TEMPERATURE FIELD DISTRIBUTION FROM COOLING OF A MAGMA CHAMBER

Surendra Pal **VERMA** [1,2] and Jorge **ANDAVERDE** [1,3]

[1] Depto. 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 (~ 5 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), Prol 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. Prol 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 km^3 volume) emplaced at a shallow depth (the top of the source at a depth of – 5 km). Elders *et al.* (1984) used the hydrothermal mineral zones, stable isotope 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 Phlegraean 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-Romin *et al.*, 1991; Verma and Andaverde, 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).

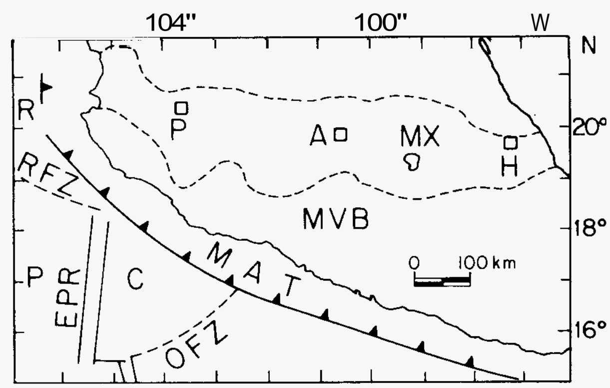

Figure 1. Location and present tectonic setting of three geothermal fields (H = Los Humeros, Puebla; A = Los Azufres, Michoacán; P = La Primavera, Jalisco), located in the Mexican Volcanic Belt (MVB). The map is modified after Verma *et al.* (1992) and Verma (1994). MAT = Middle America Trench; EPR =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

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 Andaverde, in prep.). Finally, we numerically solve (finite difference explicit method) the energy-conservation equation for conductive heat flow in two-dimensions (Castillo-Romin and Verma, 1989; Verma *et al.*, 1990):

$$\frac{\partial T}{\partial t}(x,z,t) = \frac{\kappa}{\rho c}\nabla^2 T(x,z,t) \qquad (1)$$

where T = temperature, t = time, κ = thermal conductivity, ρ = 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°C) at the surface, and equality of temperature ($T_1 = T_2$) and heat flux ($\kappa_1(\partial T_1/\partial z) = \kappa_2(\partial T_2/\partial z)$) 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 (Contreras **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

These have been summarized by Verma and López-M. (1982), Verma (1984a, b, 1985a, b, 1990), Ferriz (1985), Dobson and Mahood (1985), Carrasco-Núñez (1989), Castillo-Román *et al.* (1991).

3.1. Tectonic setting

Both geothermal fields are located in the Mexican Volcanic Belt (MVB; Figure 1), a Miocene to Recent volcanic 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

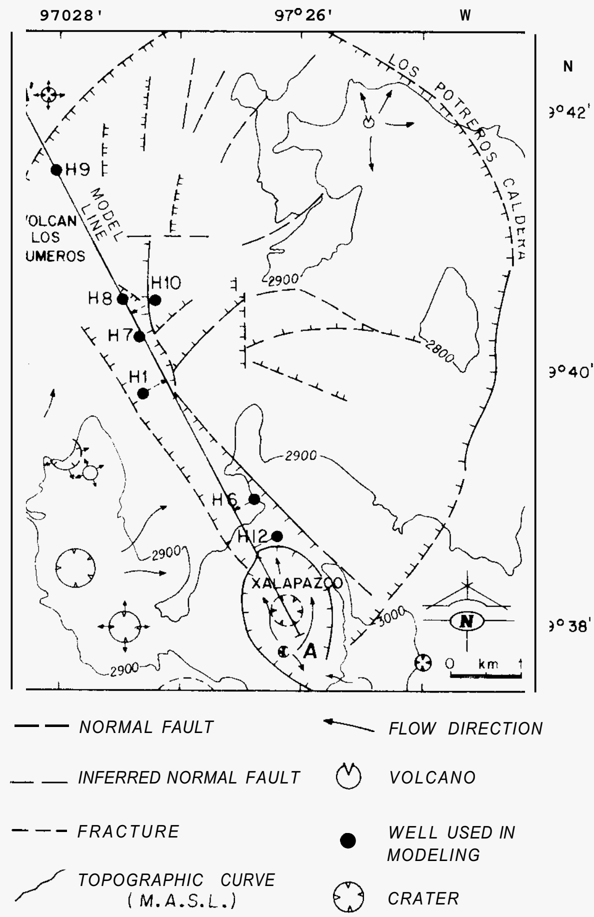

Figure **2. A** simplified geologic map of Los Potreros caldera, a part of Los Humeros caldera, Puebla, with location of the wells used for thermal modeling along the line AA' (modified after Castillo-Román *et al.,* 1991).

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 isotopes 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 km' (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 ~400 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.

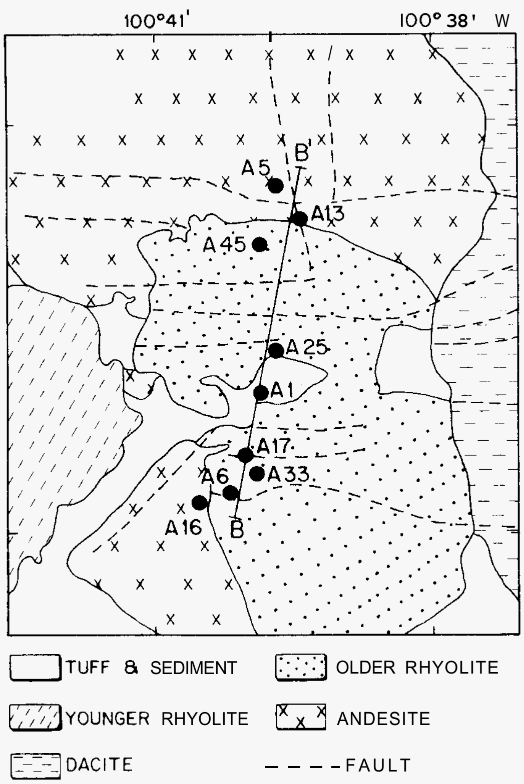

Figure 3. A simplified geologic map of Los Azufres caldera, Michoacán, with location of the wells used for thermal modeling along the line BB' (modified after Dobson and Mahood, 1985; Santoyo *et al.*, 1991; Verma and Andaverde, in prep.).

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 −1200°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(±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 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°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 (κ) of the rocks,

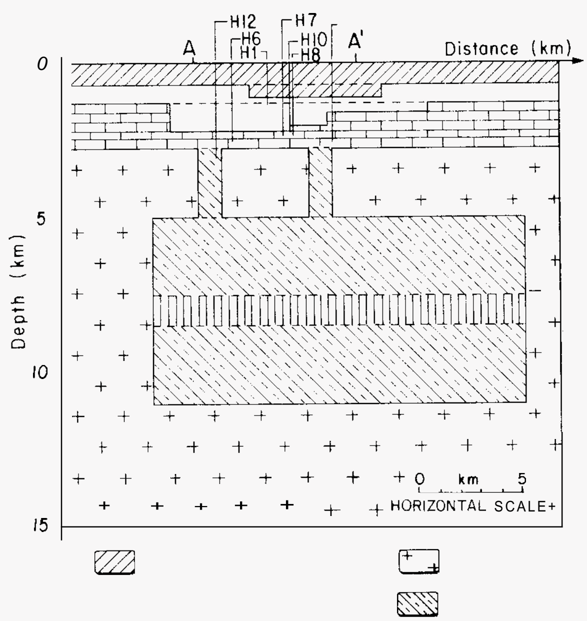

Figure 4. A computational model for Los Humeros used in the numerical simulations for predicting temperature field distribution in the system along the model line AA'. In addition to a simple conductive cooling (SCC) of the large magma chamber during about 0.6 Ma, the thermal effects of fractional crystallization (FC), a highly convective (HC) geothermal reservoir (values of effective conductivities = 20κ 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.

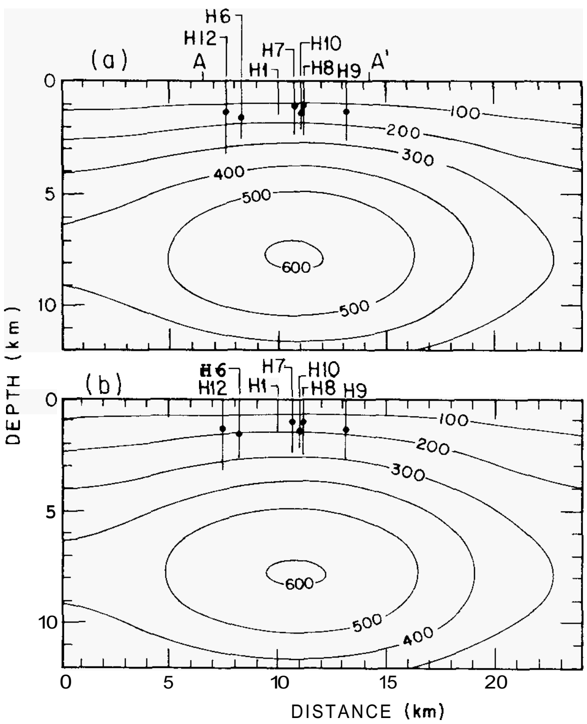

Figure 5. Predicted isotherms from cooling of a magma chamber (SCC) at a depth of – 5 km during a period of – 0.6 Ma. The thermal effects of fractional crystallization (FC) and magma recharge (MR) in the chamber are also considered in this modeling. **a)** Without convection (SCC + FC + MR), and **b)** With highly convective (SCC + FC + MR + HC) geothermal reservoir (20κ 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°C/km (curve a in Figure 7), much lower than the measured gradient of ~150°C/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°C/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^3 of basaltic magma during ~0.36 Ma), which increased the predicted gradient to ~95°C/km. Finally, very high convective (HC) regime (20 times the rock conductivities κ 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).

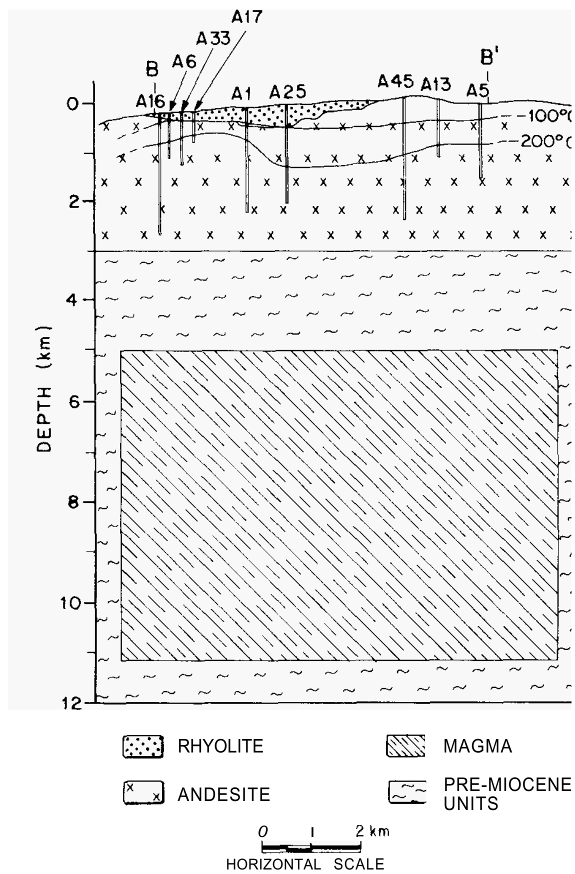

Figure 6. A computational model for Los Azufres used in the numerical simulations for predicting temperature field distribution in this system along the model line BB'. Measured isotherms for 100°C and 200°C are also shown for reference. In order to obtain the best agreement between the measured and the simulated temperatures, the thermal effects of fractional crystallization (FC), a highly convective (HC) geothermal reservoir (values of effective conductivities = 20κ 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.

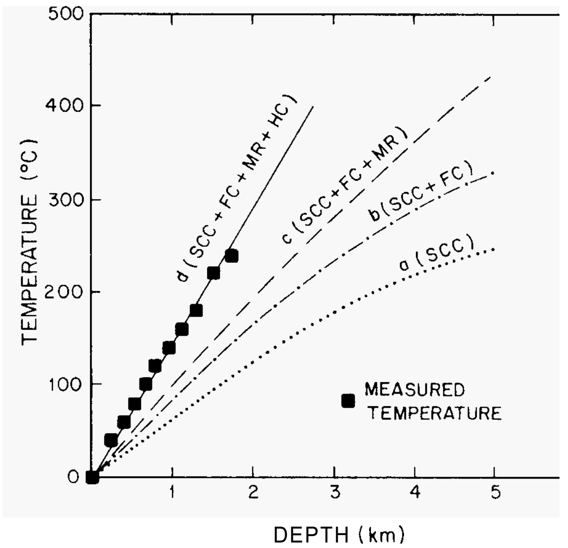

Figure 7. Temperature *versus* depth curves for the central part of the model line BB' in the Los Azufres geothermal system. Predicted results are presented from simple conductive cooling (SCC, curve a) of the chamber to the more elaborate cases involving various geological processes, viz., fractional crystallization (FC), magma recharge (MR), and high convection (HC) in the geothermal reservoir. The final model (curve d) gives the "best-fit" with the actually measured geothermal gradient in the middle part of the model line BB' (Figure 3).

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

Andaverde, J. and Verma, S.P. (1992). Modelado térmico de la cámara magmática en el campo geotérmico de Los Azufres, Michoacin, MCxico. *Actus Fac. Ciencias Tierra UANL Linares,* Vol.7, pp. 153-158.

Andaverde, J. and Verma, S.P. (1993). Programa de cómputo para involucrar la cristalizacidn fraccionada en el modelado termico de cámaras magmáticas. *Geotemia Rev. Mex. Geoener.,* Vol.9, pp. 59-74.

Andaverde, J., Verma, S.P. and Schildknecht, F. (1991). Aporte de calor al medio por el proceso de cristalización fraccionada en la cámara magmática del campo geottrmico de Los Azufres, Mich. (Mexico). *Actus Fac. Ciencias Tierra UANL Linares,* Vol.6, pp. 137-141.

Andaverde, J., Verma, S.P. and Schildknecht, F. (1993). Aporte de calor por cristalización fraccionada en dos campos geotérmicos del Cinturón Volcinico Mexicano. *Geofs. Int.*, Vol.32, pp. 331-339.

Berman, H., Daly, R.A. and Spicer, H.C. (1942). *Density ut room temperature and I atmosphere,* Geological Society of America, New York, **pp.** 7-26 p.

Carrasco-Núñez, G. (1989). Ambiente tectónico de la región volcánica Los Azufres, Mich. - Zamorano, Qro. *Geofs. Int.*, V01.28, pp. 975-991.

Castillo-Romin, J. and Verma, S.P. (1989). Modelado térmico como herramienta en estudios de Areas geotérmicas y volcánicas. *Geos UGM Bol.,* Vol.9(4), pp. 217-230.

Castillo-Romin, J., Verma, S.P. and Andaverde, J. (1991). Modelación de temperaturas bajo la caldera de Los Humeros, Puebla, MCxico, en términos de profundidad de la cámara magmática. *Geofs. Int.*, Vol.30, pp. 149-172.

Cathelineau, M., Oliver, R. and Nieva, D. (1987). Geochemistry series of the Los Azufres geothermal field (Mexico). In: *Mexican Volcanic Belt, Part 3B,* S.P. Verma (Ed)., *Geofs. Int.*, Vol.26, pp. 273-290.

Contreras L., E., Dominguez A., B., Iglesias R., E., Garcia G., A. and Huitron E., R. (1988). Compendio de resultados de mediciones petrofisicas de núcleos de perforación del campo geotérmico Los Azufres. *Geotermia Rev. Mex. Geoener.,* Vol.4(2), pp. 79-105.

Contreras L., E., Dominguez A., B. and Rivera M., O. (1990).

Mediciones petrofisicas in núcleos de perforación del campo geotérmico Los Humeros. *Georemia Rev. Mex. Geoener.*, Vol.6(1), pp. 9-42.

Dobson, P.F. and Mahood, G.A. (1985). Volcanic stratigraphy of the Los Azufres geothermal area, Mexico. *J. Volcanol. Geothem. Res.*, Vo1.25, pp. 273-287.

Drury, M.J., Allen, V.S. and Jessop, A.M. (1984). The measurement of thermal diffusivity of rock cores. *Tectonophysics,* Vol.103, pp. 321-333.

Elders, **W.A.,** Bird, D.K., Williams, A.E. and Schiffman, P. (1984). Hydrothermal flow regime and magmatic heat source of the Cerro Prieto geothermal system, Baja California, Mexico. *Geothemics,* Vol.13, pp. 27-47.

Ferrari, L., Garduño, V.H., Pasquarè, G. and Tibaldi, A. (1991). Geology of Los Azufres caldera, Mexico, and its relationships with regional tectonics. In: *Caldera: genesis, structure and unrest,* S.P. Verma **(Ed).,** *J. Volcanol. Geotherm. Res.,* Vo1.47, pp. 129-148.

Ferriz, H. (1985). Zoneamiento composicional y mineralógico en los productos eruptivos del centro volcánico de Los Humeros, Puebla, Mexico. In: *Mexican Volcanic Belt, Part I,* S.P. Verma (Ed)., *Geofis.* ***Int.,*** Vol.24, pp. 97-157.

Ferriz, H. and Mahood, G.A. (1984). Eruption rates and Compositional trends at Los Humeros volcanic center, Puebla, Mexico. *J. Geophys. Res.,* Vol.89, pp. 8511-8524.

Giberti, G., Moreno, **S.** and Sartoris, G. (1984). Thermal history of Phlegraean fields (Italy). in the last 50,000 years: a schematic numerical model. *Bull. Volcanol.,* Vol.47, pp. 331-341.

Hernandez Ramirez, I., Garcia Gutiérrez, A. and Morales Rosas, J.M. (1993). Estimación de temperaturas de los fluidos de perforación durante la circulación. *Geotermia Rev. Mex. Geoener.,* V01.9, pp. 305-319.

Horai, K. (1972). Thermal conductivity of nineteen igneous rocks. II. Estimation of the thermal conductivity of rock from the mineral and chemical compositions. *Phys. Earth Planet. Inter.,* Vol.5, pp. 157-166.

Kappelmeyer, **O.** and Haenel, R. (1974). *Geothennics,* Geopublication Associates, Berlin, 235 pp.

Nieva, D., Iglesias, E., Arellano, V., Contreras, E., Cathelineau, M. and Quijano, L. (1986). Developments in geothermal energy in Mexico—part four: evaluation of geothermal resources, multidisciplinary studies of the Los Azufes field, Mexico. *Heat Recov. Syst.*, Vol.6, pp. 201-207.

Norton, D. and Taylor, Jr., H. P. (1979). Quantitative simulation of the hydrothermal systems of crystallizing magmas on the basis of transport theory and oxygen isotope data: An analysis of the Skaergaard intrusion. ***J.*** *Petrol.,* Vol. 20, pp. 421-486.

Prol, R.M. and González-Morán, T. (1982). Modelo preliminar del regimen térmico conductivo en la caldera de Los Humeros, Puebla. *Geofis.* ***Int.,*** Vol.21, pp. 295-307.

Rodríguez-González, U. and Verma, S.P. (1992). Aporte de calor por desintegración de elementos radioactivos en el campo geotérmico de La Primavera, Jalisco, Mexico. ***Acta*** *Fac. Ciencias Tierra UANL Linares,* Vol.7, pp. 229-232.

Santoyo, E., Verma, S.P., Nieva, D. and Portugal, E. (1991). Variability in the gas phase composition of fluids discharged from Los Azufres geothermal field, Mexico. In: *Calderas: Genesis, Structure and Unrest,* S.P. Verma (Ed.), *J. Volcanol. Geothem. Res.,* Vol. 47, pp. 161-181.

Verma, M.P., Verma, S.P. and Sanvicente, H. (1990). Temperature field simulation with stratification model of magma chamber under Los Humeros caldera, Puebla, Mexico. *Georhennics,* Vol. 19, pp. 187-197.

Verma, S.P. (1984a). La petrogenesis y la fuente de calor en la caldera de Los Humeros, Puebla, MCxico. *Curso Internacional Post-Universitario en geotermia, 1er. Seminario de Actualización (IILA-IIRG),* Bogotá, Colombia, pp. 343-355.

Verma, S.P. (1984b). Alkali and alkaline earth element geochemistry of Los Humeros caldera, Puebla, Mexico. *J. Volcanol. Geothem. Res.,* Vol.20, pp. 21-40.

Verma, S.P. (1985a). On the magma chamber characteristics as inferred from surface geology and geochemistry: examples from Mexican geothermal areas. *Phys. Earth Planet. Infer.,* Vol.41, pp. 207-214.

Verma, S.P. (1985b). Heat source in Los Humeros geothermal area, Puebla, Mexico. *Geotherm. Res.* ***Coun.*** *Trans.,* Vol.9 - Part I, pp. 521-525.

Verma, S.P. (1990). Metodologia para el estudio del Cinturón Volcánico Mexicano. *Bol. IIE,* Vol. 14, pp. 224-229.

Verma, S.P. (1991). Introduction. In: Calderas: genesis, structure and unrest, S.P. Verma (Ed)., *J. Volcanol. Geotherm. Res.,* Vo1.47, pp. vii-x.

Verma, S.P. (1994). Geochemical and isotopic constraints on the origin of mafic volcanism in central Mexico. *Mineral. Mag.,* Vol. 58A, pp. 938-939.

Verma, S.P. and Andaverde, J. (in prep.). Temperature field simulation from cooling of a magma chamber in Los Azufres, Michoacán, Mexico.

Verma, S.P. and Dobson, P.F. (1987). Sr, Nd, O and Pb isotopic evidence for complex petrogenetic evolution of silicic lavas in the Los Azufres volcanic field, Michoacán, Mexico. *Eos Trans. AGU*, Vol.68, pp. 1520 (abstract).

Verma, S.P. and Lopez M., M. (1982). Geochemistry of Los Humeros caldera, Puebla, Mexico. ***Bull.*** *Volcanol.,* Vol.45, pp. 63-79.

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

Verma, S.P., Navarro-L., I. and Garcia Cacho, L. (1992). Major-element geochemistry and mineralogy of the Huichapan caldera, Hidalgo, Mexico. *J. South.* ***Am.*** *Earth. Sci.,* Vol.5, pp. 327-336.