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Magnetic characterization of retroarc extensional basin: The Loncopué Trough

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Abstract

The Loncopué Trough is a Pliocene to Quaternary extensional basin developed over the hinterland area of the Southern Central Andes. This basin is bounded by two neotectonic extensional fault systems delimiting a narrow topographic low. Previous studies have mostly focused on structural and geochemical aspects of this feature. However, geophysical surveys, aimed to unravel deep structure beneath a thick-younger than 5 My volcanic coverage, are scarce and based their interpretations on low resolution data sets. In this study, we collected new aeromagnetic data with the objective of characterizing the magnetic properties of the crust in the Loncopué Through and nearby zones. Additionally, we analyze the spatial relation between geological structures, volcanic fields and magnetic data. In order to highlight the boundaries of the magnetic sources and calculate the basement depth, we applied derivative techniques and the source parameter imaging. Also, we estimated an effective susceptibility model using the Magnetization Vector Inversion method, which takes into account the combined effects of remanence and induced magnetization. To determine the thermal structure of the area, we calculated the Curie depth points through the spectral analysis technique. From the analysis of magnetic data we were able to characterize the main structures and lineaments associated with this retroarc extensional trough. Notably, only the Loncopué eastern fault system seems to be a crustal-scale tectonic feature, while E-W-, ENE- and ESE-trending lineaments are interpreted as relatively minor structures segmenting the basement. Finally, our susceptibility model, together with the analysis of the Curie point, revealed potential magmatic/hydrothermal reservoirs in the Copahue volcano, and the Codihue and Cajón de Almanza regions that could be connected at depth forming a regional magmatic body.

Keywords: Loncopué Trough; Aeromagnetic data; Effect susceptibility model; Southern Central Andes; Magnetic characterization

1. Introduction

The Loncopué Through is one of the very few areas in the Andes where Pliocene-Quaternary retroarc extension has been documented (Folguera et al., 2006; Rojas Vera et al., 2014). This extensional basin is located in the Andean hinterland region between the Agrio Fold and Thrust Belt and the Main Andes, where oil industry and agricultural activities are mainly developed (Fig. 1). The Loncopué Trough, initially defined by Ramos (1978), constitutes a 200 km long topographic depression associated with broad basaltic and ignimbritic fields controlled by tectonically active basin boundaries.

In the last decades, a significant progress has been achieved in the analysis of the stratigraphy of the basin infill, magma sources and their geochemical signatures, surface structure and neotectonic activity (Ramos, 1978; Folguera et al., 2006, 2007; Rojas Vera et al., 2008; Folguera et al., 2010; Varekamp et al., 2010; Rojas Vera et al., 2010, 2014). However, fewer studies have been dedicated to characterize this extensional basin from a geophysical point of view. Initial geophysical surveys in the study area comprised gravity data, receiver function analysis and limited amounts of 2D seismic reflection data (Yuan et al., 2006; Folguera et al., 2007, 2010; Rojas Vera et al., 2010). These studies allowed the recognition of general lithospheric-scale and basin features associated with this basin, detecting synrift wedge geometries and an attenuated lower crust.

In this study, we use new aeromagnetic data with the aim to characterize the magnetic properties of the crust in the Loncopué Through and nearby zones and to investigate the relation between the structure, the volcanic fields and the magnetic anomalies. As the magnetic data are related to changes in magnetic susceptibilities and depths of their sources, different methods, based on the use of the magnetic field derivatives, have been developed to determine magnetic source parameters such as locations of boundaries and depths (Salem et al., 2007a).

In particular, the tilt angle derivative has been applied on the study region to highlight the boundaries of the magnetic sources. Also, the source parameter imaging was used to calculate the depth to the basement of the area. In order to highlight these susceptibilities contrasts, a 3D model was calculated using the Magnetic Vector Inversion method, which takes into account the combined effects of remanence and induced magnetization without a priori knowledge of the direction of the latter. This approach is helpful to unravel the first order geometry of geological bodies at depth (e.g. magmatic-hydrothermal reservoirs) as recently shown by (Paine et al., 2015) to the east of the study area in the Auca Mahuida shield volcano. Additionally, to understand the thermal structure of the Loncopué Through, we estimated the Curie depth points using the magnetic data based on the spectral analysis technique. The Curie temperature isotherm corresponds to the temperature at which magnetic minerals lose their ferromagnetism (approximately 580 ° C for magnetite). Thus, the Curie-temperature isotherm corresponds to the basal surface of the magnetic crust and can be calculated from the lowest wavenumber of the magnetic anomalies through the analysis of the power spectrum (Blakely, 1996; Tanaka et al., 1999).

2. Geologic Setting

The geological record of the Southern Central Andes where the study area is located is linked to the presence of marine to non-marine sedimentary sequences deposited during the Early Mesozoic extension and latest Jurassic to Cretaceous sag and synorogenic stages of the Neuquén Basin. Subsequent non-marine volcano-sedimentary deposition took place in (Eocene) Oligocene to Miocene times during a second extensional stage that affected the Andean hinterland zone in the proto-Loncopué Trough, depressing the Mesozoic and Paleozoic basement (Suarez and Emparan, 1995; Radic et al., 2002). The Mesozoic units are then exposed as extensional relicts to the east and west of the Loncopué Through axis in the Agrio and Malargüe Fold and Thrust Belts and Chilean Andean slope respectively (Fig. 2) (Zamora Valcarce et al., 2006; Rojas Vera et al., 2014). The Cenozoic units are mostly exposed over the Main Andes, west of the Loncopué Trough, through a thick-skinned west-vergent fold and thrust belt related to positive inversion of Paleogene extensional structures during the mid to late Miocene (Jordan et al., 2001; Radic, 2010; Rojas Vera et al., 2014).

The two contractional stages that took place in the Southern Central Andes, in Late Cretaceous-Eocene and Miocene times, acted in concert with significant eastward arc expansions which have been interpreted in terms of the shallowing of the subducted plate (Ramos and Folguera, 2005; Kay and Copeland, 2006). Particularly, the youngest arc expansion has been recently related to subduction of the Payenia mantle plume in Neogene times, which is currently impacting the Andean back arc region to the east of the study area (Gianni et al., 2017). This process would have ended in Pliocene times with a slab detachment and steepening of the subducting Nazca plate (Pesicek et al., 2012), the development of extension in the hinterland region of the Andes (Folguera et al., 2006; Rojas Vera et al., 2014) and contraction in the Andean foothills (e. g. Galland et al., 2007; Messager et al., 2010). From Pliocene to Quaternary times extensional activity related to the Loncopué Trough formed a narrow topographic depression between the volcanic arc to the west and the Agrio Fold and Thrust Belt to the east. The 200 km long trough is filled by 2 km of syn-extensional volcano-sedimentary successions of late Oligocene (?)-early Miocene to Quaternary age (Rojas Vera et al., 2014). The last syn-extensional volcanic stage started in the early Pliocene with wedge-like depocenters linked to extrusion of broad lava plateaux. This was followed by 2.6-2 Ma silicic volcanic sequences formed by ignimbrites and distal pyroclastic deposits associated with a series of caldera collapses. Two north-south main fault systems controlled these volcanic centers, being the latest Pliocene to Quaternary caldera systems aligned with the western structures and the Quaternary monogenetic basaltic fields to the east controlled by the eastern fault system, affecting the western sector of the Agrio Fold and

Thrust Belt (Fig. 2) (Rojas Vera et al., 2008, 2010). While the Loncopué Trough western fault system is inferred in map view, linked at the surface to local halfgrabens less than 100 m across associated with east-facing scarps affecting Quaternary lavas, the Loncopué Trough eastern fault system represents a series of west- and east-facing normal fault scarps affecting Quaternary lavas and previously deformed Mesozoic strata (Rojas Vera et al., 2014) (Fig. 2).

3. Methods

3.1. Magnetic data processing

Aeromagnetic data were collected by Carson Aerogravity over the Loncopué Trough and the western Agrio Fold and Thrust Belt during the years 2004 and 2005. Data were recorded along east-west oriented lines spaced 2 km apart and north-south control lines spaced 10 km apart, at an altitude of 1 km over the terrain with a resolution of 1 nT. The data are available in a total magnetic field grid, which is corrected by the diurnal variation and gridded by the minimum curvature method (Briggs, 1974) at 500 m cell size.

The magnetic anomaly map (Fig. 3-A) was calculated by removing from the total magnetic intensity map, the International Geomagnetic Reference Field (IGRF) at the acquisition date (Blakely, 1996).

3.1.1. Residual anomaly

In order to analyze the magnetic properties of the shallower portions of the crust, we calculated a residual anomaly map by removing the long-wavelength components of the magnetic anomaly which are linked to deeper magnetic sources. To do this, the Butterworth filter tool was applied in the frequency domain using different parameters and the interactive filtering module of the Geosoft Oasis Montaj software, which allows users to observe the application of the filter in real time.

To obtain the residual anomaly map, the Butterworth filter of 8th order and a wavelength of 40 km was applied (Fig. 3-B). The reason for choosing these parameters is to differentiate the geological structures of interest, such as the Copahue Volcano in the Agrio Caldera, the Cajón de Almanza and Codihue depocenters, the Loncopué Trough boundaries and the Agrio Fold and Thrust Belt structures.

3.1.2. Reduction to pole of the magnetic data

The dipole nature of the anomalies usually introduces some complexity to the interpretation of the different geological structures. Therefore, the usual process to remove or minimize the inclination effect is to transform the residual anomaly map into a reduction-to-the-pole map. The shape of a magnetic anomaly not only depends on the shape and susceptibility of the perturbing body, but also on the direction of its magnetization and the direction of the regional field. Therefore, the reduction-to-the-pole (RTP) operation is used for centering the anomaly above the causative body. RTP transformation is typically applied to the magnetic data to minimize the asymmetry caused by the non-vertical direction of magnetization (Baranov, 1957; Phillips, 2007), assuming that the remanent magnetism is small compared to the induced magnetism. In the study area, this assumption would be considered only valid if the remanent magnetization inclination/declination for the young Quaternary units would be similar to the induced field. Currently, there is no available data on the remanence in the area to directly test this hypothesis, but based on the young age of these rocks and considering that the magnetic field has not varied significantly since then, we consider that both vectors are similarly oriented.

In the present study, we applied this transformation to the residual magnetic anomalies adopting both inclination and declination values for the date of the survey (-38° and 6°) using Oasis Montaj software (Fig. 3-C).

3.2. Source parameter imaging

The interpretation of an anomalous magnetic response involves determining the parameters that characterize the source of the anomaly. Therefore, we used the source parameter imaging (SPI) to calculate the depth to the top of the magnetic sources (Thurston and Smith, 1997). SPI, also known as local wavenumber, is a parameter based on the extension of the complex analytic signal to estimate this depth (Thurston and Smith, 1997). For the magnetic field *T*, the local wavenumber is given by:

$$k\left(x,z\right)=\frac{\frac{\partial^2 T}{\partial x\partial z}\frac{\partial T}{\partial x}-\frac{\partial^2 T}{\partial x^2}\frac{\partial T}{\partial z}}{\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2} \quad (1)$$

where *x* and *z* are the Cartesian coordinates for the direction perpendicular to the strike and the vertical direction. For a dipping contact, the maxima of *k* are located directly over the isolated contact edges and are independent on the magnetic inclination, declination, dip, strike and remanent magnetization. Therefore, the depth is estimated from the reciprocal of the local wavenumber as:

$$Depth_{x=0}=\frac{1}{k_{max}} \qquad (2)$$

where k_{max} is the peak value of the local wavenumber *k* over the step source. In addition, the SPI method has two advantages (Thurston and Smith, 1997); one is that there is no dependence on the selected window size and the second is that it eliminates the errors caused by the survey lines.

In the practice, the method is used on gridded data by first estimating the strike direction at each grid point, and second computing the vertical gradient in the frequency domain and the horizontal derivatives in the direction perpendicular to the strike using the least-squares method (Thurston and Smith, 1997). Through the Oasis Montaj software, the SPI automatically estimated the depth of the magnetic sources (Fig. 4) using the gridded residual magnetic anomaly map (Fig. 3-B).

3.3. The tilt angle derivative

In order to highlight the edges of the structures hosted in the upper crust in the Loncopué Trough area and western Agrio Fold and Thrust Belt, we calculated the tilt angle derivative (TDR). This tool allows the enhancement of the edges and shapes of bodies that generate anomalous effects in the magnetic field, assuming a vertical contact model. TDR uses the horizontal and vertical gradients of the magnetic field, and does not require previous knowledge about the geometry.

Miller and Singh (1994) proposed the use of the tilt angle filter that was later developed by Salem et al. (2007a, b). This filter became widely used because of its fundamental and practical simplicity (Hinze et al., 2013). This filter is defined as:

$$TDR=tan^{-1}\left(\frac{\frac{\partial T}{\partial z}}{\left(\frac{\partial T}{\partial x}^{2}+\frac{\partial T}{\partial y}^{2}\right)^{1/2}}\right) \qquad (3)$$

where *T* is the magnitude of the anomalous total magnetic field and *x*, *y* and *z* are the horizontals and vertical directions. The zero contours are located close to the edges of the structures. Positive values are located directly above the sources, while negative values are located away from them.

This method was applied to the reduced-to-pole anomalies map (Fig. 3-C) in order to highlight edges and shapes of structures in the study area (Fig. 5).

3.4. Inverse modeling

In order to obtain a model of the susceptibility contrasts of the upper crust structures in the Loncopué Through and neighboring areas, we applied the Magnetization Vector Inversion (MVI) method developed by Ellis et al. (2012) only using the observed magnetic anomalies.

The magnetic field $\mathbf{B}$ at point $\vec{r}_j$ due to a volume *v*, containing a magnetization $\mathbf{M}(\vec{r})$, is given by:

$$\mathbf{B}(\vec{r}_j) = \nabla \int_v \mathbf{M}(\vec{r}) \cdot \nabla \frac{1}{|\vec{r} - \vec{r}_j|} dr^3 \qquad (4)$$

If the volume consists of a collection of N sub-volumes (v_k) each of constant magnetization m_k then:

$$B_i(\vec{r}_j) = \sum_{k,l}^{N,3} m_{k,l} \int_{v_k} \partial_l \, \partial_i \frac{1}{|\vec{r} - \vec{r}_j|} dr^3 \qquad (5)$$

Eq. (5) can be represented as:

$$\mathbf{B} = \mathbf{G}\,\mathbf{m} \qquad (6)$$

Therefore, the Magnetization Vector Inversion problem is based on the solution of Eq. (6) for $\mathbf{m}$ when $\mathbf{B}$ is given. To solve this inverse problem, it is necessary to summit $\mathbf{B}$ to a regularization conditions. MVI applies the Tikhonov minimum gradient regularization (Aisengar, 2015), which solves $\mathbf{M}$ minimizing the distance of the calculated and measured magnetic field in the minimum square sense.

The main task in the solution of inverse magnetic problems is to determine the spatial distribution of the magnetic susceptibility (χ), which is related to the magnetization ($\mathbf{M}$) by:

$$\mathbf{M} = \chi \mathbf{H}_e \qquad (7)$$

where $\mathbf{H}_e$ is the external magnetic field.

The MVI algorithm considers the anisotropic nature of the magnetic susceptibility as a 3D vector. Thus, Eq. (7) is rewritten as:

$$\mathbf{M} = \boldsymbol{\chi} |H_e| \qquad (8)$$

The algorithm also considers the normal remanent magnetization ($\mathbf{M}_{NRM}$), which is represented as a component in effective magnetization ($\mathbf{M}_{eff}$) and it is proportional to the external magnetic field as:

$$\mathbf{M}_{eff} = \mathbf{M} + \mathbf{M}_{NRM} = \boldsymbol{\chi}|H_e| + \boldsymbol{\chi}_{NRM}|H_e| = \boldsymbol{\chi}_{eff}|H_e| \qquad (9)$$

where $\boldsymbol{\chi}_{NRM}$ is a pseudo magnetic susceptibility caused by the normal remanent magnetization and $\boldsymbol{\chi}_{eff}$ is the effective susceptibility (anisotropic + remanent).

In this work, the MVI technique was applied to the residual magnetic anomaly data (Fig. 3-B) to obtain an effective susceptibility cube (Fig. 6) using VOXI Earth Modeling from Geosoft. The cells in the mesh, each measured $500 \times 500 \times 250$ m, and the data were inverted subjected to a uniform uncertainty of 15 nT (5% of the data range). Due to the lack of specific remanent magnetization intensity and directional measurements within the area, it was not possible to build specific observation-based geological constraints.

3.5. Curie point depth

In order to understand the thermal structure of the Loncopué Through, we applied the spectral analysis on the magnetic anomaly grid, from which the depth of the Curie Isotherm can be determined using the Tanaka et al. (1999) method.

The Curie isotherm corresponds to the temperature at which the magnetic sources lose their ferromagnetism (approximately 580° C for magnetite), thus they become essentially nonmagnetic (Blakely, 1996; Ross et al., 2006). The depth at which this process takes place is known as Curie point depth. Below this depth, ferromagnetic rocks become paramagnetic and their ability to generate detectable magnetic anomalies disappears. The technique used to estimate the Curie point depth of the magnetic sources is based on the statistical analysis of the magnetic anomalies in frequency domain. The magnetized basement can be simulated by a horizontal semi-infinite plate, whose top, bottom and centroid are found at depths of Z_t , Z_b and Z_c , respectively. If its magnetization is a random function of the horizontal directions and uncorrelated, the depths of the top (Z_t) and the centroid (Z_c) of the magnetic basement are determined from the power-density spectra of the total field anomaly (Blakely, 1996; Tanaka et al., 1999).

Following Tanaka et al. (1999), the bottom of the plate is determined as: $Z_b = 2Z_c - Z_t$, where Z_t and Z_c are related to the power-density spectra of the magnetic anomalies by Eq. (10) and (11). For wavelengths less than about twice the thickness of the layer:

$$\ln[\Phi_{\Delta T}(|k|)^{1/2}] = \ln(A) - |k|Z_t \qquad (10)$$

and, for long wavelengths:

$$\ln\left[\frac{\Phi_{\Delta T}(|k|)^{1/2}}{|k|}\right] = \ln(B) - |k|Z_c \qquad (11)$$

where $\Phi_{\Delta T}(|k|)$ is the power-density spectra of magnetic anomalies, *k* is the wavenumber and *A* and *B* are constants related to magnetic masses.

The depths of the top and the centroid (Z_t and Z_c) are estimated by fitting a straight line through the high and low wavenumber parts from the respective logarithms of the radially averaged spectrum. The obtained bottom depth (Z_b) of the magnetic basement is assumed to be the Curie point depth, which reflects the average value of the area.

To determine the Curie point depth for the study area (Fig. 7), we used the CuDePy program, which was developed by Soler (2015) in the Instituto Geofísico-Sismológico Volponi (IGSV). This program allows making an interactive selection of square sub-regions of the magnetic anomaly grid and calculates the power spectrum using the Eq. (10) and (11) to determine a Curie point depth in each sub-region. Fig. 8 shows an example of the implementation of this program. The size of the sub-regions to calculate the Curie point depth was chosen between 30 and 40 km.

4. Interpretation of the results

The magnetic anomaly map (Fig. 3-A) displays a range of values from -418 nT to 116 nT that decreases from the northeast to the southwest. It reveals two magnetic domains: N-NE parts of the study area, with maximum intensity between -125 nT to 116 nT; and the other on the S-SW with minimum values between -418 nT to -170 nT. In the central-western part of the map, there is a large dipolar anomaly, located above the Agrio Caldera and Copahue Volcano. In addition, the residual anomaly map (Fig. 3-B) has a range of values from -120 nT to 175 nT and shows the anomalies limited to the upper crust.

The reduction to the pole of the residual magnetic anomalies (RTP) is shown in Fig. 3-C, assuming that the entire observed magnetic field is due to the induced magnetic effects. Therefore, the RTP map (Fig. 3-C) is considered as an auxiliary map for interpretation in order to analyze the correspondence between the anomalies and the geological structures of the area. This map (Fig. 3-C) displays that some anomalies are symmetric and centered over their causative structures, therefore, their dipolar nature was successfully removed/minimized by the RTP transformation. This may be due to that the near surface rocks and structural features are young enough and probably formed under the same magnetic inclination/declination of the core field. These anomalies are located on the Agrio Caldera, Mandolegüe Cordillera, Cajón de Almanza and Codihue depocenters areas. On the contrary, Fig. 3-C shows that a negative-positive magnetic effect persists in other areas, which may be indicative of the presence of remanent magnetization in certain regions such as the Copahue Pino-Hachado Block, in the Loncopué Trough and the Ranku-Lom depocenter.

The total magnetic anomaly, the residual anomaly and reduced-to-pole maps (Fig. 3) display positive values in the volcano-tectonic depression of the Agrio Caldera (next to the Copahue Volcano) and through different regions such as the Agua Fría, Cajón de Almanza and Codihue. Noteworthy, they also show a strong E-W gradient that coincides at surface with the Loncopué Trough eastern fault system (Fig. 3). In addition, some magnetic domains seem to be segmented by structures that correlate with E-W-, ENE- and ESE-trending lineaments at surface (white dashed lines in Fig. 3).

The estimated depths of the top of the magnetic sources using the source parameter imaging (SPI) method are presented in Fig. 4. Deeper values can be found in the region of the Agrio Caldera-Copahue Volcano (-2900 m), in the northern part of Loncopué Trough (-3900 m) and in the Cajón de Almanza (-3000 m) and Agua Fría (-3900 m) depocenters. However, shallower values (-1600 m deep) are found in the southern Loncopué Trough, towards the east of the Agrio Fold and Thrust Belt and in the Mandolegüe Cordillera.

The result of the tilt derivative (Fig. 5) can be analyzed by following the zero isoline, which enhances geological structures. This map highlights the edges of the Agrio Caldera, Codihue and Cajón de Almanza depocenters, the Loncopué Trough eastern fault system and the Copahue-Pino Hachado Block. Fig. 5 also shows a predominant SW-NE direction on the western region of the map and a N-S direction on the eastern region.

The effective susceptibility model obtained with the MVI technique is shown in Fig. 6. In this figure we show different views and horizontal slices of the model at variable depths. The model has a range of values from $\chi = 0.002$ SI to $\chi = 0.01$ SI and a maximum depth of 12 km, where the highest effective susceptibility values are located below the region of the Agrio Caldera-Copahue Volcano and Codihue and Cajón de Almanza depocenters. The resulting model shows that the above mentioned regions are apparently connected at depth. Fig. 6 also exhibits that these anomalies get compartmentalized at upper structural levels decreasing in size, and being finally circumscribed to the known volcanic fields. Finally, the depths calculated by the inversion model and the SPI for the structures mentioned above are similar (Fig. 4 and 6). In addition, they can be correlated to depths found in Mamaní et al. (2000) through magnetotelluric sounding, in the Copahue and Caviahue towns surroundings, to low resistivity values between 9 to 20 km depth, which have been associated with the magma chamber of the Agrio Caldera.

The determination of the Curie isotherm was performed indirectly from the magnetic anomalies using variable windows (30-40 km). The depths Z_t and Z_c corresponding to the center of each window, were determined to estimate the Z_b, which is linked with the depths of the Curie isotherm. Fig. 7 presents the results of the Z_b over the RTP map obtained for each analyzed point with an average error of 1.6 km. The minimum depths are found in the Agrio Caldera-Copahue Volcano region (approx. 8 km) and the Codihue and Cajón de Almanza depocenters region (approx. 9 km), with an average depth of 8 km, while in the surrounding areas the average depth is 11 km. These results imply relatively higher heat flows in these zones with respect to neighboring areas. Additionally, the Curie point depths obtained in the study area are relatively similar to the values obtained by Li et al. (2017) by a robust inversion algorithm and the Earth Magnetic Anomaly Grid of 2-arc-minute resolution (Maus et al., 2009). These authors calculated Curie point depth values ranging between 11 and 15 km in the study area.

5. Discussion and Conclusions

Results obtained from the residual anomaly and the reduced to the pole maps (Fig. 3) show positive magnetic responses in structures neighboring the Loncopué Through such as the Mandolegüe Cordillera, Agrio Caldera and Copahue Volcano, Copahue-Pino Hachado Block, Codihue and Cajón de Almanza depocenters and Agrio Fold and Thrust Belt, which had been barely identified in gravimetric studies (Rojas Vera et al., 2010). Contrastingly, negative anomalies are present in the area of the Loncopué Trough which could be associated with different sedimentary depocenters infills.

Magnetic data show that only the eastern boundary of the through, the Loncopué Trough eastern fault system, has a significant crustal expression, while the Loncopué Trough western fault system is not evidenced by magnetic anomalies. Additionally, E-W-, ENE- and ESE-trending lineaments interpreted at surface affect the basement of the Loncopué Through and surrounding regions. These are interpreted as reactivated transfer zones linked to the Mesozoic depocenters of the Neuquén Basin (Rojas Vera et al., 2014).

The positive response of the magnetic data in the area of Agrio Caldera-Copahue Volcano and Copahue-Pino Hachado Block could be associated with surficial volcanic and volcaniclastic deposits (Rojas Vera et al., 2010). In addition, these anomalies could be linked with a higher concentration of monogenetic volcanic centers in these areas (García et al., 2007; Blanco-Montenegro et al., 2011; López–Loera et al., 2011; Delgado, 2012; Anci et al., 2016). Other positive anomalies present in the volcanic fields such as the Codihue and Cajón de Almanza depocenters could be also associated with surficial and sub-surficial volcanic products (Rojas Vera et al., 2010).

As already mentioned, in the study area, there are no available measurements of susceptibility and remanence. Therefore, the effective susceptibility model obtained by the MVI method (Fig. 6), presented in this study, constitutes the only information of these characteristics in the study area.

This effective susceptibility model (Fig. 6) shows that the regions of the Agrio Caldera (Copahue Volcano), Codihue and Cajón de Almanza depocenters have the highest susceptibility values in the study area. The Agrio Caldera (Copahue Volcano) is an active volcanic zone, whereas the Codihue and Cajón de Almanza areas have abundant surficial evidence of Pleistocene (Holocene?) volcanic eruptions (Rojas Vera et al., 2008, 2010) but not documented historical eruptions. These observations, along with the presence of similar values of susceptibility, the positive magnetic response and the shallow depth of Curie isotherm in these regions lead us to interpret that the Codihue and Cajón de Almanza volcanic fields could potentially be emplaced over magmatic-hydrothermal active reservoirs. Moreover, and more speculatively, according to our model, these reservoirs could be connected at depth.

Quaternary extensional and volcanic activity in the Loncopué Trough (Rojas Vera et al., 2010) and potential magmatic reservoirs at depth identified in this work are consistent with the asthenospheric upwelling linked to the Nazca slab tearing described through a seismic tomography survey by Pesicek et al. (2012). Even though the study region is occupied by broad monogenetic basaltic fields and calderas associated with ignimbritic plateaux, some of them with recognized Holocene activity, no historical eruptions have been described associated with any of these vents, with the only exceptions of the active Copahue Volcano which is part of the arc front and the neighbor Huecú volcanic field, where Mapuche's chronicles documented recent activity (Rojas Vera et al., 2008, 2010). However, magnetic data analyzed in this work allow interpreting some of these poorly known volcanic fields as potentially active since these would be connected with hydrothermal and/or magmatic reservoirs in the upper crust. Thus, even though this linkage is clear for the Agrio Caldera where the Copahue Volcano is hosted, it could also be suggested for the Cajón de Almanza and Codihue depocenters regions, where no eruptions were registered historically.

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Figure 1: Tectonic setting of the Southern Central Andes showing the Loncopué Trough in a retroarc position in the Andean hinterland area. Abbreviation is: LOFZ: Liquiñe-Ofqui fault zone.

Figure 2: Simplified geological and structural map of the Loncopué Trough and the western Agrio Fold and Thrust Belt (modified from Rojas Vera et al. (2010). The location of the study area is interposed between the Agrio Fold and Thrust Belt and the Main Andes, representing an active

retroarc basin associated with widespread volcanic eruptions. The locations of the monogenic retroarc volcanic centers were taken from Garcia Morabito and Folguera (2005) and Folguera et al. (2010).

Figure 3: A) Magnetic anomaly. B) Residual anomaly obtained with the Butterworth filter of 8th order and a wavelength of 40 km. C) Reduced to the pole anomaly map. The black triangle is the position of the Copahue Volcano. Abbreviation: AC: Agrio Caldera; RLD: Ranku-Lom depocenter; AFD: Agua Fría depocenter; CMD: Cerro Mocho depocenter; CAD: Cajón de Almanza depocenter; LD: Las Lajas depocenter; CD: Codihue depocenter; LT: Loncopué Trough.

Figure 4: Depth to magnetic basement, calculated using the source parameter imaging technique. The black triangle is the position of the Copahue Volcano. Abbreviation: AC: Agrio Caldera; RLD: Ranku-Lom depocenter; AFD: Agua Fría depocenter; CMD: Cerro Mocho depocenter; CAD: Cajón de Almanza depocenter; LD: Las Lajas depocenter; CD: Codihue depocenter; LT: Loncopué Trough.

Figure 5: Application of the tilt angle derivative on the reduction-to-pole residual anomalies map. Zero contours (black color) indicate the location of the magnetic sources edges. The black triangle is the position of the Copahue Volcano. Abbreviation: AC: Agrio Caldera; RLD: Ranku-Lom depocenter; AFD: Agua Fría depocenter; CMD: Cerro Mocho depocenter; CAD: Cajón de Almanza depocenter; LD: Las Lajas depocenter; CD: Codihue depocenter; LT: Loncopué Trough.

Figure 6: Magnetic inversion map from the residual magnetic anomaly map using the Magnetization Vector Inversion method. A) Magnetic inversion model with and without topographic map (ETOPO1, Amante and Eakins (2009)). B) Lateral view of the model slices at the middle and in the bottom of the vertical axis.

Figure 7: Determination of the Curie Depth Point (DCP) in kilometers. The black numbers indicate the center of the window where the DCP was determined with an average error of 1.6 km. The CDP is plotted over the reduced to the pole anomaly map. The black triangle is the position of the Copahue Volcano. Abbreviation: AC: Agrio Caldera; RLD: Ranku-Lom depocenter; AFD: Agua Fría depocenter; CMD: Cerro Mocho depocenter; CAD: Cajón de Almanza depocenter; LD: Las Lajas depocenter; CD: Codihue depocenter; LT: Loncopué Trough.

Figure 8: Example of a power spectrum of a variable window from the magnetic anomaly data (Fig. 3-A) calculated using CuDePy software (Soler, 2015); applying Eq. (10) for wavelengths less than about twice the thickness of the layer and Eq. (11) for long wavelengths.

Highlights

- We study the Loncopué trough a Pliocene to Quaternary extensional basin
- We analyze aeromagnetic data and we apply different processing techniques
- We calculate an effective susceptibility model by an inversion method
- The results show the existence of previously unknown magmatic/hydrothermal reservoirs
- This is compatible with slab tearing hypotheses and plume upwelling