonably well. One of the important findings from the modeling exercise is the sensitivity of the SP to deep recharge.

By way of contrast, we had no success in fitting the East Mesa SP to production-related effects. East Mesa data reveal a complex assortment of small (20 to 30 mV) positives and negatives. A few of these correlate to man-made sources (e.g., redox reaction of a well casing and pumps) or to non-geothermal fluid flow (e.g., leakage from the East Highline Canal). Attempts to model individual SP anomalies using production-injection well doublets, natural convective flow and thermal sources gave anomalies with the wrong sign, that were too small in amplitude and/or too broad. Our models may be inaccurate, but there also could be another source of SP voltage. As evidenced by the apparent shallow nature of SP sources at East Mesa, it is possible that the anomalies are electrochemical and result from thermal fluid leakage guided by faults that penetrate the clay caprock. It also seems that for reasons of temperature, fluid chemistry (i.e., speciation) and rock chemistry, the East Mesa system is not as effective at causing streaming potentials as Cerro Prieto.

In spite of our difficulties in modeling the East Mesa data, we have shown that where an accurate hydrogeologic model, well production data, and subsurface rock parameters are available, carefully made repetitive SP surveys may be able to help understand and estimate fluid recharge in the system.

ACKNOWLEDGMENTS

We would like to acknowledge our colleagues in industry with whom we had numerous helpful discussions. These include Chan Swanberg, Zohn Ziagos and James Tennison of GEO, Tom Hinrichs of Magma Power, and Doug Miller of ORMAT, all of whom reviewed and discussed East Mesa data with us. We had extremely useful discussions with Marcelo Lippmann (LBL) on the Cerro Prieto system. Mike Wilt installed his modified version of program SPXCPL on the LBL computer and advised us on the use of this code. We would also like to thank our colleagues of the Coordinadora Ejecutiva de Cerro Prieto, Comisión Federal de Electricidad, for carrying out the SP survey and making the results available. These include Francisco Bermejo, Benjamín Terrazas and Jorge Rodríguez Bahena.

The East Mesa SP survey and the modeling study was supported by the Assistant Secretary for Conservation and Renewable Resources, Office of Renewable Technologies, Geothermal Technology Division of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

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