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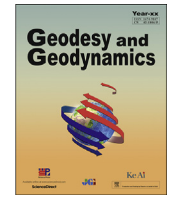

Depth to the bottom of magnetic layer in South America and its relationship to Curie isotherm, Moho depth and seismicity behavior

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A B S T R A C T

We have estimated the DBML (depth to the bottom of the magnetic layer) in South America from the inversion of magnetic anomaly data extracted from the EMAG2 grid. The results show that the DBML values, interpreted as the Curie isotherm, vary between ~10 and ~60 km. The deepest values (>~45) are mainly observed forming two anomalous zones in the central part of the Andes Cordillera. To the east of the Andes, in most of the stable cratonic area of South America, intermediate values (between ~25 and ~45 km) are predominant. The shallowest values (<~25 km) are present in northwestern corner of South America, southern Patagonia, and in a few sectors to the east of the Andes Cordillera. Based on these results, we estimated the heat flow variations along the study area and found a very good correlation with the DBML. Also striking is the observation that the thermal anomalies of low heat flow are closely related to segments of flat subduction, where the presence of a cold and thick subducting oceanic slab beneath the continent, with a virtual absence of hot mantle wedge, leads to a decrease in the heat transfer from the deeper parts of the system.

After comparing our results with the Moho depths reported by other authors, we have found that the Curie isotherm is deeper than Moho in most of the South American Platform (northward to ~20°S), which is located in the stable cratonic area at the east of the Andes. This is evidence that the lithospheric mantle here is magnetic and contributes to the long wavelength magnetic signal. Also, our results support the hypothesis that the Curie isotherm may be acting as a boundary above which most of the crustal seismicity is concentrated. Below this boundary the occurrence of seismic events decreases dramatically.

1. Introduction

Estimating the DBML (depth to the bottom of magnetic layer) is critical to constrain the temperatures in the crust and therefore the rheological behavior of the Earth's lithosphere and seismicity. Generally, the crust thermal structure has been determined from thermal data available, such as heat flow. Because the heat flow data come from relatively shallow depths and the measurements are geographically unevenly distributed, they are frequently not sufficient to define regional-scale thermal structures. In last decades, methods based on spectral analysis of magnetic anomalies have become a powerful tool for derivating the depth to the bottom of the magnetic layer [1–14]. These methods are based on the principle that short wavelength signals due to surface sources usually dominate the magnetic anomalies in the spatial domain, and to highlight the effect of the deepest sources these anomalies must be transformed to the Fourier domain and then its spectrum must be analyzed [15]. The use of regional magnetic databases allows the inference of the deepest discontinuities in the frequency domain [15].

The depth to the bottom of magnetic layer may represent the depth at which ferromagnetic minerals pass to a paramagnetic state, when they reach the Curie point temperature (Curie point

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depth-CPD, [16]) or the depth of a compositional change where magnetic rocks are replaced by non-magnetic rocks [14]. In the latter case, the extent in depth of the magnetic basement has been correlated with Moho discontinuity, since generally the mantle is considered to be non-magnetic [17,18]. However, several studies have argued that some magnetic phases may occur in upper mantle rocks in some geological environments [13,19–22]. In subduction systems, the DBML has been correlated with the boundary between the brittle and ductile crust regime, which is generally located in the 600 °C isotherm [23].

The thermal and crustal structure of South America is not fully understood and constrained at present. In recent years, there have been some studies that have tried to determine variations in the crust/lithosphere structure and thickness on a continental to local scale from seismological information [24–28] and gravity data [29–34]. With regard to the thermal structure, some contributions from Hamza and Muñoz [35], Springer and Förster [36], Springer [37], and Hamza et al. [38] have improved the knowledge about the regional heat flow in South America. Meanwhile, the current understanding about the DBML and its relation to the lithospheric thermal structure is even scarcer. The published papers about this topic are of local and regional nature and show results about the modeling of the CPD in Venezuela and Eastern Caribbean [39], northwestern corner of South America [40], and the thermomagnetic characteristics of the crust in central Brazil [41,42].

According to the above, the aim of this paper is to estimate the DBML in the South American continent, by applying three spectral methods to magnetic anomaly data extracted from the EMAG2 grid [43]. The results are interpreted taking into account the available data on thermal and rheological structure of the lithosphere along the study area. Also, the relationship between the DBML and other geophysical-geological constraints, like heat flow, Moho depth, gravity anomalies, and seismicity are discussed.

2. Geology and tectonics of the study zone

From the geologic and tectonic point of view, South America is a complex continent that is a product of the amalgamation of highly diverse morphotectonic provinces: Tectonically active Andean Cordillera in the west and north, the stable Precambrian South American Platform in the center and east, and the Late Paleozoic Patagonia province in the south [34,44,45] (Fig. 1).

The Brazilian shield and Patagonia province are known as the South American Platform [45]. According to van der Meijde et al. [34] this platform includes several cratonic blocks as the Guyana and Guapore Shields, located to the north and south of the Amazon basin, respectively, and known collectively as the Amazonian and São Francisco cratons. The Transbrasiliano lineament is an old lithospheric structure in the South American Platform and corresponds to 2000 km long, NE–SW oriented megasuture which is considered as the result of the collision between the Amazonia and the São Francisco cratons during Neoproterozoic times [34,52]; it is believed that this structure concentrates active seismicity [53]. Several large Paleozoic basins are included in the South American stable platform: Amazonas, Solimões, Parnaiba, Parana, and Chaco [33].

The South American arc extends for about 7000 km from southern Chile to the southern coast of Panama, and marks ~200 Ma of continuous subduction of the oceanic lithosphere of the Nazca plate beneath the South American continent [54,55] (Fig. 1). This subduction process is thought to be the responsible for the uplift of the Andes Cordillera and the volcanic arc building that is present along most of the continental margin. Nowadays, the Nazca plate moves eastward at a rate ranging between 74 mm/year (in the south) and 54 mm/year (in the north) with respect to the fixed South American plate [46,47], and in the coupling contact is oldest (~48 Ma) at ~20°S, decreasing in age to the south and north [33]. The seismicity of this subduction system is complex due to the variety of tectonic processes producing the deformation. In this sense, the crustal deformation and subsequent construction of the mountainous chains on the South American plate generates shallow earthquakes; on the other hand, slip along the inclined interface between the two plates generates large interplate earthquakes at depths between 10 and 60 km (see e.g. Ref. [46]). Seismic events also occur at depths greater than 600 km related to internal deformation processes in the subducting Nazca plate [46]. Throughout the Pacific margin of South America, the Nazca subduction zone is characterized by a highly changing geometry along the plate boundary strike, and several segments exhibiting flat subduction processes have been described, such as Ecuador, Nazca and Pampean segments [44,49,50,56,57] (Fig. 1). In the same way, along the Caribbean margin of South America there is another flat subduction area, known as Bucaramanga segment [56], where the oceanic Caribbean plate is going down beneath the South American plate at an average rate of 20 mm/year [47,58].

3. Data and methods

3.1. Magnetic anomalies data

The magnetic database used in this study (Fig. 2A) comes from the grid EMAG2 [43]. This model is a 2-arc-minute resolution global grid of magnetic intensity anomalies at 4 km elevation above the geoid compiled from satellite, ship, and airborne magnetic surveys. Also, the longest wavelengths (>330 km) have been replaced with the CHAMP satellite lithospheric magnetic field model MF6 [43]. According to Maus et al. [43], the high resolution and consistency of this grid allow a variety of geologic and tectonic applications, including global- and continental-scale mapping of the Curie point depth.

3.2. Spectral analysis of magnetic data

In order to estimate the DBML we made the inversion of the EMAG2 magnetic data by applying three different spectral methods: spectral peak method, centroid method, and forward modeling of the spectral peak method (Fig. 2B).

According to Ravat et al. [14], the first two have been the most commonly used methods in the spectral estimation of the DBML. The spectral peak method was originally proposed by Spector and Grant [1], whereas the centroid method was presented by Bhattacharyya and Leu [3]. The latter has undergone some variations in the work by Okubo et al. [6] and Tanaka et al. [9]. Spector and Grant [1] showed that the slopes of logarithms of Fourier spectra of magnetic anomalies are related to the depth to the top of the magnetic source, and that the spectra have peak positions on the frequency or wave number axis that are related to the thickness of the magnetic source layers. The corresponding equation is [14,59]:

$$|\boldsymbol{F}(k)|^2 = 4\pi^2 C_m^2 |\theta_m|^2 \left|\theta_f\right|^2 M_o^2 e^{-2|k|Z_t} \left(1 - e^{-|k|(Z_b - Z_t)}\right)^2 S^2(a,b) \quad (1)$$

where F is the Fourier power spectrum, k is wavenumber in cycles km^{-1} or 2π km^{-1}, θ_m is a factor related to magnetization direction, θ_f is a factor related to magnetic field direction, M_o is magnetization, Z_t and Z_b are the depths to the top and the bottom of the ensemble of magnetic sources, and $S^2(a,b)$ is the factor related to horizontal dimensions of sources.

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