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Temperature distributions from cooling of a magma chamber in Los Azufres geothermal field, Michoacán, Mexico

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RESUMEN

Se modela la distribución de temperaturas en el campo geotérmico de Los Azufres, Michoacán, asumiéndose que la fuente de calor es una cámara magmática emplazada en los niveles más superficiales de la corteza, localizándose la cima de la cámara a ~5 km de profundidad. En dicha cámara tienen lugar los procesos de reinyección de magma y cristalización fraccionada, siendo este último, según modelos geoquímicos, el proceso petrogenético dominante. Se desarrolla una metodología a fin de considerar la contribución de estos procesos en las simulaciones a partir de la cámara magmática. La ecuación de conservación de energía para flujo de calor por conducción en dos dimensiones se resuelve numéricamente mediante el esquema explícito de diferencias finitas.

El proceso de cristalización fraccionada requiere un período de ~0.1 Ma con el fin de llevarse a cabo totalmente. Al involucrar este proceso se aumenta en ~410°C la temperatura de la cámara, siendo esta cantidad mayor que la calculada en el enfriamiento de magma en un sólo paso (300°C). Se considera una reinyección de ~36 km^3 de material basáltico en la cámara hace 0.36 Ma. Esto se modela térmicamente suponiendo una recarga de 0.1 km^3 cada 1000 años durante dicho período. Es necesario modelar la convección en el yacimiento al menos por 0.1 Ma para que junto con los procesos de cristalización fraccionada y reinyección, se logre una concordancia entre el gradiente térmico modelado y el medido en los pozos.

PALABRAS CLAVE: Los Azufres, México, modelado térmico, cámara magmática, campo geotérmico, gradiente térmico.

ABSTRACT

The temperature distribution in Los Azufres geothermal field, Michoacán, has been modelled assuming a shallow magma chamber at a depth of ~5 km. The evolution of the magma chamber is controlled by the processes of magma recharge as well as fractional crystallization, the latter being the dominant petrogenetic process. The heat contribution of these processes is taken into account. The heat transfer equation was solved by a finite difference explicit method.

The process of fractional crystallization requires a time interval of ~0.1 Ma for the chamber to cool from basalt to rhyolite liquidus temperatures. The corresponding heat contribution amounts to a temperature increase of ~410°C. This value is considerably larger than the ~300°C estimated for "one-step" cooling. The recharge of the chamber is assumed equivalent to ~36 km^3 of basaltic magma during the past 0.36 Ma. This was modelled thermally by assuming a recharge rate of 0.1 km^3 of magma per 1000 years over 0.36 Ma. Convective processes within the geothermal reservoir were considered at least during the past 0.1 Ma. The processes of fractional crystallization, magma recharge and convection must all be considered for optimal agreement between the simulated and measured temperatures.

KEY WORDS: Los Azufres, Mexico, thermal modelling, magma chamber, geothermal field, temperature gradient.

INTRODUCTION

The Mexican Volcanic Belt (MVB) is a ~1000 km long, approximately E-W, Miocene to Recent, geological structure in Central Mexico. It contains a large number (~8000) of volcanic edifices (Figure 1) and extends from near Puerto Vallarta to Veracruz (Aguilar-Y-Vargas and Verma, 1987). The MVB has a great geothermal potential, at present exploited in a few geothermal fields, such as Los Azufres in Michoacán and Los Humeros in Puebla (Figure 1). These fields are related to the cooling of subsurface magma chambers and therefore, it is important to model the temperature field distribution and its relationship with the hydrological and structural systems. These systems play an important role in the thermal state of the geothermal reservoir (Castillo-Román *et al.*, 1991).

The Los Azufres geothermal field (LAGF) is located in the state of Michoacán, ~200 km NW of Mexico City, between 19°45' and 19°50'N latitude and 100°38' and 100°43' W longitude. It covers an area of ~72 km^2 (Dobson and Mahood, 1985).

Verma (1985) presented a geological, geochemical, and geophysical integrated methodology to model temperature field distributions in geothermal fields. He proposed to use these data to estimate chemical and physical parameters related to the magma chambers. The less expensive thermal modelling approach could provide the present state of thermal regime, and a thermal history of the geothermal fields (Castillo-Román *et al.*, 1991; Verma, 1990).

The geological processes and parameters to be consid-

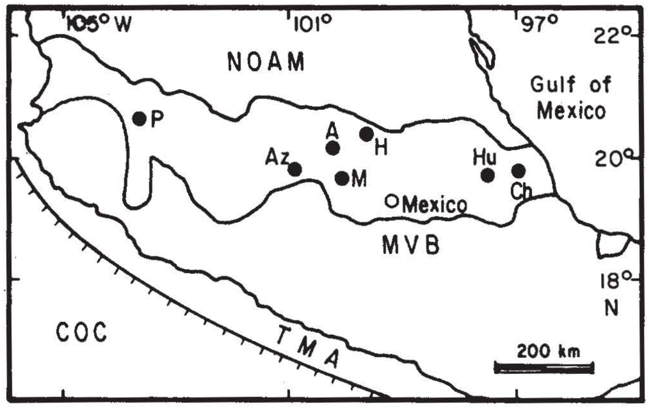

Fig. 1. Simplified map of the Mexican Volcanic Belt (MVB), modified after Verma *et al.* (1992). P = La Primavera, Az = Los Azufres, A = Amealco, M = Mazahua, H = Huichapan, Hu = Los Humeros, and Ch = Chiconquiaco. Three of these calderas (P, Az, and Hu) are also geothermal fields. TMA = Middle America Trench.

ered for the thermal modelling include: magmatic processes within the magma chamber, depth of the magma chamber, physical properties of reservoir rocks and their temperature dependence, as well as processes in the reservoir. The magmatic processes to be considered are fractional crystallization, magma recharge, assimilation, magma mixing, convection and radioactive heat generation (Andaverde *et al.*, 1991, 1993; Rodríguez-González and Verma, 1992; Verma and Rodríguez-González, 1995).

Few studies involving thermal modelling and heat sources have been carried out in Mexico. They have been focussed on Los Humeros geothermal field (Prol and González-Morán, 1982; Verma, 1985; Verma *et al.*, 1990; Castillo-Román *et al.*, 1991) and Cerro Prieto (Elders *et al.*, 1984; Goldstein *et al.*, 1984; Quintanilla M. and Suárez V., 1994). The present work reports temperature field simulations for a magma chamber in the LAGF. A summary has recently been presented by Verma and Andaverde (1995).

Geology

The geology of the area was described by Dobson and Mahood (1985), Cathelineau *et al.* (1987), Carrasco-Núñez (1989), Ferrari *et al.* (1991) and Pradal and Robin (1994), among others. On the basis of these studies, the LAGF can be defined as an extensive field of dacitic, rhyodacitic and rhyolitic domes, surrounded by a large number of Quaternary basaltic and andesitic cinder cones. The pre-volcanic basement consists of Eocene to Oligocene shales (which are slightly folded and metamorphosed), sandstones and conglomerates.

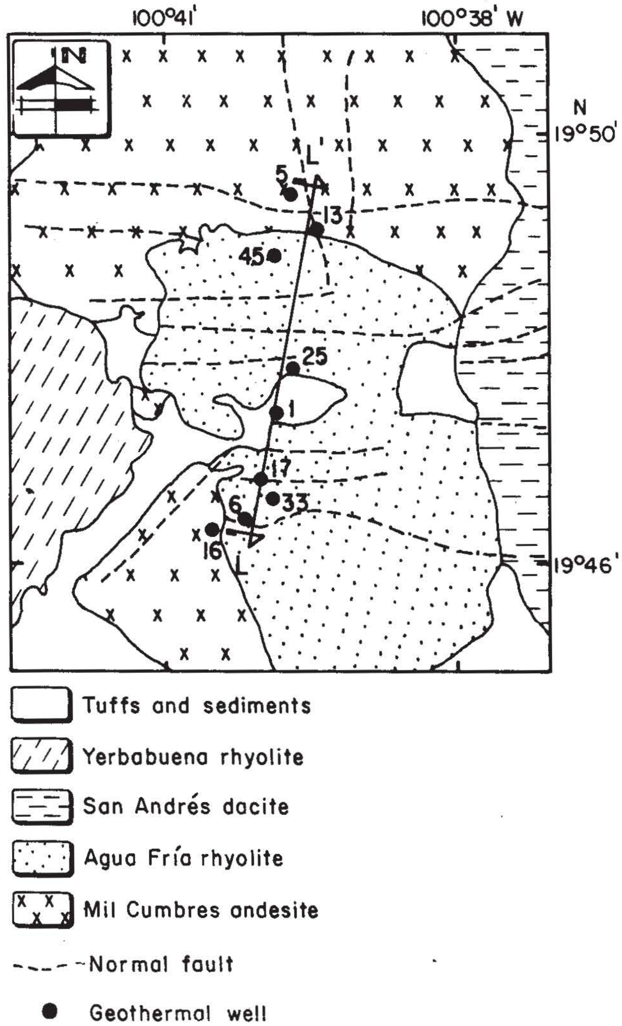

Fig. 2. Geologic map of Los Azufres geothermal field (LAGF) (modified after Dobson and Mahood, 1985 and Santoyo *et al.*, 1991). Broken lines indicate normal faults. Also shown are the locations of some wells and the model axis L-L'.

Table 1

Main geological units of the Los Azufres geothermal field

Geological unit	Age (Ma)	SiO_2 (%)	Volume (km^3)
Ciudad Hidalgo basalt	0-0.15	50-57	4.6
Yerbabuena rhyolite	0.14-0.30	73-75	12.2
San Andrés dacite	0.33-0.36	65-72	19.3
Zinapécuaro andesite	0.75-0.87	53-59	~2
Agua Fría rhyolite	0.84-1.60	70-76	12.2
Mil Cumbres andesite	5.9-18.2	50-60	-

Figure 2 and Table 1 show the distribution of some geological units comprising the LAGF and a summary of their main characteristics. The LAGF can be subdivided into two production zones: Marítaro at the north and Tejamaniles towards the south. A total of 52 wells was drilled in the LAGF.

The geological units are described in chronologically descending order from the oldest to the youngest as follows:

(a) Mil Cumbres andesite: This unit consists of ~3000 m of mostly andesitic rocks, including some basalts, dacites and pyroclastic horizons. Outcrops are found in the northern and southern part of the LAGF. This unit can be subdivided into three main lava emission sequences: approximately 600 m of mostly basalts towards the base, about 1700 m of andesites in the central part, and about 700 m of dacites at the top. Radiometric ages vary from about 18.1 Ma for the basalts at the base to about 5.9 Ma at the top. This unit is considered as local basement, in which the geothermal reservoir of the LAGF is located.

(b) Agua Fría rhyolite: It consists of three rhyolitic domes located within the LAGF and eight domes outside the LAGF towards its northeast. It discordantly and partially covers the Mil Cumbres andesite unit. The total volume of the Agua Fría rhyolite unit is estimated as approximately 12.2 km^3 (~5.3 km^3 for the three central domes and ~6.9 km^3 for the other eight domes). The age of this unit varies from 1.6 Ma to 0.84 Ma.

(c) Zinapécuaro andesite: This unit consists of basaltic-andesite and andesite lavas that crop out in the vicinity of Zinapécuaro. The total volume of this unit is ~2 km^3 and its age is between 0.87 Ma and 0.85 Ma. It is not shown in Figure 2 because these rocks are found outside the area covered by this map.

(d) San Andrés dacite: The emission of ~19.3 km^3 of dacitic magma, at 0.36 Ma to 0.33 Ma, is the most voluminous event in the LAGF. It overlies the earlier volcanic units.

(e) Yerbabuena rhyolite: This unit consists of ten rhyodacitic and rhyolitic domes located in the western part of the LAGF. Its estimated volume is ~12.2 km^3 and its age varies from 0.30 Ma to 0.14 Ma.

(f) Tuffs and sediments: These have been described by Ferrari *et al.* (1991) as alluvial deposits and pyroclastic deposits related to Late Pleistocene activity. They consist of fluviolacustrine deposits made of moderately consolidated thin layers of siltstones and ashes with horizons containing pumice, obsidian and andesite fragments.

(g) Ciudad Hidalgo basalt: This youngest unit consists of 52 cinder cones located in the eastern and western parts of the LAGF. It contains about 4.6 km^3 of basaltic and basaltic-andesite lavas, ashes and breccias. Its age varies from ~0.15 Ma to the Present. These basalts are not shown in Figure 2 as they outcrop away from the area covered in this Figure.

Geochemistry

Using the geochemical data presented by Dobson and Mahood (1985) and the TAS diagram of Le Bas *et al.* (1986), the Los Azufres volcanic rocks have been classified from basalt to rhyolite (Andaverde *et al.*, 1991, 1993). Verma (1985) used mass balance calculations to estimate a minimum volume of about 400 km^3 for the magma chamber in Los Azufres. A fractional crystallization model for Los Azufres was proposed by Cathelineau *et al.* (1987). Verma and Dobson (1987) presented Sr, Nd, O, and Pb isotope data on volcanic rocks from the Los Azufres area and concluded that the fractional crystallization process played a dominant role in the evolution of these magmas. However, some assimilation of the crust might have also occurred during this process, particularly for the rhyolitic magmas.

Geophysics

Gravimetry, magnetometry, geoelectrical and well-logging studies have been carried out in the LAGF (Romero and Palma, 1983; Ballina, 1987; Campos-Enríquez and Garduño-Monroy, 1995), with the purpose of determining the geological structure in relation with the geothermal reservoir. There are no geophysical studies in the LAGF related to the magma chamber and simulation of the temperature field distribution. This is the first attempt to model, from available data, the cooling of the magma chamber during the volcanic history of the Los Azufres area. The present results are subject to modification when more constraints can be placed on the various physical and chemical parameters involved in the thermal modelling and when more elaborate simulations involving convective processes of heat and mass transfer in the reservoir can be carried out.

GEOLOGICAL MODEL

The geological model of the Los Azufres area was obtained from the geological, geochemical and geophysical data, in addition to well data about the model axis L-L' (Figure 2). Criteria used in locating this model axis include the number of wells (16, 6, 33, 17, 1, 25, 45, 13 and 5) on this line; major faults crossing the line; small topographic changes along this line (about 400 m); and three wells (5, 16, and 17), with an extensive production history situated in the north and south of the LAGF.

We have constructed a geological model (Figure 3), in which the magma chamber is considered to be emplaced in a metamorphic complex, at a depth of about 5 km. The shallow depth of the magma chamber is assumed from analogy with thermal modelling in Los Humeros caldera, Puebla (Verma *et al.*, 1990; Castillo-Román *et al.*, 1991), where the best agreement between the measured and simulated temperatures was obtained for a chamber at a depth of ~5 km.

The geophysical evidence available so far does not constrain the shape nor the dimensions of the magma chamber. We infer a volume of 400 km^3 from geochemical models and assume a cylindrical shape with a radius of 4.5 km and a thickness of 6 km. The total area modelled in this study measures about 10 km horizontally and 12 km vertically, in which a rectangular section of the magma chamber is located at a depth of ~5 km.

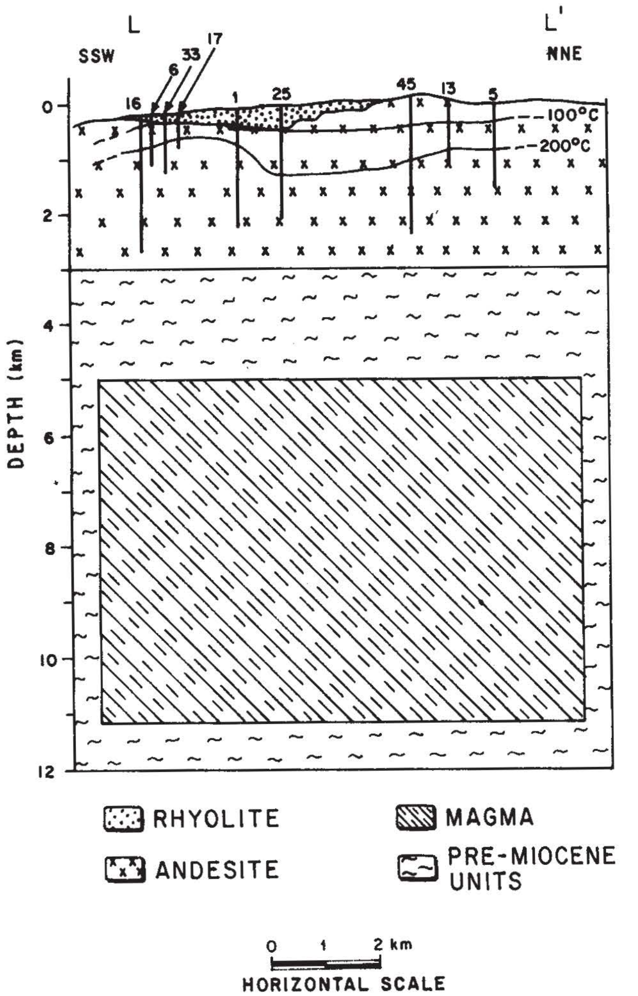

Fig. 3. Geological section from regional geology and well data about the model axis L-L'. Also shown are the isotherms of 100°C and 200°C, estimated from measured temperatures in wells. The model of the magma chamber at a depth of 5 km is also presented schematically.

HEAT RELEASED FROM FRACTIONAL CRYSTALLIZATION

In earlier work (Castillo-Román and Verma, 1989; Castillo-Román *et al.*, 1991), the heat contribution from fractional crystallization and solidification of the magma was modelled by increasing the initial magma temperature by 300°C, as in Giberti *et al.* (1984).

In the present work, the heat released by fractional crystallization and consequent solidification of the magma takes into account the geochemical evolution of the magma chamber. The methodology and its application in the Los Azufres have been described in detail by Andaverde *et al.* (1991, 1993). They show that the amount of heat liberated in Los Azufres is equivalent to temperature increases of the magma chamber by ~204°C corresponding to the differentiation of the original magma to basalts, by ~163°C for the differentiation from basalts to andesites, by ~37°C from andesites to dacites, and by ~7°C for dacites to rhyolites, giving a total of ~411°C for the entire period estimated about 0.1 Ma (see below in section B of SIMULATION RESULTS). The solidification temperatures were taken as 950°C for basalts, 875°C for andesites, and 800°C for rhyodacites and rhyolites. Thus, a temperature increase of approximately 4.1°C/1000 years (410°C/0.1 Ma) was incorporated into the magma chamber model. This simple basalt-andesite-rhyolite or basalt-andesite-dacite-rhyolite model could be refined to include more steps of geochemical evolution, given a detailed model for Los Azufres such as the one proposed for Huichapan caldera by Verma *et al.* (1992).

The computer program for modelling temperature field distribution was initially developed by Verma *et al.* (1990). The heat-transfer equation in two dimensions is solved by the explicit finite differences. The energy-conservation equation is:

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

where T = temperature, t = time, κ = thermal conductivity, ρc = product of the density and heat capacity of the medium, x, z = space coordinates.

The boundary conditions are constant temperature (T=0°C) at the surface, and equal temperatures ($T_1=T_2$) and heat fluxes ($\kappa_1(\partial T_1/\partial z)=\kappa_2(\partial T_2/\partial z)$) at the boundaries between the grids dividing the area being modelled. The equation is solved assuming that these boundaries have a very small, finite thickness. This thickness of the boundary is divided into layers and the interpolated κ-value at the middle of each layer is used for the layer. The temperature curve is smoothed at every step of calculation.

The heat contribution from fractional crystallization and magma recharge is computed by new subroutines which have been incorporated into the original program (Andaverde and Verma, 1993).

Modelling parameters

The model section (Figure 3) measures 10 km horizontally (x-axis) by 12 km in depth (z-axis). A uniform grid of 250 m x 250 m was used. Two main geologic layers are considered. The upper, dominantly andesitic layer is about 3 km thick and has a rhyolite flow in the middle. In order to consider this flow in the computer program, four rectangular bodies are modelled within the andesite. The lower layer is a metamorphic complex which contains the magma chamber as described earlier. The topography is modelled as two rectangular bodies having very small values of thermal conductivity and diffusivity.

The initial magma temperature is assumed to be 1200° C, appropriate for a basaltic magma. A "normal" temperature gradient of 30°C/km was assumed initially for the geological section, in such a way that T = 0°C at z = 0 and T = 360°C at z = 12 km. Thermal properties of rocks used in the modelling are given in Table 2. These figures are assumed to be constant in the present work, as their temperature dependence is not known at present.

Table 2

Thermal properties of rocks assumed in temperature simulations

Rock type	Thermal conductivity (W/m°C)	Thermal diffusivity (m^2/s) x 10^{-6}
Andesite	1.72 *(a)*	0.66 *(a)*
Rhyolite	3.44 *(b)*	0.64 *(c)*
Metamorphic complex	2.73 *(d)*	1.30 *(d)*
Basaltic magma	1.42 *(e)*	0.67 *(e)*

References: *(a)* Contreras *et al.* (1988); *(b)* Horai (1972); *(c)* Drury *et al.* (1984); *(d)* Kappelmeyer and Haenel (1974); *(e)* Giberti *et al.* (1984).

Measured temperature field distribution in the LAGF

From measured temperatures in wells on or near the model axis L-L' (Figure 2), isotherms for 100°C and 200°C are constructed (Figure 3). In the central part of the LAGF, there exists at present a geothermal gradient of ~150°C/km. This gradient is used for comparison purposes in the simulations. Gradients in the north and south zones of the LAGF (Figure 3) are higher (~230°C/km), which may be related to the large number of faults and fractures. The effect of such geological structures on the temperature field distribution will be the subject of future studies. We attempted to match only the lower temperature gradient because it is less likely to be affected by hydrothermal activity. We use a simple conductive cooling model and *not* a convective model.

Magma recharge

In order to predict the temperature field in the LAGF, magma recharge in the chamber must be taken into account. From the volume estimates presented by Carrasco-Núñez (1989), the total volume of the geologic units younger than 0.36 Ma can be estimated as ~36 km^3. These eruptions have not caused any observable caldera collapse in the area. Magma recharge in the chamber might be a viable process to compensate for these emissions.

We assume an intrusion rate of ~ 0.1 km^3 of basaltic magma in the chamber, at a temperature of about 1200°C during 1000 years, which comes to about 36 km^3 of magma in 0.36 Ma. This magma supply rate should keep part of the chamber at about 1200°C.

On the basis of available evidence, magma recharge seems to be an essential process along with fractional crystallization which dominates in the magma chamber. The thermal effects of these processes are taken into account in our present work, but the geochemical implications will have to be considered elsewhere.

SIMULATION RESULTS

We present the results of simulations of temperature field distributions obtained under different modelling conditions. For comparison we select the central part of the field where convective processes are likely to be less important than in the northern or southern zones of the LAGF.

(A) Simple conductive cooling of the magma chamber

A simple conductive cooling (SCC), without any geological process occurring within or outside the magma chamber, predicts a temperature gradient of ~60°C/km for the first 2 km below the surface. This is much lower than the measured value (~150°C/km) in the central part of the LAGF. Hence, the SCC of the magma chamber is not sufficient to model the temperature gradient in the LAGF. Considerations of geological processes in the magma chamber is justified for predicting the actual geothermal gradient.

(B) SCC + Fractional Crystallization (FC)

The simulation suggests that the time period required for the magma chamber to cool from an initial temperature of 1200°C to 950°C (the latter is taken as the solidification temperature for basaltic magma) is ~0.06 Ma. The corresponding figures for andesitic (875°C) and rhyolitic magmas (800°C) are ~0.08 Ma and ~0.1 Ma respectively. These time estimates mean that if we were to withdraw more evolved dacitic and rhyolitic magmas at about 0.36 Ma, the magma chamber should have been emplaced at least 0.46 Ma ago, i.e., for the 0.36 Ma eruption age of the evolved magmas plus 0.1 Ma required to differentiate the original basaltic magmas to dacitic and rhyolitic compositions.

The simulations under conditions of combined simple conductive cooling and fractional crystallization (SCC+FC) for 0.46 Ma thus predict a present temperature gradient of ~80°C/km, which is still lower than the measured values in the LAGF.

(C) SCC+FC+recharge in the magma chamber (MR)

We suggested that a magma recharge (MR) rate of about 0.1 km^3/1000 years was a reasonable estimate for the LAGF. We may simulate the MR by maintaining a temperature of 1200°C at two nodal points at a depth of 7 km for the 250 m x 250 m grid during the past 0.36 Ma. Results of the simulation (SCC+FC+MR) are shown in

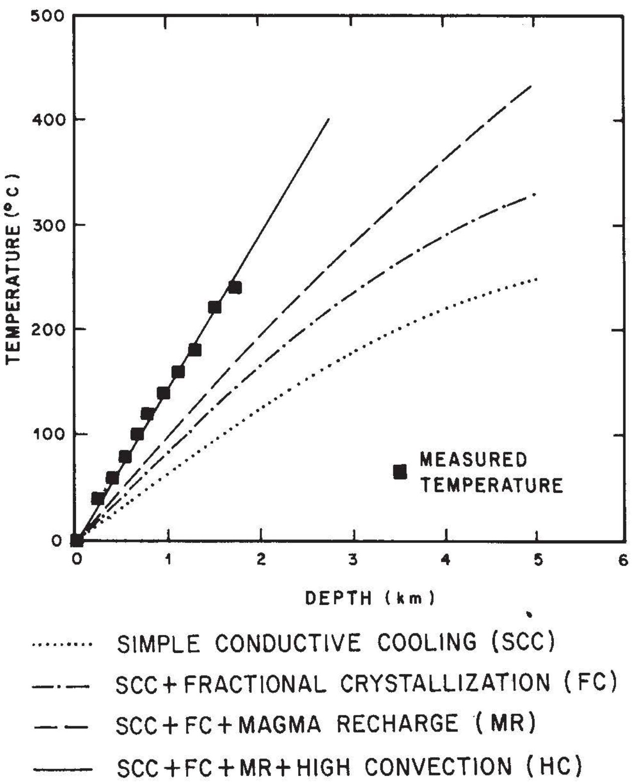

Fig. 6. Temperature as a function of depth in the central part of the LAGF for the following simulations: SCC (dotted curve), SCC+FC (dashed-dotted curve), SCC+FC+MR (dashed curve), and SCC+FC+MR+CR (continuous curve). See text for explanation.

CONCLUSIONS

From the available geochemical evidence in the LAGF and from the present thermal simulations, the effects of fractional crystallization in the magma chamber must be taken into account for at least ~0.1 Ma. In the central part of the LAGF, the measured temperature gradient is ~150° C/km. A simple conductive cooling (SCC) model predicts a present temperature gradient of only ~60°C/km. The fractional crystallization (FC) process increases this value to ~80°C/km, which is further increased to ~95°C/km when the magma recharge (MR) is considered. Finally, it is necessary to also consider the convection in the reservoir (CR), during at least ~0.1 Ma in order to obtain a better agreement between the simulated and measured temperatures.

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