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Long-lived crustal damage zones associated with fault intersections in the high Andes of Central Chile

Zonas de daño cortical de larga vida, asociadas con intersecciones estructurales en los altos Andes de Chile central.

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Abstract:

Long-lived, high-angle fault systems constitute high-permeability zones that can localize the upward flow of hydrothermal fluids and magma throughout the upper crust. Intersections of these types of structures can develop complex interference patterns, which constitute volumes of damaged rock (networks of small-scale faults and fractures) where permeability may be significantly enhanced. This is relevant for understanding regional-scale structural controls on the emplacement of hydrothermal mineral deposits and volcanic centers, and also on the distribution of areas of active upper-crustal seismicity. In the high Andes of central Chile, regional-scale geophysical (magnetic, gravimetric, seismic) and structural datasets demonstrate that the architecture of this Andean segment is defined by NW- and NE-striking fault systems, oblique to the N-S trend of the magmatic arc. Fault systems with the same orientations are well developed in the basement of the Andes. The intersections of conjugate arc-oblique faults constitute the site of emplacement of Neogene intrusive complexes and giant porphyry Cu-Mo deposits, and define the location of major clusters of upper- crustal earthquakes and active volcanic centers, suggesting that these fault systems are still being reactivated under the current stress regime. A proper identification of one-dimensional, lithospheric-scale high-permeability zones located at the intersections of high-angle, arc-transverse fault systems could be the key to understanding problems such as the structural controls on magmatic and hydrothermal activity and the patterns of upper-crustal seismicity in the high Andes and similar orogenic belts.

Keywords: Basement fault intersections, Magma and hydrothermal fluid flow, Central Chile..

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Resumen:

Los sistemas de falla de alto ángulo y de larga vida constituyen zonas de alta permeabilidad que pueden focalizar el flujo ascendente de fluidos hidrotermales y magma a través de la corteza superior. La intersección de estructuras de este tipo involucra el desarrollo de patrones de interferencia complejos, que constituyen volúmenes de roca dañada (redes de fallas y fracturas de pequeña escala) en las cuales la permeabilidad está particularmente incrementada. Esto es relevante para la comprensión tanto del control estructural regional sobre el emplazamiento de depósitos minerales y centros volcánicos, como de la distribución de áreas de sismicidad cortical activa. En los Andes de Chile central, estudios geofísicos de escala regional (magnetismo, gravimetría, sismicidad) y datos estructurales demuestran que la arquitectura de este segmento andino está definida por sistemas de falla con rumbos NW y NE, oblicuas al eje N-S del arco magmático. Sistemas de falla de la misma orientación están bien desarrollados en el basamento andino. La intersección de fallas conjugadas oblicuas al arco constituye el sitio de emplazamiento de complejos intrusivos neógenos y de pórfidos de Cu-Mo gigantes, y define la ubicación de agrupaciones mayores de sismos corticales y de centros volcánicos activos, lo cual sugiere que estos sistemas de falla continúan siendo reactivados bajo el régimen de esfuerzos actual. Una adecuada identificación de zonas unidimensionales de alta permeabilidad y de escala litosférica, ubicadas en la intersección de sistemas de falla de alto ángulo oblicuos al arco, puede ser clave para la comprensión de problemas como el control estructural de la actividad magmática e hidrotermal y los patrones de sismicidad cortical en los Andes y otros cinturones orogénicos similares.

Palabras clave: Intersección de fallas de basamento, Flujo de magmas y fluidos hidrotermales, Chile central.

1 Introduction

Major high-angle fault systems, under favorable combinations of fluid pressure and orientation relative to the prevailing stress tensor, can act as pathways for both magmas and hydrothermal fluids to rise through the crust, enabling them to control the location of different types of mineral deposits (*e.g.,* Tosdal and Richards, 2001; Sillitoe, 2003; Amilibia *et al.,* 2008; McCuaig and Hronsky, 2014) and volcanic systems (*e.g.,* Cembrano and Lara, 2009; Tibaldi *et al.,*2017). Moreover, intersecting conjugate faults develop complex interference patterns characterized by fracturing and the growth of subsidiary faults, creating one-dimensional, highly-permeable damage zones (Horsfield, 1980; Hodgson, 1989; Schwarz and Kilfitt, 2008). However, there are several mineral districts or belts where the emplacement of magmatic-hydrothermal centers is not related to any obvious, major fault system (*e.g.,* Perelló *et al.,* 2003; Sillitoe and Perelló, 2005; Mpodozis and Cornejo, 2012; Leveille and Stegen, 2012), posing an important challenge for the development of conceptual exploration models. The Mio-Pliocene metallogenic belt of the high Andes of central Chile is one such example (*e.g.,* Mpodozis and Cornejo, 2012). It contains the world's largest exploitable concentrations of Cu and Mo in two giant porphyry copper deposits: Río Blanco-Los Bronces and El Teniente (*e.g.,* Sillitoe, 2010). The ore deposits are hosted by Cenozoic volcanic and intrusive rocks, which define a late Eocene to early Pliocene magmatic arc characterized by the opening and subsequent inversion of the intra-arc Abanico Basin (Godoy *et al.,* 1999; Charrier *et al.,* 2002). The volcanic stratigraphy has traditionally been divided into four main successions (Fig. 1): the northern part of the belt is characterized by the syn-extensional Abanico Formation (late Eocene to early Miocene) and the syn-inversion Farellones Formation (early to late Miocene; Aguirre, 1960; Klohn, 1960; Charrier *et al.,*2002; Piquer *et al.,* 2017), while to the south most of the high Andes of central Chile are composed of the syn-extensional Coya-Machalí Formation (early to middle Miocene; Klohn, 1960; Piquer *et al.,* 2017) and the syn-inversion Teniente Volcanic Complex (middle to late Miocene; Godoy, 1993; Kay *et al.,* 2005; Piquer *et al.,* 2017).

Segments of the inverted basin-margin faults have been documented (Charrier *et al.,* 2002; Fuentes *et al.,* 2002; Fock, 2005; Farías *et al.,* 2010), and the internal architecture of the inverted basin was refined by Piquer *et al.* (2016). While the inverted basin-margin faults correspond to segmented, N-striking faults parallel to the continental margin, the faults controlling the internal segmentation of the inverted basin are oblique to the axis of the magmatic arc (Fig. 1), their surface expression is less evident and have been interpreted as basement faults reactivated during the Cenozoic (Piquer *et al.,* 2016). Most of the syn-inversion plutonic bodies (early to late Miocene) and in particular the mineral deposits and their associated subvolcanic complexes (late Miocene-early Pliocene) were emplaced in the central part of the inverted basin (Fig. 1); consequently, understanding the relationships between magmatism, hydrothermal activity and large-scale fault systems within the inverted basin is of critical importance. Here we use recently-acquired and pre-existing geophysical datasets, including upper-crustal seismicity and regional-scale gravimetry and magnetometry, to complement the structural data presented by Piquer *et al.* (2016) and new field data collected during 2016-2017. The combination of these independent datasets allows us to propose a regional-scale structural model which can explain the distribution of porphyry Cu-Mo deposits, active volcanoes, upper- crustal seismicity, and the regional-scale patterns observed in gravimetric and magnetic maps. The proposed structural model has implications for the interpretation of structural controls on magmatism in other segments of the high Andes, as well as in other active or fossil orogenic belts globally.

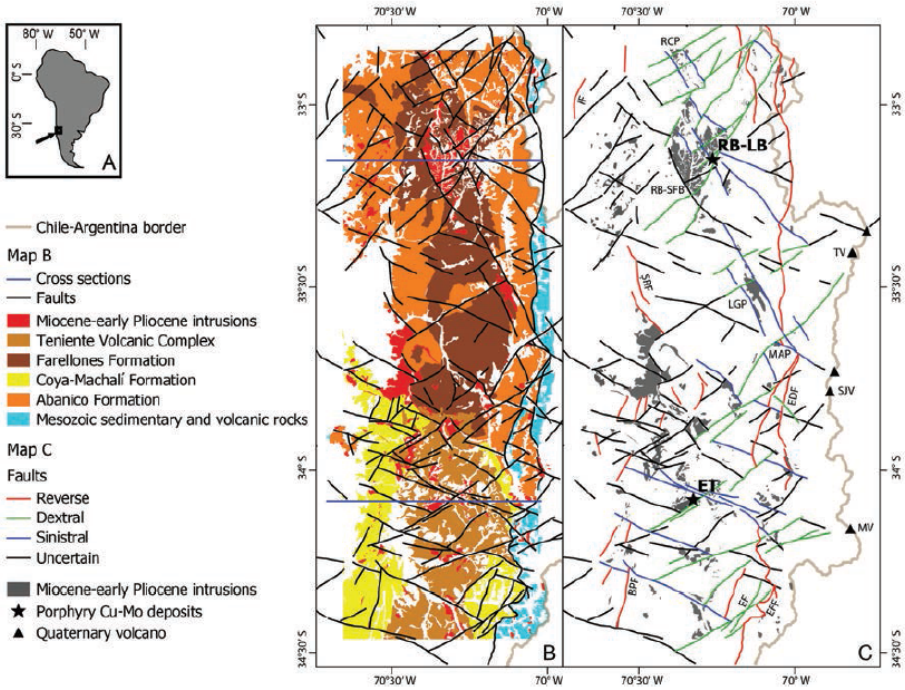

FIG. 1
A. Location of the study area in South America. B. Geology of the Andes of central Chile, based on Rivera and Cembrano (2000), SERNAGEOMIN (2002), Fuentes et al. (2004), Fock (2005) and this work. Quaternary sediments and volcanic deposits not shown. C. Main arc-oblique and arc-parallel fault systems, interpreted from mapped faults shown in B. Each fault system is colored according to its predominant sense of movement during the Miocene-early Pliocene. The figure also illustrates the correlation between the structural architecture of the inverted Abanico Basin, the emplacement of Mio-Pliocene plutons and mineral deposits and the location of active volcanoes. RB-LB: Río Blanco-Los Bronces; ET: El Teniente; RCP: Río Colorado pluton; RB-SFB: Río Blanco-San Francisco batholith; LGP: La Gloria pluton; MAP: Meson Alto pluton; TV: Tupungatito Volcano; SJV: San José Volcano; MV: Maipo Volcano; IF: Infiernillo fault; SRF: San Ramón fault; EDF: El Diablo fault; BPF: Barahona-Perales fault system; EF: Espinoza fault; EFF: El Fierro fault.

2 Structural geology of the High Andes of Central Chile

Structural mapping of this Andean segment shows that within the inverted Abanico Basin, faults show preferred NW and NE strikes (±25°; Fig. 1). Stratigraphic correlation across major faults indicates up to several hundred meters of normal displacement, with evidence of syn-tectonic deposition of the volcanic sequences (Piquer *et al.,* 2015). Normal faulting has affected late Eocene-Oligocene rocks of the Abanico Formation (Fig. 2A) and locally early Miocene rocks of the lower part of the Farellones Formation (*e.g.,* Fig. 2B), suggesting that the first pulse of deformation, responsible for widespread progressive unconformities found between the Abanico and Farellones Formations, was followed by a period of renewed extension, at least locally. However, kinematic indicators in individual fault planes, given by syn-tectonic hydrothermal minerals, commonly show strike-slip movements with variable amounts of reverse component (Fig. 2C; Piquer *et al.,* 2016), indicating that several normal faults were subsequently reactivated with kinematics consistent with broadly E-directed compression (Piquer *et al.,* 2016). Consistently, sense of movement is preferably dextral in NE faults and sinistral in NW faults (Fig. 2C). The strike-slip displacement is small, usually on the order of meters to tens of meters for an individual fault. The syn-tectonic hydrothermal minerals used as kinematic indicators (fault steps in epidote, tourmaline, quartz, calcite, chlorite, biotite and muscovite; Piquer *et al.,* 2016; Fig. 2C) form part of different hydrothermal systems with a total age range of 14 to 4 Ma (Maksaev *et al.,* 2004; Toro *et al.,* 2012; Deckart *et al.,* 2013; Piquer *et al.,* 2016), thus constraining the age of fault reactivation.

The Cenozoic kinematic evolution of arc-oblique fault systems described involved transtensional deformation during the late Eocene-early Miocene, and transpressional faulting during the middle Miocene-early Pliocene. This is consistent with previous interpretations of the kinematic history of arc-parallel (broadly N-striking) basin-margin faults, such as the El Fierro, Espinoza and El Diablo faults which define the eastern basin margin (Charrier *et al.,* 2002; Fock, 2005; Piquer *et al.,* 2010) and the San Ramón, Infiernillo and Barahona-Perales faults, defining the western margin (Fuentes *et al.,* 2002; Fock, 2005; Rivera, 2017). In all of the previous cases, authors have interpreted an early (Paleogene) normal fault movement, indicated by syn-extensional growth strata and stratigraphic correlations, while a later (Neogene) reactivation in reverse mode is indicated by drag folds and syn-compression growth strata observed in fault-related folds.

In the eastern part of the inverted Abanico Basin, NW- and SW-dipping, arc-oblique faults commonly bound structural blocks with contrasting deformation styles (Fig. 2B, D, E). Towards the central part of the former basin, the hanging wall blocks contain younger, mostly flat-lying rocks that have been affected by local ramp-flat thrusts (*e.g.,* Piquer *et al.,* 2015). Towards the east, in turn, the footwall Cenozoic volcanic rocks are older and tightly folded. They have been affected by the thin-skinned deformation which characterizes the Aconcagua fold and thrust belt on the eastern flank of the Andes in Argentina (*e.g.,* Giambiagi *et al.,* 2003).

Major oblique structures are intimately related with the location and geometry of Miocene-early Pliocene intrusive bodies (Fig. 1C). Plutons were emplaced along major fault systems, and the individual plutonic facies are either strongly elongated with their major axis following the fault trend, or have rhombic shapes with their margins defined by intersecting NW- and NE-striking faults (Fig. 1C). In particular, the two porphyry copper deposits contained in this segment were emplaced at the intersections of NW- and NE-striking fault systems, acting as conjugate faults at the moment of mineral deposit emplacement (Fig. 1C; Piquer *et al.,* 2016).

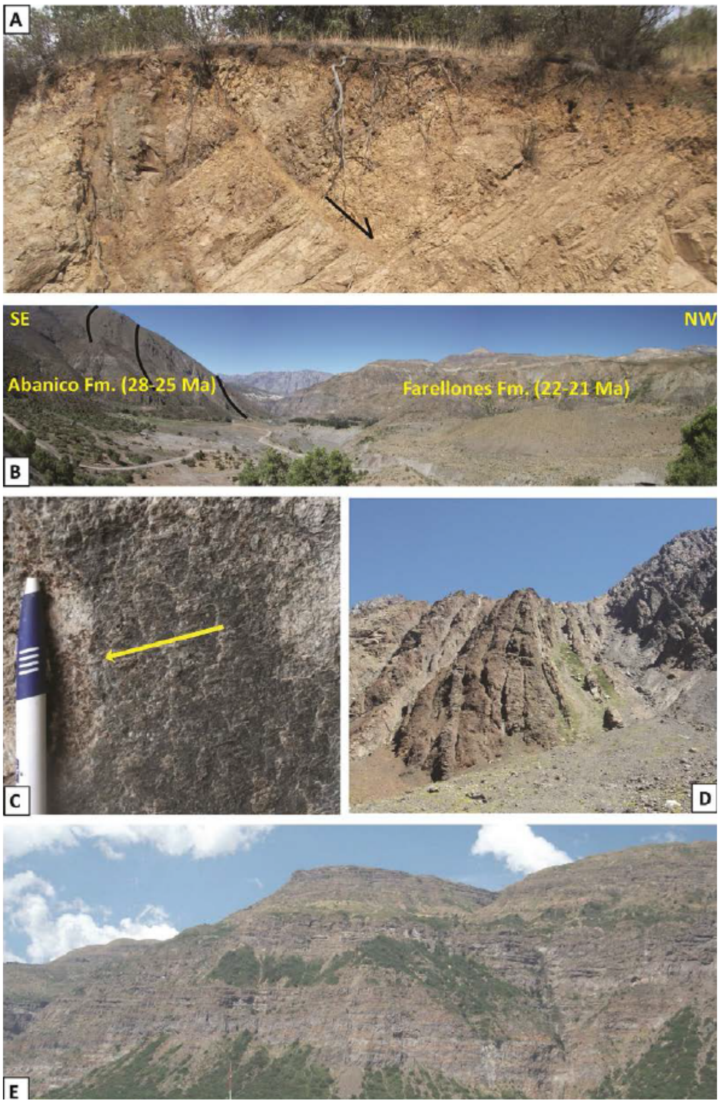

FIG. 2
Field photographs illustrating different aspects of the arc-oblique fault systems which affect Cenozoic volcanic rocks in the Andes of central Chile. A. WNW-striking, S-dipping normal fault affecting pyroclastic and sedimentary deposits of Abanico Formation at 373809mE, 6310183mN. The fault is part of a WNW system of normal faults without evidence of subsequent reverse or strike-slip reactivation. B. View SW from 393700mE, 6266260mN, looking along strike of the NE-striking, NW- dipping fault system to which the fault plane of C belongs. The structure juxtaposes strongly folded, Oligocene Abanico Formation rocks in the footwall with flat-lying, Early Miocene Farellones Formation rocks in the hanging wall. Black lines highlight bedding surfaces. Ages from Baeza (1999), Charrier et al. (2002) and Fock (2005). C. Syn-tectonic crystallization of tourmaline in a NE-striking, NW-dipping fault plane, with steps in mineral fibers indicating dextral strike-slip movement. Yellow arrow indicates the sense of movement of the missing block. Picture taken at 387888mE, 6255000mN. D. Strongly folded early to middle Miocene volcanic and sedimentary rocks, which occur within wedges formed between the N-striking thrust faults at the inverted eastern margin of the Abanico Basin and NW- and NE-striking fault systems acting as conjugate strike-slip faults. View S from 387050mE, 6192200mN. E. To the west of D, flat-lying middle Miocene rocks, typical of the central part of the inverted Abanico Basin. View SSW from 370500mE, 6201900mN.

3 Geophysics

Regional geophysical information has been gathered in the study area from different sources, qualities and resolution over the last 30 years. Relevant to this study are the crustal seismicity, gravity and magnetic data. Crustal seismicity is a key parameter given the fact that deformation within the inverted Abanico Basin remains active today, whereas gravity and magnetic signals are complementary tools that can be used to define major lithological and structural domains.

3.1 Seismicity

Within the last 20 m.y., the Andes of Central Chile and Argentina have experienced ~100 km of shortening (Farías *et al.,* 2010), corresponding to a deformation rate on the order of 5 mm/year. This permanent deformation is about 5-7% of the convergence rate between the Nazca and South American plates, and produces active crustal seismicity and sporadically some large intraplate earthquakes, such as the Las Melosas 1958 Mw 6.9 earthquake (Sepúlveda *et al.,* 2008; Alvarado *et al.,* 2009; Fig. 3A). Instrumental information at teleseismic distance is available for the last 50 years (National Earthquake Information Centre, errors in the range of 10/20 km in the horizontal/vertical direction and completeness above 3 Mw). In addition, two local networks (CHASE 2005, Pardo *et al.,* 2008; ANILLO 2006-2008, Farías *et al.,* 2010), provide a representative data set that characterizes the active deformation of the crust in the study area. In these local databases completeness is above 2.5 Mw with errors in the range of 5-10/8-15 km in horizontal/ vertical direction. Time windows of 40 years and 4 years for the regional and local networks respectively, ensure that enough small seismic events have been recorded to characterize crustal deformation, because the mean deformation rate is about 5 mm/yr and relatively large intraplate earthquakes (~6.5 Mw) occur every ~25 years. Figure 3A shows the total crustal seismicity over the structural network of the study area, with a depth cut-off at 20 km. Figure 4 shows the hypocenter distribution along two cross-sections, passing through the porphyry Cu-Mo deposits (Río Blanco-Los Bronces and El Teniente). The seismic events suspected to be associated with the mining operations were eliminated. Although errors involved in the location of individual earthquakes can be significant, even at the regional scale discussed in this work, the spatial trends of large numbers of events (clustering, alignments) and their correlation with the regional-scale structural architecture are highly relevant for understanding the structural controls on active deformation within the study area. Seismicity is mostly concentrated in the N-striking eastern border of the former Abanico basin, in particular in the southern segment. However, clustering of seismic events and both NE and NW trends are observed in the central and western parts of the inverted Abanico Basin, some of them spatially correlated with the location of the Río Blanco-Los Bronces and El Teniente deposits (Figs. 3A, 4). These seismic clusters and alignments are strongly concentrated along regional-scale oblique structures, particularly at their intersections (Fig. 3A).

3.2 Gravimetry

Gravity data have being gathered within the framework of the Ring Project ACT N°18 (Yáñez *et al.,* 2008). This is a regional data set with stations at an average sampling distance of 5 km, with differential GPS height control and errors on the order of 0.3 mGal. The residual gravity field for the study area is shown in figure 3B, along with the structural network and crustal seismicity. Residual gravity anomalies are referred to a “normal” crustal density of 2.7 gr/cc, thus positive/negative anomalies implies crustal densities above/below 2.7 gr/cc, respectively. The exact location of these anomalous crustal blocks require a formal modeling effort which is beyond the semi-quantitative approach of the present paper. A simple interpretation of the gravimetric data set shows that the strongest deformation of the Cenozoic volcanic rocks, observed in the structural geology and seismicity record, is spatially correlated with a gradient between medium and low density domains on the eastern flank of the area. In the southern part, this gradient is N-oriented and follows the eastern margin of the Abanico Basin. Towards the north, this transition zone acquires a NW trend, parallel to the NW-striking faults which traverse the Río Blanco- Los Bronces district (Fig. 3B). Both porphyry Cu-Mo deposits (Río Blanco-Los Bronces and El Teniente) are located at the center of negative gravimetric anomalies. Although in absolute terms the associated negative anomaly is more intense in the case of Río Blanco-Los Bronces deposit compared to El Teniente, the difference is due to the closer proximity with a dense block to the west of El Teniente deposit, thus the positive anomaly associated with this dense block rises the background level towards the El Teniente deposit domain. The mass deficiency in both deposits might be due to a combination of two factors: the presence of large intermediate to felsic batholiths at depth, which are less dense than the surrounding basement rocks, and the intense fracturing and fluid flow associated with major structural intersection zones, which reduces the overall density of the rock mass. In the western part of the study area, long wavelength positive anomalies not fully covered by the data set used in this paper, suggest the presence of dense and deep crustal blocks. Previous studies (Yáñez and Rivera, 2009; Rivera and Cerda, 2012) have suggested a relationship between these dense blocks and the emplacement of nearby giant copper deposits, and according to modeling the depth to the roof of the dense body is in the range of 8-12 km (Yáñez *et al.,* 2008; Yáñez and Rivera, 2009).

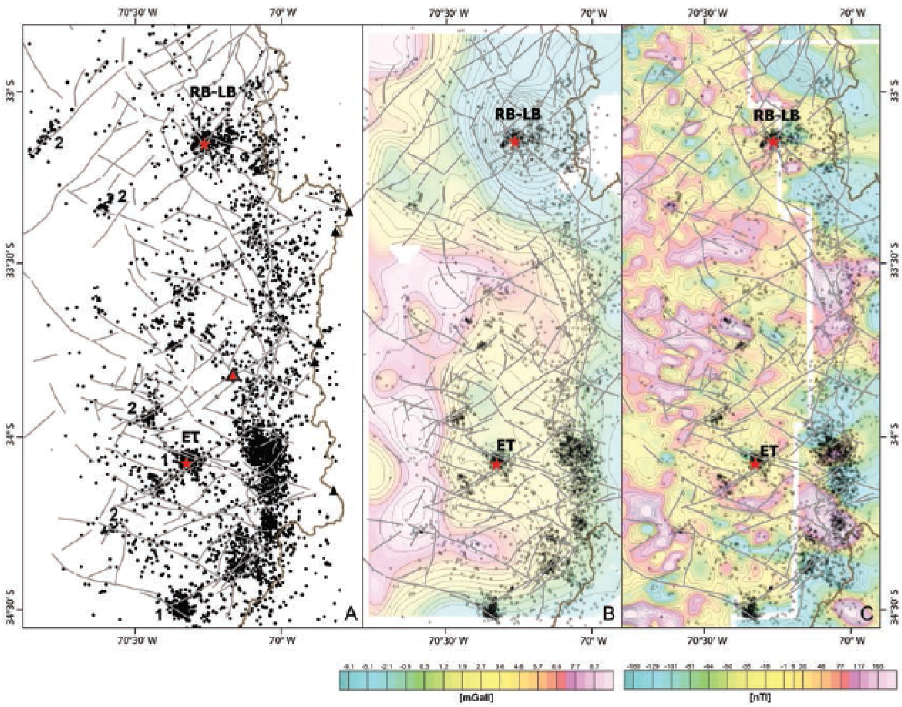

FIG. 3
Main arc-oblique and arc-parallel fault systems (from Fig. 1C) plotted against different regional geophysical data: A. Shallow hypocenters. Red triangle marks the location of the Las Melosas 1958 Mw 6.9 earthquake, and black triangles show the position of active volcanoes. 1. seismic clusters at fault intersections; 2. seismic alignments along arc-oblique faults. B. Shallow hypocenters and gravity field. C. Shallow hypocenters and the reduced to pole magnetic field. The two different surveys mentioned in the text are delimited by a narrow mask zone in order to clarify which domain belongs to each survey. RB-LB: Río Blanco-Los Bronces Cu-Mo deposit; ET: El Teniente Cu-Mo deposit.

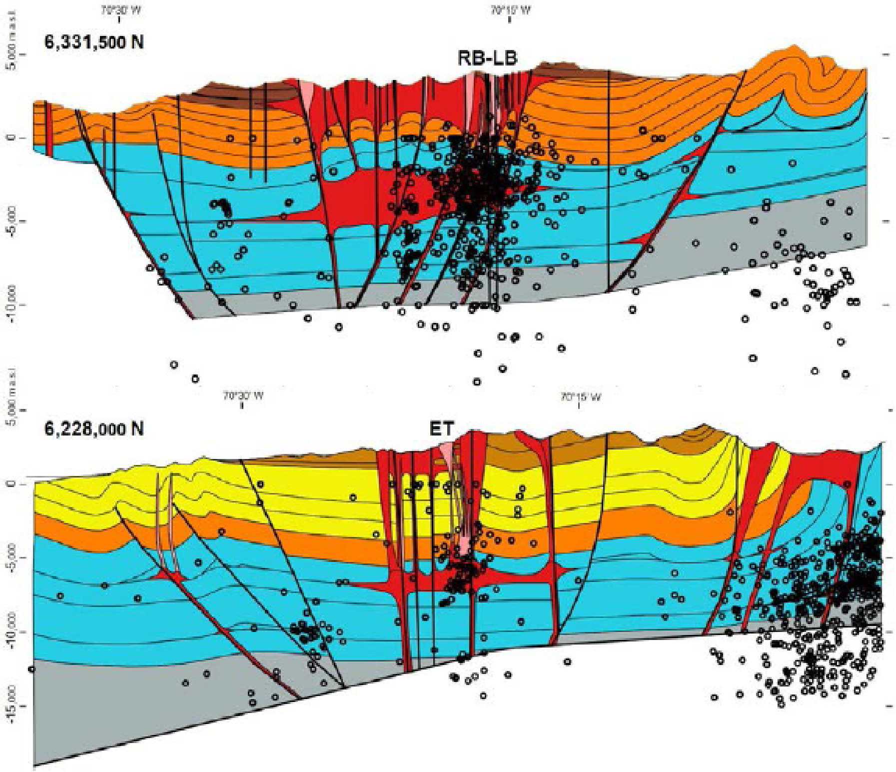

FIG. 4
Representative cross-sections of the study area. Location and legend shown in figure 1B. At the cross-sections, the pre-Mesozoic basement is shown in grey, and the porphyry Cu-Mo-related complexes of porphyritic stocks and hydrothermal breccias are highlighted in pink.

3.3 Magnetometry

The regional magnetic field of the western part of the study area was surveyed in the early 1980s by the Chilean Geological Survey. The eastern part was surveyed in the early 1990s by CODELCO. Even though the technical conditions at the time of the two surveys were less robust than nowadays (*i.e.,* pre GPS era for the western survey and without the appropriate aircraft for high altitude surveys on the eastern side), the data quality are good enough for the purposes of the present study. Both surveys were flown along N-S flight lines, with line separation between 600- 1000 m and a clearance of 600-1,500 m. Figure 3C shows the reduced to the pole magnetic field of the study area, overlain by the structural network and crustal seismicity. The magnetic data highlights the major oblique structural trends much better than the gravity data, due in part to better resolution and also to line orientations (N-S) at high angles with respect to the structural pattern. Despite the low resolution of the magnetic data set, the magnetic fabric of the region (Fig. 3C) is consistent with the structural architecture of the study area (Fig. 1), in particular the NW and NE lineaments.

4 Fault intersections, damage and permeability

Structural and geophysical patterns confirm that the internal architecture of the inverted Abanico Basin is dominated by regional-scale faults oblique to the Andean belt and to the axis of the magmatic arc. These NW- and NE-striking faults were active both during the extensional period as normal faults, and then as conjugate strike-slip faults during tectonic inversion (Figs. 1, 2). As illustrated by figure 1C, the damage zones at the intersections of conjugate strike-slip faults were a highly favorable geometric location for the rise and emplacement of Miocene magmatic bodies, some of them precursors of late Miocene-early Pliocene porphyry Cu-Mo deposits. Both known porphyry Cu-Mo clusters (Río Blanco- Los Bronces and El Teniente), are located at the intersection zone of regional-scale fault systems, acting as conjugate strike-slip faults at the time of mineral deposit emplacement (Fig. 1C). Gravity data (Fig. 3B) shows that these highly permeable domains, the locus of large deposit emplacement, are located over negative to neutral gravity anomalies, in agreement with the expected physical nature of damage zones and large, differentiated upper-crustal magma chambers (reduced density relative to more intact basement rock).

As shown in figure 1C, Plio-Quaternary volcanic centers are also located along strike of major arc- oblique fault systems. In fact, the alignment of eruptive vents in individual stratovolcanoes shows a very good correlation with the strike of regional- scale faults controlling the location of the volcanic complexes (Figs. 1C, 5). The Tupungato-Tupungatito complex is built over a major NE-striking, NW- dipping dextral strike-slip fault system, which show evidence of earlier normal movement. The alignment of the main volcanic centers follows this same NE trend (Fig. 5A). In the case of the San José volcanic complex, individual craters are aligned along NNW and NW trends (Fig. 5B), parallel to a major fault system that can be followed from the volcanic complex to the NNW, and which appear to have controlled the emplacement of the Mesón Alto and La Gloria plutons, the Río Blanco-San Francisco batholith, the Río Colorado pluton and the Río Blanco-Los Bronces porphyry Cu-Mo deposit (Fig. 1C). The Maipo volcano, in turn, has two main craters aligned along a WNW trend (Fig. 5C), parallel to a regional-scale fault system which can be followed across the entire inverted Abanico Basin and which is at least spatially related to the El Teniente porphyry Cu-Mo deposit (Fig. 1C). This confirms the relevance of arc-oblique fault systems as pathways for the ascent of magmas and magmatic-derived hydrothermal fluids in the high Andes of central Chile. A similar conclusion has been reached by previous authors in the Andes of southern Chile (Cembrano and Lara, 2009; Sielfeld *et al.,* 2017; Pérez-Flores *et al.,* 2016).

Similarly, previous workers have demonstrated the strong control exerted by active faults in the circulation of hydrothermal fluids in active geothermal systems of southern Chile (*e.g.,* Sánchez *et al.,* 2013). However, there are no specific studies addressing this issue in central Chile. Figure 6 show the distribution of thermal springs in central Chile over the structural architecture of the study area. Thermal springs located close to the eastern margin of the Abanico Basin or in the Eastern Main Cordillera are in some cases associated with fumaroles and show chemical characteristics typical of thermal waters discharge around active volcanoes (Benavente *et al.,* 2012). In contrast, those located near the western margin of the Abanico Basin or in the Coastal Cordillera correspond to low-temperature waters whose chemistry indicate interaction with meteoric waters during transport along faults (Benavente *et al.,* 2012). The distribution of thermal springs (Fig. 6) suggests a strong correlation between fault architecture, fluid flow and the location of active hydrothermal cells. Most of the thermal occurrences are located over the trace of arc-oblique fault systems, commonly at their intersections with the inverted basin-margin faults of the Abanico Basin or at the intersections of pairs of arc-oblique faults.

The distribution of upper-crustal seismicity in central Chile (Fig. 3A) shows that most fault ruptures occur at the eastern inverted margin of the basin, particularly at the southern part of the study area. In general, little activity is observed at the inverted western basin margin. However, localized clusters of seismic activity are observed in the central and western parts of the inverted Abanico Basin, unrelated to the eastern basin margin faults. Their distribution shows a strong correlation with the intersections of regional-scale, arc-oblique fault systems (Fig. 3A), suggesting that these types of structures are also active and accommodate a relevant part of the permanent deformation of the South American margin. The largest crustal-related seismic event recorded in the region, the 1958 6.9 Mw Las Melosas event, shows a focal mechanism compatible with the activation of a NNE- or WNW-striking fault (Alvarado *et al.,* 2009). Both fault planes are consistent with the orientation of regional fault trends in the area (Fig. 3A), but with the existing data it is not possible to discriminate between the two possible solutions (Alvarado *et al.,* 2009). In the southern part of the studied Andean segment, in the area located towards the west of the

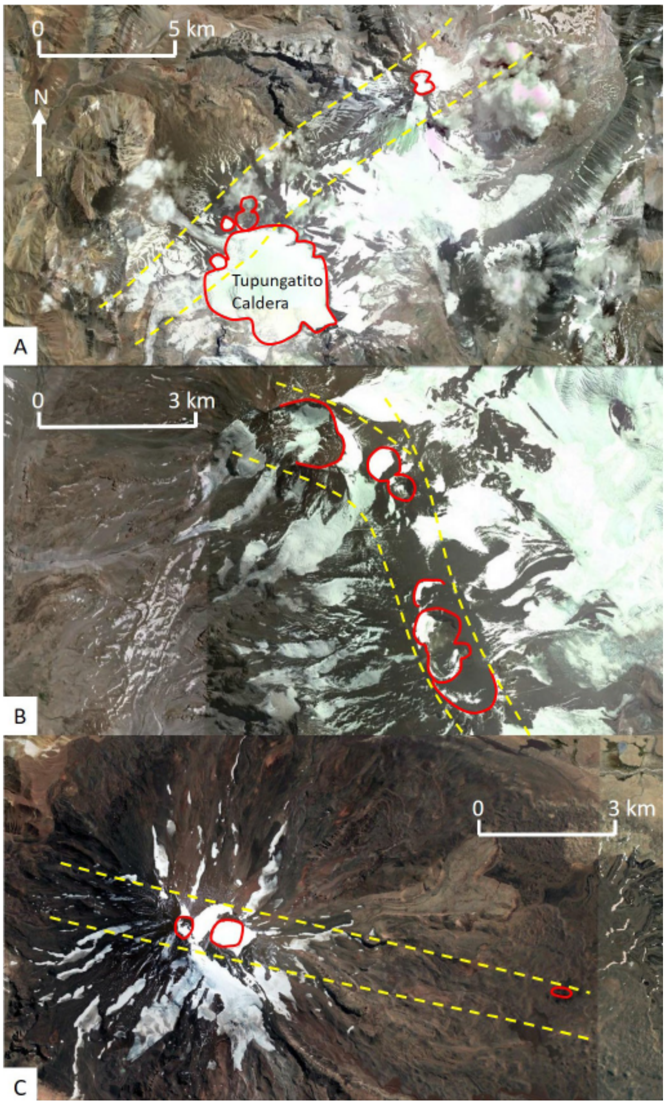

FIG. 5
Alignment of individual eruptive vents in the three active volcanic centers of central Chile. Satellite images from Google Earth. A. Tupungato-Tupungatito volcanic complex. B. San José volcano. C. Maipo volcano.

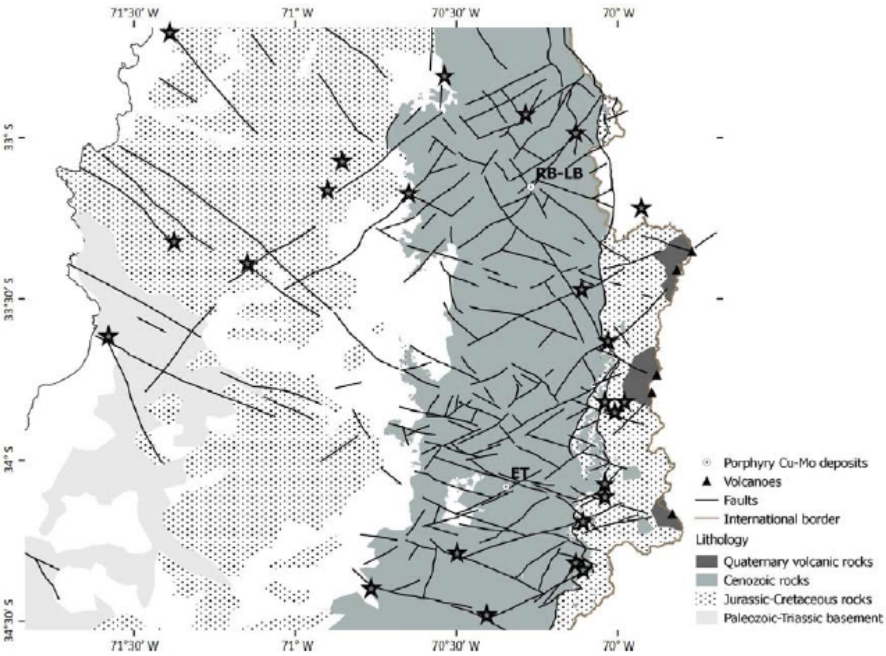

FIG. 6
Distribution of thermal springs, represented by stars, shown over a simplified version of the geological map of central Chile (from SERNAGEOMIN, 2002, and this work). Thermal occurrences from the compilation of Benavente et al. (2012) and personal field observations of the first author.

El Teniente porphyry Cu-Mo deposit, seismic clusters are also observed at the intersections between major arc-oblique fault systems and the NNE-striking, W-vergent reverse faults cropping out at the inverted western margin of the Abanico basin (Barahona-Perales fault system of Rivera, 2017; Fig. 3A). Neotectonic activity of arc-oblique structures within the study area has been demonstrated by Lavenu and Cembrano (2008). They showed that Quaternary terraces of the Maipo river have been faulted and folded by NE and WNW-striking reverse faults, parallel to the trend of regional-scale faults recognized by this study (Fig. 7). This is relevant for the seismic hazard for the city of Santiago, as some parts of the city are located over the projection towards the west of major potentially active arc-oblique fault systems (Yáñez *et al.,* 2015). As illustrated in figure 7, this is the case of both the El Salto fault (Piquer *et al.,* 2015) and the Piuquencillo fault (Rivera and Falcón, 2000; Piquer *et al.,* 2017).

All of the above have significant implications for mineral exploration in the area, and for the understanding of structural controls on active volcanism, geothermal systems and intra-plate earthquakes in this Andean segment. We interpret regional scale, strike-extensive but discontinuous arc-oblique fault systems to be reactivated basement structures, inherited from pre-Andean tectonic cycles: *e.g.,* suture zones formed during accretion of continental blocks to the western margin of Gondwana in the Palaeozoic, and basin-margin and transfer faults active during Triassic rifting events (Charrier *et al.,* 2015). These oblique fault systems are well developed in the basement of the Andes. They have been identified in the Coastal Cordillera of central Chile (Fig. 7), where NW-striking faults played a first-order role in controlling the ascent and emplacement of syn-tectonic early Mesozoic plutons and dike swarms (Gana and Zentilli, 2000; Creixell *et al.,* 2011). Similar arc-oblique fault systems have been recognized in basement blocks cropping out in the Andes of northern Chile (Niemeyer *et al.,* 2004), where NW-striking faults also played an important role for the emplacement of porphyry Cu-Mo deposits (Richards *et al.,* 2001). NW- and NE-striking faults have also been studied in the Argentinean basement to the east (Salfity, 1985; Chernicoff *et al.,* 2002; Acocella *et al.,* 2011; Sagripanti *et al.,* 2014). These high-angle, long-lived basement structures, and in particular their intersections, constitute major weakness and high-permeability zones, which have focused the ascent of magma through the brittle upper crust (Figs. 8, 9). Individual fault planes within these long-lived fault systems may be partially "sealed" by hydrothermal fluids or magma. However, as other fault segments and secondary faults will not be sealed, the fault systems as a whole will continue to act as lithospheric-scale weakness and permeability domains. Moreover, even an individual plane which has been "sealed" can be reactivated thousands of times, under a high fluid-flux regime, in repeated cycles of sealing and slip/opening (Sibson, 1990; Cox, 2016). This occurs because the contacts of veins and dikes emplaced along faults still constitute weakness planes which tend to accommodate subsequent fault ruptures and hydrothermal fluid or magmatic flow.

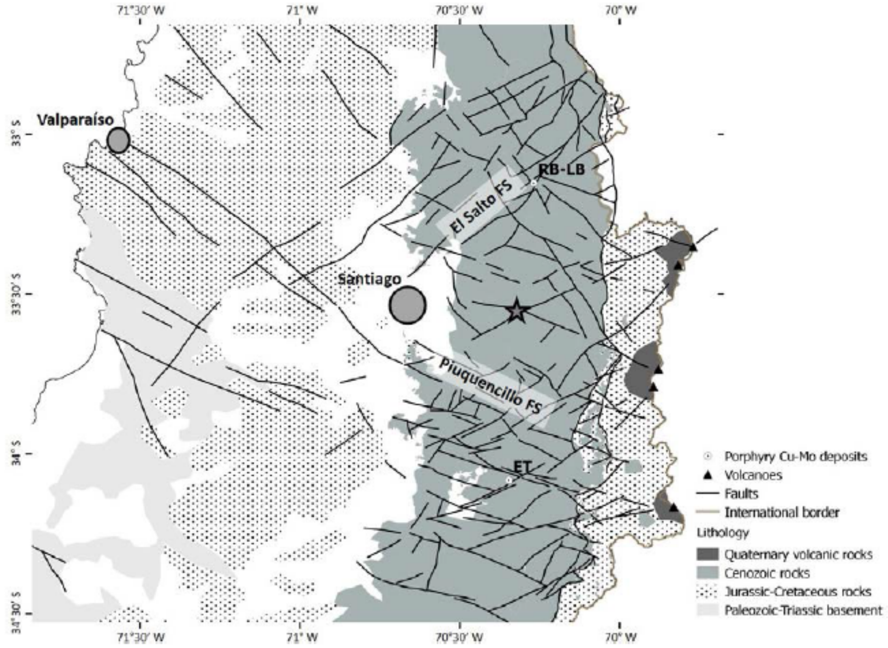

FIG. 7
Position of the regional-scale Piuquencillo and El Salto fault systems in relation to the city of Santiago. The star marks the locality studied by Lavenu and Cembrano (2008) with Quaternary terraces affected by NE- and WNW-striking reverse faults. Background geology simplified from SERNAGEOMIN (2002) and this work.

Field evidence for these long-lived, arc-oblique structures can be subtle where they have been covered by Meso-Cenozoic rocks and overprinted by more obvious, recent arc-parallel faults. In the high Andes of central Chile, with its continuous deposition of Cenozoic volcanic and sedimentary products, basement structures can manifest as small-displacement, discontinuous fault systems, as the fault has to propagate upwards through the younger rocks (Fig. 9). But as we show here, they can still be traced across the orogenic belt (Figs. 1, 3) by a combination of structural, stratigraphic and geophysical methods. This type of fundamental basement structures, typically orogen-oblique and difficult to recognize in the field, are a critical element for ore genesis in magmatic and magmatic- hydrothermal ore deposits (Fig. 9; McCuaig and Hronsky, 2014).

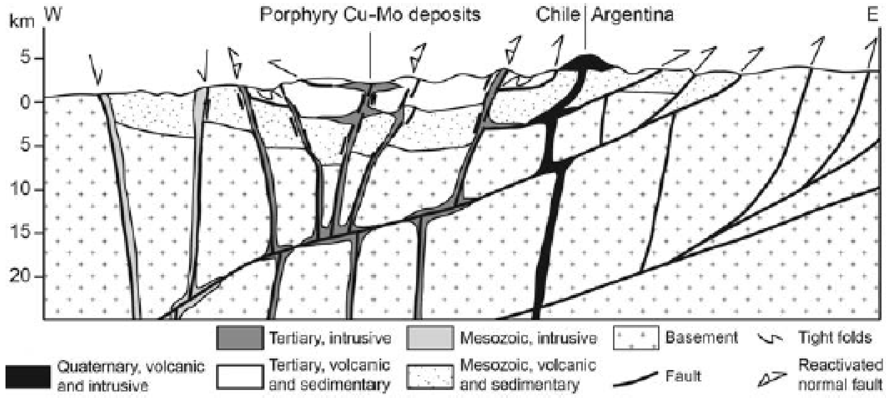

FIG. 8
Schematic W-E cross-section of the upper crust across the Andes of central Chile and Argentina, illustrating the complex interaction between high-angle, arc-oblique, basement-inherited faults and low-angle, arc-parallel thrusts formed during Andean orogenesis. High-angle oblique faults have played a prominent role channeling magmatism through the upper crust in the Mesozoic, Cenozoic and Quaternary magmatic arcs. Geology of the eastern flank of the Andes and geometry of the main thrusts based on Giambiagi et al. (2003).

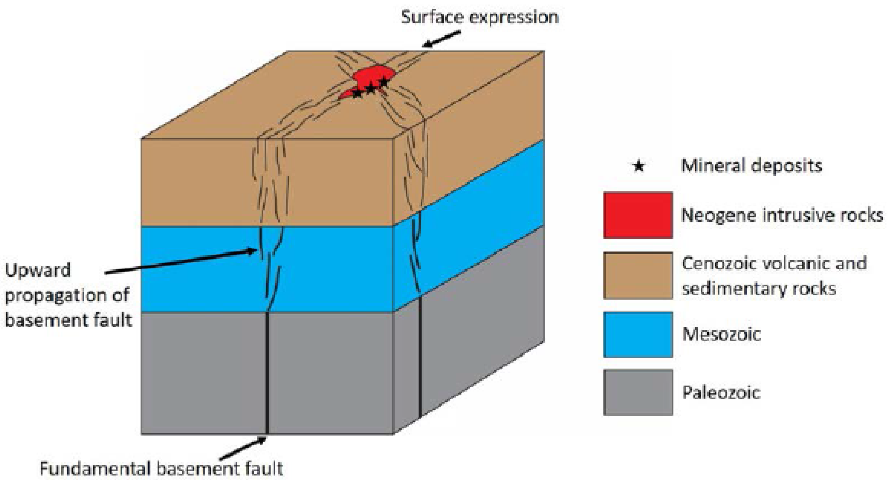

FIG. 9
Schematic diagram showing how fundamental basement faults propagate upwards trough younger rocks, being represented at the current surface by a network of minor faults, often difficult to recognize in the field. The diagram also illustrates the relationship between the intersections of fundamental basement faults and the emplacement of intrusive complexes and mineral deposits. Adapted from figure 7 of McCuaig and Hronsky (2014).

5 Conclusions

A combination of structural and stratigraphic data and the analysis of large-scale geophysical studies allowed us to interpret the relationship between the regional-scale structural architecture of the inverted Abanico Basin and the emplacement of intrusive bodies, volcanic centers, hydrothermal systems and the patterns of upper-crustal seismicity. Existing geological and geophysical data indicate that the internal architecture of the inverted basin is dominated by NE- and NW-striking faults, which we interpret as reactivated weakness zones inherited from the pre-existing structural architecture of the Andean basement. Some fault systems bound regional-scale gravimetric domains, suggesting that they define the deep architecture of the crust beneath the high Andes. During the Meso-Cenozoic, basement faults were reactivated with different kinematics according to the prevailing stress tensor, and they were propagated vertically through the Mesozoic and Cenozoic volcanic and sedimentary cover. This can explain why in the Cenozoic rocks of the Andes of central Chile, continental-scale faults which are interpreted to control the rise of magma through the upper crust are represented at the current surface only by minor faults with small (metric) displacements. During the early Miocene to early Pliocene, in particular, arc- oblique faults were active as conjugate strike-slip faults with minor reverse components, consistent with broadly E-directed compression. During this period, they separated packages of volcanic rocks with contrasting deformation styles. The intersection zones of conjugate, arc-oblique, regional-scale fault systems correspond to areas of maximum damage and enhanced permeability, and are strongly related to the distribution of Miocene intrusive bodies, late Miocene-early Pliocene porphyry Cu-Mo deposits, active volcanic centers and their eruptive vents, the location of thermal springs and the position of clusters of upper-crustal seismicity, showing that they are being reactivated under the current stress regime.

By combining field-based structural geology with regional-scale geophysics, major oblique fault systems can be identified even where they have been obscured by young volcanic and sedimentary deposits and/or arc-parallel structures. This approach can be applied to other Andean segments and to orogenic belts elsewhere, leading to improved exploration models for subduction-related mineral deposits and also to a better understanding of the structural controls on volcanism, geothermal activity and crustal seismicity.

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