TEMPERATURE FIELD DISTRIBUTION FROM COOLING OF A MAGMA CHAMBER

Surendra Pal VERMA 1,2 and Jorge ANDAVERDE 1,3

1 Dept. de Geotermia, IIE, A. P. 1-475, Cuernavaca, Mor. 62001, Mexico.
2 (present address) Lab. Energia Solar, IIM, UNAM, A. P. 34, Temixco, Mor. 62580, Mexico.
3 (present address) Fac. Ciencias de la Tierra, UANL, A. P. 104, Linares, N.L. 67700, Mexico.

Key words: Magma chamber, Los Humeros, Los Azufres, geothermal exploration, thermal modeling, Mexico

Abstract

An integrated geological-geochemical-geophysical approach is presented for the thermal modeling of a magma chamber in order to predict the temperature field distribution in two geothermal fields (Los Humeros, Puebla and Los Azufres, Michoacán) located in the Mexican Volcanic Belt (MVB). For both geothermal systems, it is shown that the temperature field simulated from cooling of a shallow (~3 km depth) magma chamber for the entire volcanic history of the caldera and taking into account the thermal effects of geological processes, such as fractional crystallization (FC), magma recharge (MR) and high convection (HC) in the geothermal reservoir, is in general agreement with the temperatures actually measured in wells.

1. INTRODUCTION

For geothermal exploration and exploitation it is necessary to develop new methods that not only complement the existing ones but also prove more valuable, efficient and economic. Relating a magmatic heat source to geothermal reservoir and drill well data is perhaps one such new development (Verma, 1984a, 1985a). Previous studies of geothermal and magmatic systems include Norton and Taylor, Jr. (1979), Proff and González-Morán (1982), Elders et al. (1984) and Giberti et al. (1984).

Norton and Taylor, Jr. (1979) presented an excellent quantitative simulation of the hydrothermal systems of crystallizing magmas in Skaergaard intrusion using transport theory and oxygen isotope data in rocks and xenoliths. Proff and González-Morán (1982) carried out a preliminary conductive thermal modeling in Los Humeros caldera, Puebla, Mexico, assuming a small spherical magmatic heat source (~100 km³ volume) emplaced at a shallow depth (the top of the source at a depth of ~3 km). Elders et al. (1984) used the hydrothermal mineral zones, stable isotopes ratios, temperature gradients, well logs and other data to propose a detailed three-dimensional model of natural flow regime of the Cerro Prieto geothermal field in Mexico and relate it to a magmatic heat source of basaltic intrusions. 4 km wide at the top, emplaced at a depth of 5 - 6 km, at about 0.04 to 0.05 Ma. Giberti et al. (1984) reproduced the thermal history of the Phlegrean field (Italy) for the last 0.05 Ma through a numerical simulation of cooling of a magma chamber.

We have been developing a novel integrated geological, geochemical and geophysical approach (Verma, 1984a, 1985a, b, 1990, Verma et al., 1990; Castillo-Román et al., 1991; Verma and Andaeverde, in prep.) for predicting temperature field distributions from cooling of a magma chamber. Here we present our results on two geothermal fields: Los Humeros, Puebla, and Los Azufres, Michoacán (Figure 1), located in the Mexican Volcanic Belt (MVB). Both systems are housed in volcanic calderas that are considered favorable geological structures for geothermal developments (Verma, 1990, 1991).

2. TECHNIQUES

First, we obtain a summary of the main results of geological, geochemical and geophysical research in each area (Verma, 1985a, 1990). Then, we prepare a geological and a computational model of the field. The parameters of the magma chamber (volume, dimensions, depth, temperature, time of emplacement, composition, etc.) are then incorporated into the computational model (Castillo-Román et al., 1991; Verma and Andaeverde, in prep.). Finally, we numerically solve (finite difference explicit method) the energy-conservation equation for conductive heat flow in two-dimensions (Castillo-Román and Verma, 1989; Verma et al., 1990):

$$\frac{\partial T}{\partial t}(x,y) = -\frac{k}{\rho c} \frac{\partial^2 T(x,y)}{\partial x^2}$$

(1)

Figure 1. Location and present tectonic setting of three geothermal fields (H = Los Humeros, Puebla; A = Los Azufres, Michoacán; P = La Primavera, Jalisco), located in the Mexican Volcanic Belt (MVB). The map is modified after Verma et al. (1992) and Verma (1994). MAT = Middle America Trench; EPR = East Pacific Rise; OFZ = Orozco Fracture Zone; RFZ = Rivera Fracture Zone; R = Rivera plate; C = Cocos plate; P = Pacific plate; MX = Mexico City.

1119
where \( T \) = temperature, \( t \) = time, \( \kappa \) = thermal conductivity, \( \rho \) = density of the medium, \( c \) = heat capacity of the medium, and \( x \), \( z \) = space coordinates. The boundary conditions used are: a constant temperature \( (T = 0^\circ C) \) at the surface, and equality of temperature \( (T_s = T) \) and heat flux \( \kappa (\partial T_s/\partial z) = \gamma (\partial T/\partial z) \) at the boundary layers, of very small finite thickness, between discrete bodies of the grid subdividing the entire medium.

The physical properties used are either the actual determinations on the rocks from the area (Contrasa L. et al., 1988, 1990) or the literature values on similar rocks when no measurements are available on the reservoir rocks (e.g., Berman et al., 1942; Horai, 1972; Kappelmeyer and Haenel, 1974; Drury et al., 1984; Giberti et al., 1984).

In addition to the simple conductive cooling (SCC) of the magma chamber, we have incorporated other geological processes, such as fractional crystallization (FC) and magma recharge (MR) in the chamber after its emplacement, as well as convective effects in the geothermal reservoir by increasing the thermal conductivity of the reservoir rocks by a factor of 10 (medium convective system, MC) or 20 (highly convective system, HC) (Andaverde et al., 1991, 1993; Andaverde and Verina, 1992, 1993; Castillo-Román et al., 1991; Verma and Andaverde, in prep.).

3. RESULTS OF PREVIOUS GEOSCIENTIFIC STUDIES


3.1. Tectonic setting

Both geothermal fields are located in the Mexican Volcanic Belt (MVB; Figure 1), a Miocene to Recent volcano province in central Mexico. They are housed in calderas whose dimensions are about 21 x 15 km diameter for Los Humeros (Verma and López-M., 1982; Ferriz and Mahood, 1984; Ferriz, 1985) and about 28 x 26 km for Los Azufres (Ferrari et al., 1991).

3.2. Geology

Los Humeros

The basement rocks in Los Humeros consist of a Paleozoic metamorphic and intrusive complex, a folded Mesozoic sedimentary sequence, Late Tertiary granitic-granodioritic intrusions and Pliocene andesites. The first caldera collapse (Los Humeros caldera of about 21 x 15 km diameter), dated at -0.46 Ma, was caused by the eruption of a voluminous ignimbrite (~115 km³) of a dominantly rhyolitic composition (Ferriz and Mahood, 1984; Ferriz, 1985). Other smaller collapses are documented at -0.1 Ma for Los Potreros caldera and at -0.06 Ma for El Xalapazco (Figure 2). The volcanic activity ranging to mafic compositions has continued up to the Recent (~0.02 Ma).

Los Azufres

The pre-volcanic basement consists of slightly folded and metamorphosed shales, sandstones and conglomerates of Eocene to Oligocene age. The older volcanics (18.2 - 5.9 Ma) are dominantly andesites, with minor basalts, dacites and pyroclastic rocks. Later during 1.6 - 0.84 Ma, several rhyolitic domes were emplaced amounting to a total volume of ~12.2 km³. The most important voluminous eruption (~19.3 km³) in the Los Azufres area was of dacites, during about 0.36 - 0.33 Ma, perhaps causing the caldera collapse. The silicic to mafic volcanic activity has followed up to the Recent. Several wells have been drilled in this field. Those used in the thermal modeling are shown in Figure 3.

3.3. Geochemistry

Los Humeros

The erupted rocks in this caldera range from basalt to rhyolite and belong to the calc-alkaline and high-K calc-alkaline series. The geochemical modeling of major and trace elements and radiogenic isotope suggests that the fractional crystallization (FC) has been a dominant petrogenetic process for the evolution of the magmas. A minimum volume of a shallow level magma chamber has been estimated to be ~1500 km³ (Verma, 1985a). The water and gas geochemistry also suggests a shallow heat source near the El Xalapazco (Figure 2).
Los Azufres

The volcanic rocks in the Los Azufres area also range from basaltic to rhyolitic compositions. Preliminary mass balance estimates show that the magma chamber has a minimum volume of $\sim 400 \text{ km}^3$ (Verma, 1985a). The geochemical and isotopic data also suggest that the fractional crystallization (FC) was a dominant petrogenetic process (Cathelineau et al., 1987; Verma and Dobson, 1987).

3.4. Geophysics

Los Humeros

Different geophysical methods (gravimetric, aeromagnetic, magnetic, magnetotelluric, electrical, telluric, autopotential, thermometric and thermal modeling) have been applied in the Los Humeros caldera. These have contributed to a better knowledge of sub-surface structures, such as the existence of two volcanic conduits, a shallow heat source and the presence of highly conductive layers between 5 and 10 km. The actual well data have confirmed some of these interpretations.

Los Azufres

Several geophysical studies involving gravimetry, magnetics, geoelectricity and well-logging have also been carried out in this area, which have provided us with a better understanding of the structural geology and its relationship with the geothermal reservoir.

4. RESULTS OF SIMULATIONS

4.1. Los Humeros

Figure 4 shows schematically a computational model for the Los Humeros system. The magma chamber is assumed to be at a depth of 5 km under the Los Humeros caldera. The thermal effects of the emplacement and cooling of this magma chamber (initially at $\sim 1200^\circ$C, the temperature assumed for the mantle-derived basaltic magma) are computed for a period of $-0.6$ Ma. This period includes a time interval of at least $-0.1$ Ma required for the differentiation of the basaltic magma to form the rhyolitic magma that was erupted at about $0.47 \pm 0.04$ Ma from the Los Humeros caldera. Castillo-Romin et al. (1991) have evaluated the thermal effects of variations in depth of the underlying magma chamber (from 4 to 6 km), thermal properties of rocks (from the actual thermal conductivities of reservoir rocks up to 20 times these values) and magma recharge in the chamber. We present here one plausible thermal model for this caldera. A recharge of fresh magma batch ($-62 \text{ km}^3$ volume) in the chamber, at about 0.24 Ma, has been postulated on the basis of the eruptive history of the caldera (Castillo-Romin et al., 1991). The effects of crystallization are taken into account by increasing the initial magma temperature by $-300^\circ$C, following the method of Giberti et al. (1984).

The temperature field distributions computed from this model are presented in Figures 5a and 5b. The upper diagram (Figure 5a) gives the results for a purely conductive model (SCC + FC + MR), whereas the lower one (Figure 5b) presents the temperature simulations for a highly convective system (SCC + FC + MR + HC) based on the increase of thermal conductivity ($\kappa$) of the rocks.

Figure 4. A computational model for Los Humeros used in the numerical simulations for predicting temperature field distribution in the system along the model line AA’. In addition to a simple conductive cooling (SCC) of the large magma chamber during about 0.6 Ma, the thermal effects of fractional crystallization (FC), a highly convective (HC) geothermal reservoir (values of effective conductivities $= 20 \kappa$ for the 700 - 2200 m depth interval) and recharge (MR) of a fresh batch of basaltic magma are considered.
for the last 0.04 Ma, to the values of $20K$ in the convective interval of 700 - 2200 m estimated from the measured temperature gradients in the wells (Castillo-Román et al., 1991). A better agreement of the measured temperatures of 200°C (small dots in the wells) with the 200°C predicted isotherm of Figure 5b (than of Figure 5a) confirms that the geothermal system is under highly convective (HC) conditions, with an effective conductivity of about $20K$ in the Los Humeros geothermal reservoir.

The thermal effects of fractional crystallization (FC) are estimated (Andaverde et al., 1991, 1993) and incorporated into this model. This increased the predicted geothermal gradient in the Los Azufres to ~$80^\circ$/km (curve b, SCC + FC). The next curve c (SCC + FC + MR) in Figure 5 is obtained by additionally incorporating magma recharge (MC) in the chamber (~36 km$^2$ of basaltic magma during ~0.36 Ma), which increased the predicted gradient to ~$95^\circ$/km. Finally, very high convective (HC) regime (20 times the rock conductivities $\kappa$ in the convective layer between the 200 - 2500 m depth, an interval estimated from the data reported by Nieva et al. (1986) had to be assumed for a period of 0.1 Ma, in addition to the other geological processes, in order to obtain the final “best-fit” gradient curve (curve d, SCC + FC + MR + HC) in Figure 5. The computer program used for this final convective modeling was modified from Hernández Ramirez et al. (1993).

**Figure 5.** Predicted isotherms from cooling of a magma chamber (SCC) at a depth of ~5 km during a period of ~0.6 Ma. The thermal effects of fractional crystallization (FC) and magma recharge (MR) in the chamber are also considered in this modeling. a) Without convection (SCC + FC + MR), and b) With highly convective (SCC + FC + MR + HC) geothermal reservoir ($20K$ for the 700 - 2200 m depth interval).

### 4.2. Los Azufres

The geological, geochemical, geophysical and the well data are integrated along the model line BB' (Figure 3) in order to obtain a computational model of Figure 6 (Andaverde and Verma, 1992; Verma and Andaverde, in prep.). As in the case of the Los Humeros caldera, we assume the magma chamber at a depth of 5 km underlying the Los Azufres geothermal field (Figure 6). The time period for the simulations are assumed to be ~0.46 Ma, which includes a time interval of ~0.1 Ma required for the differentiation of the basaltic magmas to the dacitic and rhyolitic compositions, before the ~0.36 Ma voluminous eruption of dacites in the Los Azufres area.

The temperature gradients obtained under different simulation conditions (Figure 7) are compared with the actually measured temperatures in the central part of the model line BB' (Figure 3). A simple conductive cooling (SCC) of the magma chamber without any additional geological processes predicts a temperature gradient of only ~$60^\circ$/km (curve a in Figure 7), much lower than the measured gradient of ~$150^\circ$/km. The thermal effects of fractional crystallization (FC) are estimated (Andaverde et al., 1991, 1993) and incorporated into this model. This increased the predicted geothermal gradient in the Los Azufres to ~$80^\circ$/km (curve b, SCC + FC). The next curve c (SCC + FC + MR) in Figure 7 is obtained by additionally incorporating magma recharge (MC) in the chamber (~36 km$^2$ of basaltic magma during ~0.36 Ma), which increased the predicted gradient to ~$95^\circ$/km. Finally, very high convective (HC) regime (20 times the rock conductivities $\kappa$ in the convective layer between the 200 - 2500 m depth, an interval estimated from the data reported by Nieva et al. (1986) had to be assumed for a period of 0.1 Ma, in addition to the other geological processes, in order to obtain the final “best-fit” gradient curve (curve d, SCC + FC + MR + HC) in Figure 7. The computer program used for this final convective modeling was modified from Hernández Ramirez et al. (1993).

**Figure 6.** A computational model for Los Azufres used in the numerical simulations for predicting temperature field distribution in this system along the model line BB'. Measured isotherms for 100°C and 200°C are also shown for reference. In order to obtain the best agreement between the measured and the simulated temperatures, the thermal effects of fractional crystallization (FC), a highly convective (HC) geothermal reservoir (values of effective conductivities $\approx 20K$ for the 200 - 2500 m depth interval) and recharge (MR) of fresh batches of basaltic magma have to be considered (see Figure 7), along with the cooling of the chamber for ~0.46 Ma.
Thus, in order to obtain the best agreement between the measured and the modeled temperatures in the Los Azufres geothermal field, all processes (FC, MR and HC), have to be incorporated in the final simulation of cooling of the magma chamber (SCC), as in the case of the Los Humeros caldera.

5. DISCUSSION

We have shown that the temperature field distribution from cooling of a magma chamber (SCC) and incorporating the thermal effects of fractional crystallization (FC), magma recharge (MR) and high convection (HC) in the geothermal reservoir, is acceptable for both the Los Humeros and Los Azufres geothermal systems. Future developments must also include other natural processes, such as thermal contribution from radioactive elements in the entire system (Rodríguez-González and Verma, 1992), heat loss by assimilation of country rock by the magma, convection by mass transport in the reservoir, convection in the magma chamber, a more powerful and efficient implicit method of numerical solution, and its application in other younger calderas, such as La Primavera in Mexico (Verma and Rodríguez-González, in prep.).

6. CONCLUSIONS

Models of a shallow magma chamber at a depth of about 5 km, having a geochemically estimated volume and geologically consistent horizontal and vertical dimensions of the chamber, are adequate to predict the average temperature gradients in two Mexican geothermal fields. Several geological processes, such as fractional crystallization and recharge in the chamber and high convection in the reservoir, must be considered in order to obtain a better agreement between the measured and the simulated temperatures. Finally, further work should include detailed considerations of time-dependent hydrothermal convection processes in order to predict more precisely the temperature field distributions in geothermal fields.

7. ACKNOWLEDGEMENTS

We are grateful to J. Castillo-Román and H. Sanvicente for suggestions concerning the use of the original computer program. Paul Kasameyer is thanked for reviewing an earlier version of this paper.

8. REFERENCES


Verma, S.P. and Rodríguez-González, U. (in prep.). Temperature field simulation from cooling of a magma chamber in La Primavera caldera, Jalisco, Mexico.