Title
ANALYSIS OF THE NUEVO LEON MAGNETIC ANOMALY AND ITS POSSIBLE RELATION TO THE CERRO PRIETO MAGMATIC-HYDROTHERMAL SYSTEM

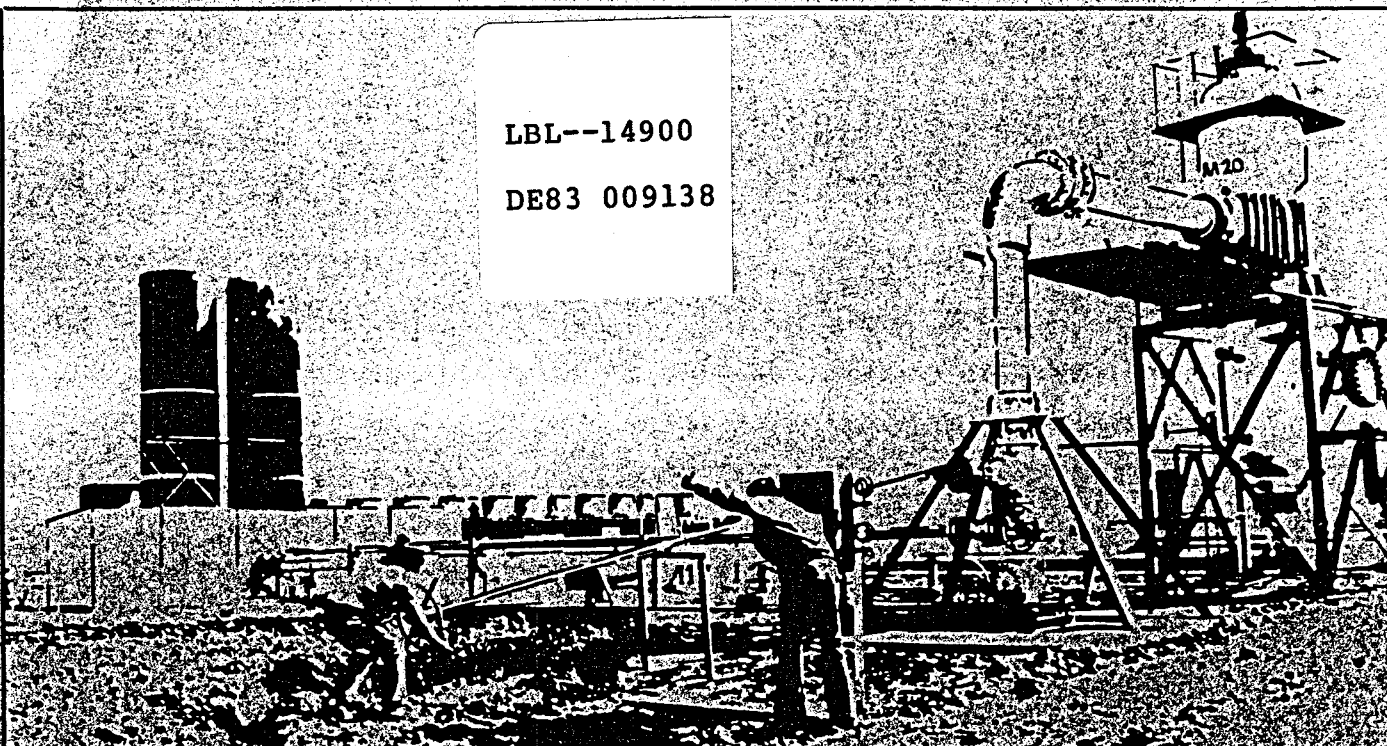
Authors
Goldstein, N.E.
Wilt, M.J.
Corrigan, D.J.

Publication Date
1982-10-01

LBL-14900
CERRO PRIETO-28
Conf—8208109--3

MEXICAN-AMERICAN COOPERATIVE PROGRAM AT THE CERRO PRIETO GEOTHERMAL FIELD

LBL--14900
DE83 009138



Presented at the Fourth Symposium on the Cerro Prieto Geothermal Field, Guadalajara, Mexico, August 10-12, 1982

ANALYSIS OF THE NUEVO LEÓN MAGNETIC ANOMALY AND ITS POSSIBLE RELATION TO THE CERRO PRIETO MAGMATIC-HYDROTHERMAL SYSTEM

N. E. Goldstein, M. J. Wilt, and D. J. Corrigan

October 1982

A Joint Project of

COMISION FEDERAL DE ELECTRICIDAD
Mèxico

DEPARTMENT OF ENERGY
Division of Geothermal Energy
United States of America

Coordinated by

Coordinadora Ejecutiva
de Cerro Prieto
Apdo. Postal No. 3-636
Mexicali, Bja. Cfa., México
and P. O. Box 248
Calexico, Ca. 92231

Lawrence Berkeley Laboratory
Earth Sciences Division
University of California
Berkeley, California 94720

Operating for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

Presented at the 4th Symposium on the Cerro Prieto Geothermal Field, Guadalajara, Mexico, August 10-12, 1982.

LBL-14900
CP-28

ANALYSIS OF THE NUEVO LEÓN MAGNETIC ANOMALY AND ITS POSSIBLE RELATION TO THE CERRO PRIETO MAGMATIC-HYDROTHERMAL SYSTEM

by

N. E. Goldstein, M. J. Wilt, and D. J. Corrigan

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

October 1982

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Hydrothermal and Hydropower Technologies, of the U.S. Department of Energy under Contract No. DE-AC03-76SF 00098.

Analysis of the Nuevo Leon Magnetic Anomaly and its Possible Relation to the Cerro Prieto Magmatic-Hydrothermal System

N. E. Goldstein, M. J. Wilt, and D. J. Corrigan
Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720, USA

ABSTRACT

The broad dipolar magnetic anomaly whose positive peak is centered near Ejido Nuevo Leon, some 5 km east of the Cerro Prieto I Power Plant, has long been suspected to have a genetic relationship to the thermal source of the Cerro Prieto geothermal system. This suspicion was reinforced after several deep geothermal wells, drilled to depths of 3 to 3.5 km over the anomaly, intersected an apparent dike-sill complex consisting mainly of diabase but with minor rhyodacite. A detailed fit of the observed magnetic field to a computer model indicates that the source may be approximated by a tabular block 4 by 6 km in area, 3.7 km in depth, 2.3 km thick, and dipping slightly to the north.

Mafic dike chips from one well, NL-1, were analyzed by means of electron microprobe analyses which showed them to contain a titanomagnetite that is paramagnetic at <u>in-situ</u> temperature conditions. As the dike mineralogy does not account for the magnetic anomaly, the magnetic source is believed to be a deeper, magnetite-rich assemblage of peridotite-gabbro plutons. The suite of igneous rocks was probably passively emplaced at a shallow depth in response to crustal extension and thinning brought on by strike-slip faulting. The bottom of the magnetic source body, at an estimated depth of 6 km, is presumed to be at or near that of the Curie isotherm (575°C) for magnetite, the principal ferromagnetic mineral in peridotitic-gabbroic rocks.

The geological model derived from the magnetic study is generally supported by other geophysical data. In particular, earthquake data suggest dike injection is occurring at depths of 6 to 11 km in an area beneath the magnetic source. Thus, it is possible that heat for the geothermal field is being maintained by continuing crustal extension and magmatic activity.

INTRODUCTION

The nearly symmetrical, dipolar magnetic anomaly centered 2 km south of Ejido Nuevo Leon and 5 km east of the power plant I has attracted interest for many years because of its proximity to the geothermal field (Fonseca and Razo, 1979; Lyons and van de Kamp, 1980). Our curiosity about this anomaly was intensified after the first of the deep step-out wells (NL-1) drilled by the Comisión Federal de Electricidad (CFE) over the anomaly to evaluate the extent of the reservoir returned igneous rock cuttings from depths of 3 km. These chips were later identified to be material from basic dikes (diabase) and a more silicic dike (rhyodacitic) (Elders et al., 1981). This discovery was not unexpected in view of the magnetic anomaly, and it rekindled discussions of the geologic model proposed by Lomnitz et al. (1970) and Elders et al. (1972). The central idea of this model is that the Cerro Prieto area, among other known geothermal sites in the Salton Trough, is a spreading center, where the crust is being pulled open by right-lateral strike-slip movement. Under such tectonic stresses an extensional sedimentary basin or pull-apart basin (McKenzie, 1978; Vonder Haar and Howard, 1979) would begin to form as the lithosphere thins and begins to subside. Where thinning of the crust and basin development is rapid, there will be a passive upwelling of denser upper mantle rock, creating a new oceanic-type lithosphere at depth (McKenzie, 1978). Elders (1982, personal communication) noted that the Nuevo Leon magnetic anomaly (abbreviated NLMA in this report) was probably caused by the same assemblage of mafic rocks found at oceanic spreading centers, except for pillow basalts, and that it was highly likely the anomaly is related to the magnetic heat source responsible for the Cerro Prieto Geothermal Field. To learn more about this proposed heat source we studied the magnetic field data and magnetic properties of the

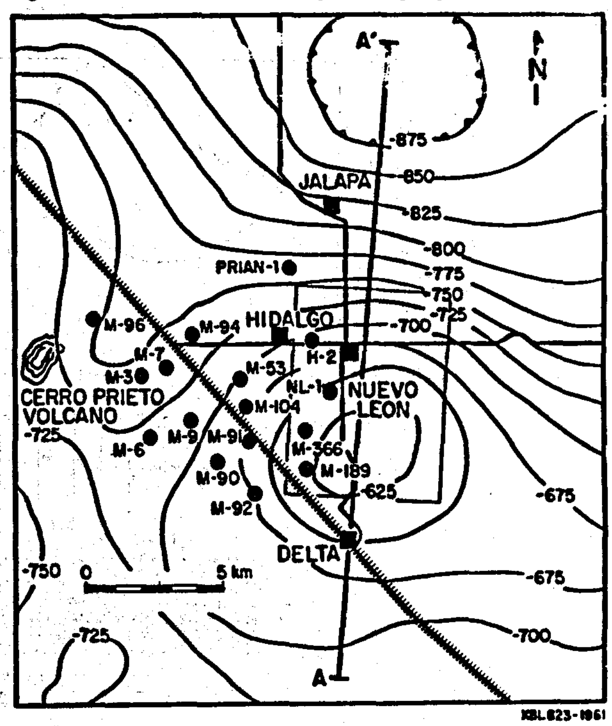


Figure 1. The Nuevo Leon magnetic anomaly (NLMA) and its relation to drill holes. The shaded rectangle is the approximate surface projection of the magnetic mafic rocks. Dark circles are wells. Dark squares are villages. Power plant I lies near the railroad between wells M-9 and M-53.

diabase rock chips. Other geophysical data collected by various workers were also used to test the magnetic model.

THE NUEVO LEON MAGNETIC ANOMALY

The Nuevo Leon magnetic anomaly (Figure 1) is a nearly symmetrical dipolar magnetic anomaly with a peak-to-peak amplitude of 300 γ. It was measured at ground level by CFE with a total field (proton precession) magnetometer (Fonseca and Razo, 1979). We interpreted the anomaly by fitting the observed data to fields calculated using a vertical prism code in combination with a 2-D Talwani-type code. Because the positive and negative maxima of the anomaly are nearly equal, a prism model cannot alone fit the observed data for the present field inclination. We surmised that a portion of the anomaly, in particular the magnetic low, must be due to a drop in the depth to the magnetic basement. Consequently, the 2-D Talwani code was used to model the basement configuration.

A comparison between observed and calculated fields, shown in plan view in Figure 2 and along profile line A-A′ in Figure 3, reveals that we were able to match the observed anomaly very well using a prismatic magnetic source with an apparent magnetic susceptibility (k_A) of 5,300 x 10^{-6} cgs within a less magnetic basement (k_A = 2,100 x 10^{-6} cgs). Both features lie beneath a thick cover of non-magnetic sediments. The main magnetic source comes within 3.4 km of the surface, and its upper surface appears to dip slightly to the north. The magnetic

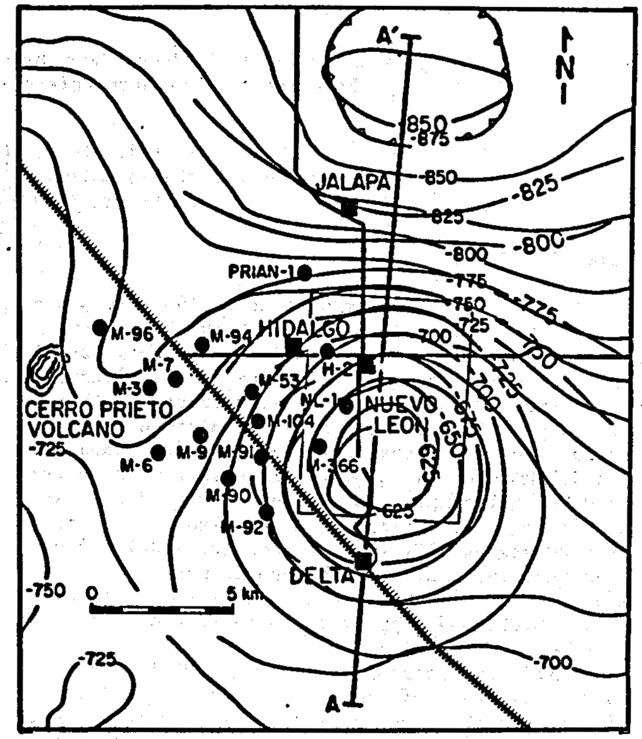


Figure 2. The relationship between the observed magnetic anomaly in Figure 1 and the modeled results.

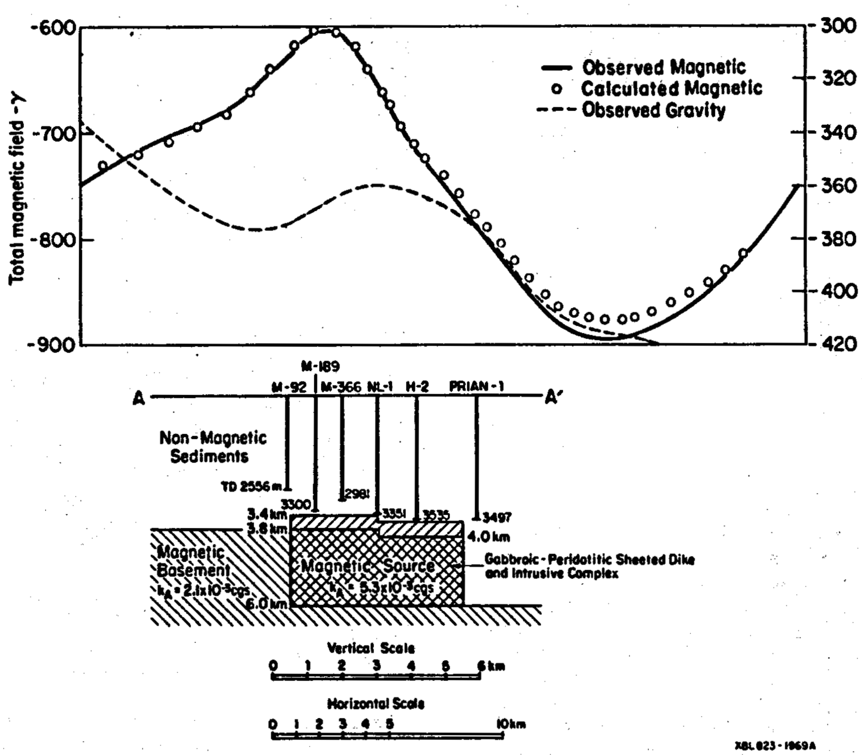


Figure 3. The relation of the NLMA to the subsurface model shown in profile along line A-A′. The wells are all projected to this section.

Table 1
Results of Microprobe Analysis
Mafic Dike Rock, Well NL-1, 3330 m Depth

	Maximum Mole Percent Spinel Phase		Maximum Mole Percent Rhombohedral Phase		Curie Temp(°C) (T_c)	Temperature of Crystallization (°C)	$-\log f_{O_2}$
Chip Number	Fe_3O_4	Fe_2TiO_4	Fe_2O_3	$FeTiO_3$			
1	39	61	4.5	95.5	180	890	13.4
2	31	69	4.0	96	115	950	12.4
3	31	69	5.6	94.4	110	1007	11.2
4	33	67	6.1	93.9	125	1003	11.2
5	40	60	6.2	93.8	185	936	12.2

basement, possibly granodiorite similar to the rock of the Cucapá Range, appears to be considerably shallower (3.8 km) south of the main source than to the north, where it drops away to considerable depth, a feature qualitatively consistent with the gravity data for that part of the Mexicali Valley. However, due to the large indicated depth of the magnetic rock and the poorness of fit to the anomaly we are less confident in our modeled results north of the main source.

The magnetic prism has a bottom at a depth of 6.0 km, where its magnetization is assumed to decrease to that of the host rock. However, as it is difficult to resolve the apparent susceptibilities at depths of 6.0 km from the surface, it is conceivable that the actual magnetization of rocks at this depth could be lower. This subject is discussed in terms of Curie temperature in the following section.

ANALYSIS OF MAFIC DIKE CHIPS

Abundant mafic dike chips were recovered from well NL-1 between depths of 2930 m to its total depth of 3351 m (Elders et al., 1981), from near the bottom of well H-2, depth 3540 m, from various depths below 2530 m in well M-189 and at 2850 m in well M-366. Figure 3 shows the upper surface of the magnetic source to be 400 to 500 m below the shallowest dikes intersected. Either our interpretation has overestimated the source depth or the mafic dikes do not contribute to the anomaly. Checking our computations, we could not obtain as good a fit to the anomaly using a shallower source, and thus our initial conclusion was that the dikes are not volumetrically or magnetically significant. However, this explanation seemed contrary to the findings of Weist (1980) who reported a substantial amount of mafic rock chips in NL-1 and described the chips at a depth of 3330 m as follows:

"These samples contain abundant fine-to-coarse-grained rocks of dark green-gray colour and white to green feldspar laths (ophitic texture); the interstices are filled by a green to dark-green mineral (epidote?) the grains are magnetic and some fragments consist entirely of black fine-grained magnetite."

Weist (1980) also remarked that the rock closely resembles diabase dike material recovered from a well at the Heber Geothermal Field (Browne, 1977).

However, because Weist's study was concerned mainly with the non-opaque minerals, we obtained and studied a set of five mafic rock chips that had been mounted on a slide at U.C. Riverside. These particular samples, the same as described above by Weist (1980), were selected for study because they contain an assortment of opaque minerals and had suffered far less hydrothermal alteration than many of the other mounted chip samples.

The rock chips studied at LBL contain an estimated 4 to 7 percent opaque minerals consisting of minor needle-like crystals of ilmenite, larger euhedral to anhedral crystals of titanomagnetite and a few small blebs of a sulfide, probably pyrite or chalcopyrite. No magnetite was seen. Even though these chips are the least altered, most of the titanomagnetite grains show some alteration with the followng characteristics:

1. Exsolution of ilmenite from titanomagnetite, usually on grain borders but sometimes in grain interiors.

2. A pitted to black mineralization usually toward grain centers that might be sphene ($CaTiSiO_5$), rutile (TiO_2) or anatase (TiO_2).

Titanomagnetite and ilmenite grains on each chip were identified and analyzed by means of an electron microprobe. Table 1 lists the average values computed for two grains per chip.

The results show that the principal magnetic phase is a titanomagnetite with a somewhat high percentage of the ulvöspinel (Fe_2TiO_4) end-member of the x $Fe_2TiO_4 \cdot (1-x)$ Fe_3O_4 solid-solution series (Nagata, 1961; Irving, 1964). This composition results in a mineral with a low Curie temperature, and, as Figure 4 reveals, these rocks would be essentially non-magnetic under in situ thermal conditions as determined by temperature logging. This result provides an answer as to why the mafic dikes do not seem to contribute to the magnetic anomaly. The results are also backed by the observations of Johnson and Hall (1977) who reported that high titanium titanomagnetite ($x = 0.65 \pm 0.02$) is the "ubiquitous dominant magnetic mineral of submarine oceanic tholeiite basalts."

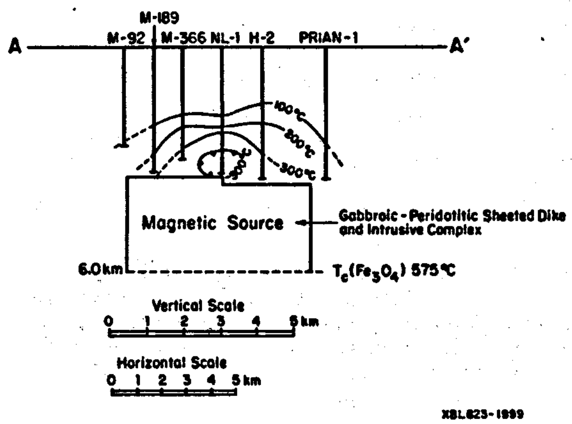


Figure 4. The relationship of the magnetic source and temperatures derived from logs made in deep wells over and near the body.

The dikes appear to have chilled quickly from the melt, crystallization of the oxide mineral having taken place at 900 to 1000°C based on the oxygen fugacity-temperature (f_{O_2} - T) stability relations for melts from which the spinel and the rhombohedral phases can coexist. After emplacement the dikes were hydrothermally altered by the circulating brine.

The observed magnetic anomaly is probably caused by a more magnetite-rich phase of titanomagnetite with a Curie temperature $T_C > 350°C$, typical of gabbroic rocks dredged from oceanic spreading centers. In a study of magnetic properties of submarine intrusive rocks taken from ocean-bottom drill holes, Prevot and Dunlop (1980) report that the principal magnetic mineral in doleritic gabbros, cumulate gabbros, serpentinized cumulate gabbros and peridotites and serpentinized lherzolites is nearly pure magnetite, with T_C = 515 to 575°C. They also found that the natural remanent magnetization (NRM) of the gabbros, the serpentinized rocks and the peridotites to be in the range of 1,000 to $10,000 \times 10^{-6}$ cgs, which is consistent with the value of apparent susceptibility interpreted for the NLMA. If the dominant magnetic constituent of the NLMA is magnetite at depth, the bottom of the source at 6 km is an estimate for the depth to the magnetite Curie point (Figure 4). As the solidus for rocks of gabbroic composition is about 900°C (Peck et al., 1966) we might expect to find a melt zone at a depth of about 10 to 12 km on the basis of a linear gradient extrapolation. Admittedly, this is a crude method for estimating the magma depth but the estimate is supported by seismic data discussed in the next section.

RELATIONSHIP BETWEEN THE MAGNETIC ANOMALY AND OTHER GEOPHYSICAL DATA

Gravity

There is no distinct Bouguer gravity anomaly coinciding with the NLMA (Fonseca and Razo, 1979). There is, however, a saddle in a complex pattern of gravity highs and lows over the NLMA area. The relationships between these gravity anomalies and subsurface structure are only sketchily known from a few drill holes and limited numerical modeling. The Bouguer gravity along line A-A' is plotted in Figure 3 so that it may be compared to the magnetic field perturbation. The small high that occurs directly over the magnetic source arises from a broad gravity high centered 13 to 15 km east of the NLMA whose flank was crossed by A-A'. The absence of a distinct gravity high over the area of postulated mafic plutons does not invalidate the geologic model presented in the previous section. This absence might be explained as the result of magmatic-hydrothermal-tectonic processes which combined to produce a degree of metamorphism and structural complexity that obscures the effect of density differences between the gabbroic plutons and granitic-sedimentary host rocks. However, density differences are likely to be small in any case. It has been established from many measurements on serpentinized gabbros and peridotites from ocean floors and orogenic zones that the more magnetic samples have relatively low densities that cluster in the range of 2.40 to 2.70 g/cm^3 (Coleman, 1971), similar to the range we can expect for the deeper sediments and the granodioritic basement complex.

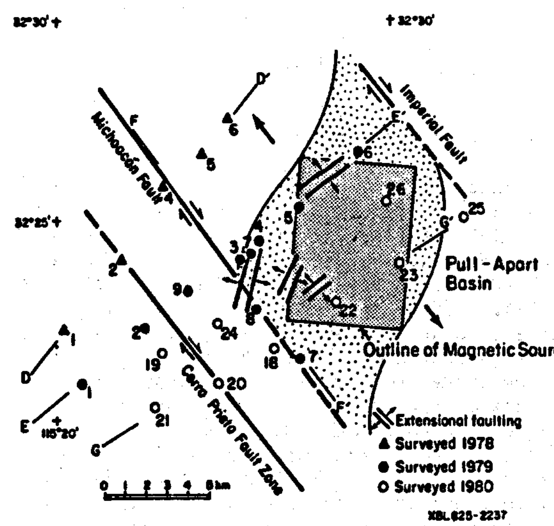


Figure 5. Relationship of the magnetic source location to extensional faulting determined by means of earthquakes (Reyes and Razo, 1979). The stations are MT stations occupied by LBL.

Natural Seismic Activity

The seismic activity over the NLMA indicates tensional stresses and normal faulting, with almost vertical displacements beneath the northern and western edges of the magnetic source body (Figure 5) (Reyes and Razo, 1979). In the vicinity of Ejido Nuevo Leon, the faulting occurs along a zone striking N 40°E; calculated focal depths range from 6 to 11 km. Reyes and Razo (1979) proposed that the tensional stresses are associated with local crustal spreading and dike injection. In connection with our magnetic-geologic model, the seismological evidence seems to support active dike injection from a magma chamber at a depth of 10 to 12 km.

Magnetotelluric Sounding

Several magnetotelluric (MT) stations had previously been placed over or near the magnetic source; the soundings made to sufficiently low frequency to provide information at depths corresponding to the mafic plutons. Station 6, line E-E′ (Figure 5) lies a short distance beyond the northern margin of the source. This was the only station where the subsurface appeared electrically one-dimensional. A one-dimensional resistivity inversion was performed and reported by Gamble et al. (1979) and is shown in Fig. 6. Here we see that between the surface and approximately 6 km there is variable resistivity whose relationship to temperature, lithology and hydrogeology was discussed by Gamble et al. (1979) and Lyons and van de Kamp (1980). At a depth of 6 ± 1.0 km the MT data show evidence for a change to a more resistive basement, but the nature of this feature which occurs at a similar basement depth to that inferred from the magnetic model (Figure 3) is not clear.

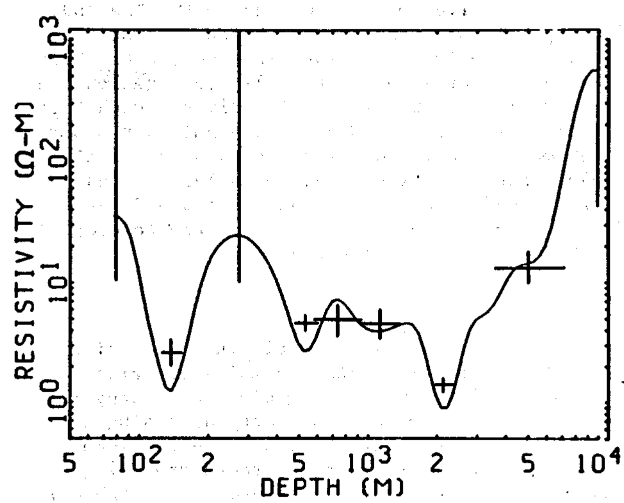


Figure 6. A one-dimensional inversion of MT resistivity data at Station 6, line E-E′ after Gamble et al. (1979).

MT line G-G′ passed over a corner of the magnetic source; stations 22 and 23 are within the indicated boundary of the mafic plutons. As seen in Figure 7, the pseudosection of the TE or electric field-parallel-to-strike mode shows a thick section of conductive material to a depth of 3 km over the magnetic source, and a vertical contact close to station 23. The 2-D interpretation of the subsurface region between stations 22 and 25 is shown in the inset diagram. As noted by Goubau et al. (1981) the thick section of 20 ohm-m rock at station 25 may represent the encroachment of colder, less sa-

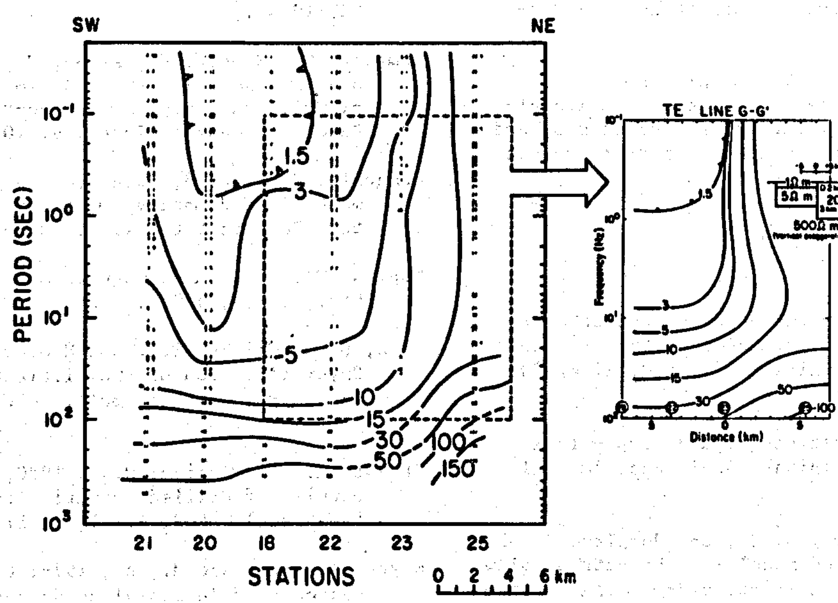


Figure 7. Comparison of observed and calculated E-parallel-to-strike MT pseudosections along line G-G′. The inset in the diagram on the right shows the 2-D subsurface model that was found to give a reasonable fit to the observed data within the dashed lines (after Goubau et al., 1981).

line Colorado River water from the east. The indicated depth to basement of 5 km beneath MT Station 25 seems generally consistent with other data. Over the magnetic source, at station 22, the shallow conductive region is the effect of sediments with hotter, more saline pore fluids. The shallower apparent basement at this locality, depth 3 km, might represent the resistive effect of a less porous mixture of hydrothermally metamorphosed sediments and the dike-sill complex, but there are no deep drill holes as yet in this area.

CONCLUSIONS

On the basis of our magnetic interpretation of the NLMA, analysis of chip samples of mafic dikes, and analysis of other geological-geophysical data, we have been able to support the geological model of the Cerro Prieto area as an extensional basin into which mantle-derived rocks are being passively emplaced. Inferences drawn from thermal data, such as well logs and depth to the magnetite Curie isotherm, suggest a melt zone (magma chamber?) at a depth of 10 to 12 km. Earthquake data indicate that the north-northwest border of the magnetized zone is the locus of present extension and possible dike injection at depths of 6 to 11 km.

These findings lead us to suggest that the heat for the Cerro Prieto Geothermal Field is being supplied by a magmatic source whose upper surface is at a depth of 10 to 12 km.

ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal and Hydropower Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

The authors would like to thank Professor Wilfred A. Elders of the University of California, Riverside for several interesting discussions, and Mark Rivers of LBL for his help in performing the electron microprobe analyses.

REFERENCES

Browne, P.R.L., 1977, Occurrence and hydrothermal alteration of diabase, Heber Geothermal Field, Imperial Valley, California: U.C. Riverside, UCR/IGPP-77/9, 65 p.

Coleman, R.G., 1971, Petrologic and geophysical nature of serpentinites: Geol. Soc. Am. Bull., v. 82, p. 897-918.

Elders, W. A., Williams, A. E., and Hoagland, J. R. 1981, An integrated model for the natural flow regime in the Cerro Prieto hydrothermal system based upon petrological and isotope geochemical criteria: in Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, Lawrence Berkeley Laboratory, LBL-11967.

Elders, W.A., Rex, R.W., Meidav, T., Robinson, P.T., Biehler, S., 1972, Crustal spreading in Southern California: Science, v. 178, p. 15-24.

Fonseca L., H.L. and Razo M., A., 1979, Estudios gravimétricos, magnetométricos y de sísmica de reflexión en el campo geotérmico de Cerro Prieto: in Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico: Comisión Federal de Electricidad, Mexicali, Mexico, p. 303-328.

Gamble, T.D., Goubau, W. M., Goldstein, N.E., Miracky, R., Stack, M., and Clarke, J., 1979, Magnetotelluric Studies at Cerro Prieto in Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico: Comisión Federal de Electricidad, Mexicali, Mexico, p. 405-413.

Goubau, W. M., Goldstein, N.E., and Clarke, J., 1981, Magnetotelluric studies at the Cerro Prieto Geothermal Field in Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico: Lawrence Berkeley Laboratory, LBL-11967.

Irving, E., 1964, Paleomagnetism and its application to geological and geophysical problems: John Wiley & Sons, Inc., New York, 399 p.

Johnson, H.P. and Hall, J.M., 1977, The magnetic mineralogy of oceanic submarine basalts and its relationship with linear magnetic anomalies (abstract): EOS, v. 58, n. 8, p. 746.

Lyons, D.J., and van de Kamp, P.C., 1980, Subsurface Geological and Geophysical study of the Cerro Prieto geothermal field, Baja California, Mexico: Lawrence Berkeley Laboratory, Berkeley, LBL-10540.

Lomnitz, C., Mooser, F., Allen, C., Brune, J.N., and Thatcher, W., 1970, Seismicity of the Gulf of California Region, Mexico-Preliminary Results: Geofis. Inst., v. 10, 37 p.

McKenzie, D.P., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

Nagata, T., 1961, Rock magnetism: Maruzen Company Ltd., Tokyo, 350 p.

Peck, D.L., Wright, T.L. and Moore, J.G., 1966, Crystallization of tholeiitic basalt at Alae Lave Lake, Hawaii: Bull. Volcanol., v. 29, p. 629-655.

Prevot, M., and Dunlop, D.J., 1980, Magnetic properties of drilled submarine intrusive rocks (abstract): EOS, v. 61, n. 17, p. 223.

Reyes, A., and Razo M., A., 1979, Estudios de microtectónica y de anomalías de potencial en el campo geotérmico de Cerro Prieto: in Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico; Comisión Federal de Electricidad, Mexicali, Mexico, p. 374-389.

Weist, B., 1980, Petrographic studies of Well Nuevo Leon -1, Cerro Prieto, Baja California, Mexico: Unpublished Geology Term Paper U.C. Riverside, 12 p. plus appendix.

Vonder Haar, S. and Howard, J.H., 1979, Intersecting faults and sandstone stratigraphy at the Cerro Prieto Geothermal Field in Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico: Comisión Federal de Electricidad, Mexicali, Mexico, p. 118-130.