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DEPTH TO THE CURIE ISOTHERM FROM AEROMAGNETIC DATA AND GEOTHERMAL CONSIDERATIONS FOR THE WESTERN SECTOR OF THE TRANS-MEXICAN VOLCANIC BELT

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RESUMEN

En este trabajo reportamos estimaciones preliminares de profundidades a la isoterma de Curie en el sector occidental del Eje Neo-Volcánico, correspondientes a siete perfiles. Las estimaciones están basadas en el análisis espectral de datos aeromagnéticos. La isoterma de Curie se estima entre 7 y 18 km de profundidad para estas localidades. Los valores correspondientes del flujo de calor, calculados con base en estas profundidades parecen delinear dos zonas de alto flujo de calor y una tercera de magnitud intermedia. Las primeras dos áreas están asociadas a estructuras geológicas relativamente jóvenes: el graben de Tepic y la caldera de Amealco. La tercera área se correlaciona con la presencia de sistemas hidrotermales más fríos y más profundos en la vecindad de Puruándiro. Estas estimaciones concuerdan con mediciones directas de flujo de calor realizadas en la Faja Volcánica Trans-Mexicana, así como con estimaciones de flujo de calor basadas en los cocientes $^3He/^4He$, y también con el patrón general que presentan las temperaturas de equilibrio características de los sistemas hidrotermales en el área en estudio. Finalmente, se presenta una discusión especulativa sobre el potencial geotérmico de esta área.

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ABSTRACT

Preliminary depth estimations to the Curie isotherm in the western sector of the Trans-Mexican Volcanic Belt (TMVB) are reported. Depth estimations are based on spectral analysis of aeromagnetic data along seven profiles. The Curie point isotherm lies between 7 and 18 km deep. Corresponding heat flow values derived from the analysis roughly delineate two high heat flow zones which are related to relatively young geologic structures, *i.e.* the Tepic graben and the Amealco caldera. A third zone of intermediate heat flow values coincides with the presence of colder and deeper hydrothermal systems in the neighborhood of Puruándiro. The Curie point depth estimates correlate with the pattern of heat flow measurements and of equilibrium temperatures characteristic of TMVB hydrothermal systems. Preliminary estimations of the potential geothermal energy stored between the surface and the Curie point isotherm are also reported.

INTRODUCTION

Mexico has an installed capacity for generating 645 MW of electrical energy from geothermal resources (Alonso *et al.*, 1985). Geothermal fields in exploitation include: (1) Cerro Prieto in the Mexicali Valley (Baja California State) and (2) Los Azufres (Michoacán State). Production in the geothermal fields of Los Humeros (Puebla State), and La Primavera (Jalisco State) will start within the next two years. The Comisión Federal de Electricidad (CFE) has plans to expand, by the year 2 000, the installed geothermal generating capacity to 2 440 MW.

Mexico presents, in different geological environments, a large geothermal potential. Across its territory, numerous manifestations of this resource can be observed, *e.g.* hot springs, hot water wells, fumaroles, mud volcanoes, mud pots and active cinder cone fields and stratovolcanoes. The reconnaissance studies reveal a total of 1 283, so far identified; geothermal manifestations are related to 515 hydrothermal systems, distributed into seven provinces (Alonso *et al.*, 1985). The Trans-Mexican Volcanic Belt (TMVB), which comprises most of the historic and present-day volcanic activity, is the largest of these geothermal provinces. Geothermal prospects in this province include: Los Azufres, Los Humeros, La Primavera, Araro, Ixtlán de Los Hervores, and Los Negritos, La Soledad, El Ceboruco and Pathé. The TMVB extends across central Mexico from the Pacific ocean to the Gulf of Mexico roughly between 19° and 21° N parallels. The TMVB is generally described as a young volcanic province currently associated with the plate subduction process along the Middle America Trench (Molnar and Sykes, 1969; Urrutia-Fucugauchi and Del Castillo, 1977).

As part of a long term research program to identify, evaluate and exploit the geothermal potential in Mexico, CFE is conducting extensive geological, geochemical and geophysical studies in this province (Campos-Enríquez, 1987). Determination of the thermal regime in the TMVB is of great concern to update the assessment of the geothermal potential. In particular, mapping of the subsurface structure, of the depths to the Curie point isotherm and of the geothermal gradient. These studies can also assist to roughly delineate target zones where hot dry rock geothermal resources are to be explored in the future.

As part of a long-term cooperative project which includes paleomagnetic, rock-magnetic and magnetostratigraphic studies (*e.g.* Morán-Zenteno *et al.*, 1985; Campos-Enríquez *et al.*, 1987, Urrutia-Fucugauchi *et al.*, 1988) and subsurface structure and characteristics beneath the TMVB from ground magnetic and aeromagnetic surveys (*e.g.* Campos-Enríquez, 1986; Arroyo-Esquivel, 1986; Arroyo-Esquivel *et al.*, 1985; Contreras-Tebar, in preparation; Ramírez-Negrete, in preparation) in this paper we report preliminary results of the estimation of the depths to the Curie isotherm in the western sector of the TMVB based on spectral analysis of aeromagnetic data.

TRANS-MEXICAN VOLCANIC BELT

The TMVB comprises most of the active volcanoes in Mexico. It includes stratovolcanoes, cinder cone fields, isolated occurrences of rhyolitic volcanism, large silicic caldera centers, plateau magmatic sequences, etc. (Mooser, 1972; Urrutia-Fucugauchi and Del Castillo, 1977, Demant, 1978, 1981; Negendank *et al.*, 1985. Ferriz and Mahood, 1986) all these keeping characteristic temporal and spatial relationship, for instance, the silicic centers are consistently located behind the andesitic-dacitic stratovolcano front line.

Considering the Plio-Quaternary volcanism, Demant (1978, 1981) has defined five major sectors in the TMVB: 1) The Chapala - Tepic graben, which constitutes the western tip of the TMVB including several large stratovolcanoes; 2) The Colima graben, which is oriented almost north-south and includes the Colima stratovolcano; 3) The Michoacán - Guanajuato cinder cone field, which comprises some 3 000 cones in about 20 000 square kilometers; 4) The valleys of Toluca, Mexico, and Puebla, dominated by high stratovolcanoes around and in the large lacustrine plains (including also an extensive cinder cone field); and 5) the eastern TMVB, which includes units up to the N - S Pico de Orizaba - Cofre de Perote range (Robin, 1982) or down to the Gulf of Mexico coast (Negendank *et al.*, 1985).

For modelling and interpretation of the aeromagnetic data (Arroyo-Esquivel, 1986), a simplified regional geologic column was considered, composed of five major units: 1) The intrusive group, mainly exposed in the westernmost sector (Cretacic to Miocene granitoids); 2) The metamorphosed volcano-sedimentary group of Mesozoic age (Triassic to late Cretaceous); 3) The Sierra Madre Occidental (SMO) group of dominantly volcanic products (ignimbrites and rhyolitic tuffs and flows and smaller amounts of andesites and basalts all of Tertiary age; 4) The TMVB group *sensu stricto*; and 5) Recent sediment group (lacustrine, aluvial and residual sediments).

The TMVB is currently associated with plate subduction processes along the Middle America Trench (Molnar and Sykes, 1969; Urrutia-Fucugauchi and Del Castillo, 1977, Urrutia-Fucugauchi and Böhnel, 1988). In general, there is, however, considerable debate concerning the characteristics and age of the products constituting the TMVB and the units beneath.

ESTIMATION OF DEPTHS TO THE CURIE POINT ISOTHERM FROM AEROMAGNETIC DATA

Spectral analysis of aeromagnetic data has proved to be an efficient means to obtain the depths to the top and bottom of magnetic bodies ensembles (Spector and Grant, 1970; Hahn *et al.*, 1976; Shuey *et al.*, 1977; Boler, 1978). The slope of the power spectrum is related to the mean depth to the top of an ensemble of magnetic bodies. The mean depth to the base of the complete magnetic ensemble is related to the low frequency portion of the spectrum and can be correlated to the Curie point isotherm. Spector and Grant (1970) and Green (1972) analyzed the structure of the spectrum from aeromagnetic maps and profiles respectively. The terms whose effects dominate the low frequency portion of the spectrum are the same in both cases.

To estimate depths to the bottom of magnetic ensembles, we followed Boler's procedure (1978). This is, for an ensemble of finite magnetic sources, the relation between the frequency at which the spectral maximum occurs (in the low frequency portion of the spectrum) and the mean depth to the bottom is given by:

$$1/r_{max} = 1/(d - h)\ \mathrm{Ln}\,(d/h)$$

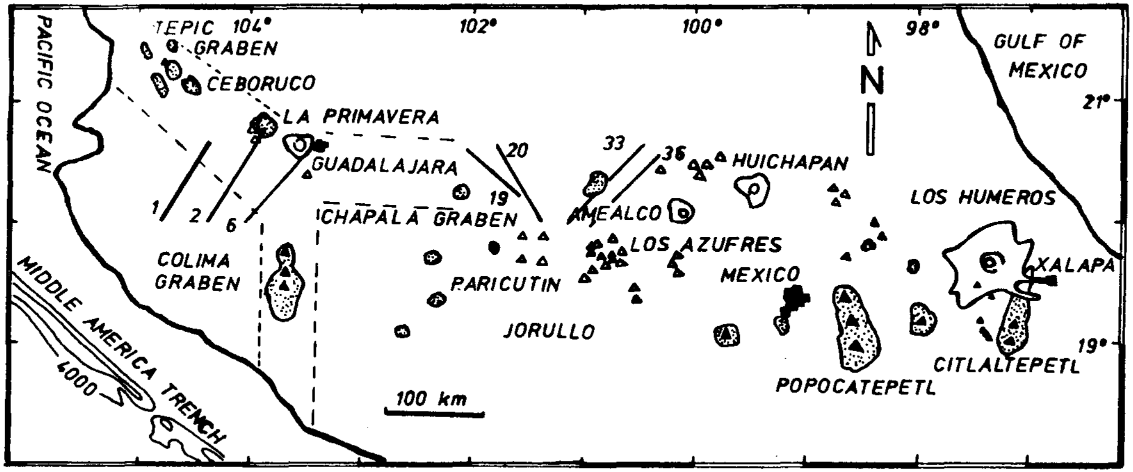

Fig. 1. Simplified regional geologic map of the Trans-Mexican Volcanic Belt, showing the main andesitic and silicic volcanic centers, as well as the location of the aeromagnetic profiles. Open triangles indicate outcroppings of rhyolitic rocks. Solid triangles and dotted patterns represent main andesitic stratovolcanoes. Subcircular concentric patterns represent major silicic calderas. Limits of grabens are indicated approximately by discontinuous lines.

where r_{max} is the frequency at which this maximum occurs, h and d are the mean depth to the top and bottom respectively. This relation is valid for aeromagnetic maps. However, since the factors shaping the low frequency portion of the spectrum have the same form in the profile case, this expression can also be used as a first approximation of the depth to the bottom of an ensemble of 2D magnetic bodies, *i.e.* in the profile case. As we will see later, the results obtained in this way agree fairly well with geology and heat flow data. Details of the procedure and a description of the aeromagnetic data analyzed have been included in Arroyo-Esquivel (1986).

The area of study corresponding to the western sector of the TMVB.

The seven regional aeromagnetic profiles analyzed by Arroyo-Esquivel (1986) to determine depths to the crystalline basement in this same area have been further examined in this work. The profiles are generally oriented perpendicularly to trends of major geologic structures. Table 1 summarizes the main characteristics of these aeromagnetic profiles. Profiles 1, 2 and 6 are located in the Tepic graben. The northeastern portion of profile 6 intersects a major silicic center: Sierra La Primavera. Profiles 19 and 20 are located to the NW of Cuitzeo lake. Profiles 33 and 36 are located to the E of Amealco caldera and to the N of Los Azufres caldera (two major silicic centers) (Fig. 1).

Table 1

Summary of main characteristics of the aeromagnetic profiles

Profile	Length (km)	Flight height (km/asl)	Mean topographic height (km/asl)	Geographic coordinates of extreme points			
				Longitude W	Latitude N	Longitude W	Latitude N
1	79.7	4	1.8	104°48.54′	20°03.19′	104°22.61′	20°39.03′
2	83.1	4	1.8	104°23.65′	20°00.00′	103°59.87′	20°38.86′
6	87.7	4	1.5	104°01.38′	20°00.22′	103°31.42′	20°38.75′
19	62.8	3	1.9	102°04.61′	20°36.33′	101°37.65′	20°13.21′
20	81.0	3	2.0	101°49.96′	20°37.65′	101°23.57′	20°00.00′
33	95.6	3	1.0	101°07.53′	20°00.00′	100°30.57′	20°39.41′
36	79.8	3	1.1	100°56.73′	20°01.65′	100°21.90′	20°28.95′

Table 2

Summary of estimations of the depth to the Curie point isotherm and respective thermal gradients and heat flow values T

Profile	Length (km)	$F_{r max}$ (cycles/km)	Depth to top (km)	Ground clearance (km a.s.l.)	Mean topographic height (km a.s.l.)	Depth to the Curie isotherm (km)	Thermal gradients based on Curie points of 580°C (°C/km)	300°C (°C/km)	Heat flow (mW/m²) K = 2.5 W/m °K 580°	300°
1	79.7	0.02	2.97	4.0	1.8	14.	39	20	97	50
			5.04			9.	59	30	147	75
			4.29			–	–	–	–	–
2	83.1	0.024	4.3	4.0	1.8	7.	77	40	192	100
		0.20	5.2			11.	52	27	130	67
		0.018				13.	42	22	106	55
						6.	95	49	237	122
						9.	62	32	155	80
						11.	49	25	122	62
6	87.7	0.0227	3.0	4.0	1.5	11.	49	25	122	62
		0.0172	4.4			18.	30	15	75	37
						9.	62	32	155	80
						14.	39	26	97	50
19	62.8	0.0318	2.25	3.0	1.9	14.	39	20	97	50
		0.0232	3.43			11.	52	26	130	65
20	81.0	0.0246	6.11	3.0	2.0	11.	51	26	127	65
		0.0185	4.4			14.	40	20	100	50
33	95.6	0.0313	5.21	3.0	1.0	5.	113	58	282	145
		0.0261	2.42			10.	55	20	137	70
36	79.8	0.0375	4.33	3.0	1.1	–	–	–	–	–
		0.0313	9.20			7.	79	41	197	102

RESULTS AND DISCUSSION

A regional-residual separation was done for each profile. It was assumed that the regional can be represented by a first order least squares polynomial. The resulting residuals were then interpolated to obtain sets of two equally spaced data points (m being a positive integer). Cubic spline functions were used (Albergh *et al.*, 1967; Campos-Enríquez *et al.*, 1983). The power spectrum was obtained by means of the Fast Fourier Transform (FFT) algorithm. Each of the seven profiles shows a well developed maximum in the low frequency portion of the spectrum. Results are summarized in Table 2. For each profile at least two different estimations were considered. Table 2 also presents the temperature gradients corresponding to Curie points of 300° and 580°C (maghemite and magnetite Curie points) (Haggerty, 1978). Corresponding heat flow values were computed for a thermal conductivity of k = 2.5 $Wm^{-1}C^{-1}$ given by Stacey (1977) as representative of igneous rocks. The Curie point isotherms for profiles 19 and 20 are located to a depth between 11 and 14 km. For profiles 33 and 36 the estimates indicate a shallower isotherm with a mean of 7 km. Inside the Tepic graben the isotherm lies at an intermediate depth, between 6 and 13 km.

The order of magnitude of the heat flow values obtained with a Curie point of 300°C are in agreement with direct heat flow measurements reported by Blackwell *et al.* (1977) and Ziagos *et al.* (1985). This Curie point corresponds to maghemite. Indeed, Haggerty (1976) reports that there is mounting evidence that stoichiometric magnetite is relatively rare.

The pattern delineated by these heat flow values seems to indicate the presence of two high heat flow areas, separated by a relatively low heat flow zone. One high heat flow area is located inside the Tepic graben, the other area is located to the west of Amealco caldera. The two structures are young. The Tepic graben is featured by recent and present day volcanism and forms part of a proposed incipient continental triple point (Luhr and Carmichael, 1981), while the Amealco caldera is a major silicic center, whose products rest on rocks dated radiometrically in 5 m.y. (Sánchez-Rubio, cited in Ferriz and Mahood, 1986), *i.e.* possibly underlain by several large high-level magma chambers.

Polyak *et al.* (1985) determined heat flow values in central Mexico based on the $^3He/^4He$ ratios in geothermal sites. An agreement between their determinations and the pattern here delineated is observed. For the Cuitzeo lake, Polyak *et al. (op. cit.)* report heat flows of 84.1 and 82 mW/m^2. They obtained a value of 81.4 mW/m^2 inside the Tepic graben, our inferred value is 80 mW/m^2. For Puruándiro (southern portion of profiles 19 and 20), they report a lower value of 78.9 mW/m^2, also in correspondence to our finding (65 mW/m^2). Geochemical studies (personal communication, Tello-Hinojosa, 1988) indicate that the thermalism present in the area of Puruándiro is associated to a deeper circulation of infiltration waters.

Equilibrium temperature prevailing in most of the hydrothermal systems in Mexico, has been systematically estimated by means of geothermometers (SiO_2, Na-K-Ca, etc.) by the geochemical studies group of CFE (Quijano and Chacón, 1982). Prol and Juárez (1985), based on this data base, elaborated a map showing the temperature pattern featuring the hydrothermal systems inside the TMVB. This map shows that low temperatures are associated to the hydrothermal systems of the Puruándiro area, in agreement with our results. A detailed 3-D cartography of the major features of the crystalline basement and of the Curie isotherm is under progress.

Table 3

Estimation of heat content between the surface and the Curie isotherm. A linear variation of temperature with depth and conductive heat transport were assumed.

Profile	Locality	Mean depth to the Curie isotherm (km)	Heat content ($\bar{Q}$ in megacal/cm^2)	Heat content per km^2 (GW_{y_t})
1		6	54.	71.
2	Tepic graben			
6		13	117.	154.
19		11	99.	131.
	Puruándiro			
20		14	126.	166.
33	North of Los Azufres and West of Amealco	7	63.	83.
36				

$\bar{Q} = \bar{Q}_{0\text{-}z_{t_e}} = c \int_0^{t_e} T\,dz$, where c is assumed constant and equal to 0.6 cal/cm^3 °C, T is the distribution, with depth (km), of the temperature (assumed linear).

GW_{y_t} = gigawatt-year (thermal) = 10 watt-year (thermal); 1 cal = 0.00116 watt-hour.

By integrating the temperature distribution by area and depth, an estimate of the heat content, based on conductive heat transport can be obtained (Diment *et al.*, 1975). The temperature distribution was assumed linear. Table 3 shows the heat contents obtained. In the Tepic graben and west of Amealco caldera, the energy stored in the first 7 km of the crust is about 75 GW_{y_t} per km^2. This figure represents an upper limit to the thermal energy stored in the crust between the surface and the Curie point isotherm, and serves primarily as a background value or upper limit for any discussion of geothermal energy in this area. This preliminary estimate, considered together with the thermal energy of convection, and igneous-related systems mainly constitute ,what is called the "resource base", the geothermal reserve being "the identified energy that can be extracted legally today at a cost competitive with other energy sources" (Muffler, 1981).

The depth estimates here reported are of a regional nature, *i.e.* they are mean depths. Therefore, inside the delineated high heat flow zones, the Curie point isotherm is expected to be located around this mean depth. Those places where the isotherm is shallower than the mean regional depth are interesting from the point of view of "hot dry rock" geothermal energy. Detailed thermometric studies (including direct heat flow measurements) are to be used to delimit hot dry rock geothermal prospects inside the high heat flow areas delineated.

CONCLUSIONS

Seven regional estimations of depths to the Curie point isotherm in the western sector to the TMVB are reported. These estimations are based on the spectral analysis of aeromagnetic profiles. The depths to the Curie point isotherm obtained correlate with the regional geology of the area. Average estimates of heat flow were inferred from these data. High heat flow values were found inside the Tepic graben and west of Amealco caldera. Both geologic structures are relatively young. The Tepic graben forms part of a proposed incipient continental triple point, whereas the Amealco caldera is a major silicic center, possibly still underlain by high level magma reservoirs. Between this two areas, relatively low heat flow values were inferred on the basis of the depths estimated. These results agree fairly well with heat flow estimations based on $^3He/^4He$ ratios of geothermal fluids and also with the general pattern featuring the equilibrium temperatures of hydrothermal systems in the TMVB.

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