Evolution and along-strike variations in the Arequipa-Tarapacá Basin structure at 21°S: Implications for Geological Exploration Models in Southern Perú and Northern Chile

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1. Abstract

The southern Peru and northern Chile Paleocene – Eocene porphyry copper metallogenic belt is mostly concealed by post-mineral cover. Mineral exploration in these areas are highly complex and expensive, requiring new strategies and approaches to minimize generative exploration failure. We used geological and geophysical data to determine geology beneath post-mineral cover in Northern Chile (~21°S), paying special attention in the relationship between the Arequipa-Tarapacá Basin structure and known mineral occurrences. 2D seismic reflection sections interpretation shows partially inverted graben and half-graben structural arrays, dominated by high angle inverted faults and related inversion anticlines. Extensional and contractional growth strata allow us to establish an extensional phase (Jurassic to Lower Cretaceous), an inversion phase (since Upper Cretaceous) and a contractional phase (since Upper Oligocene). Along strike variations in the Tarapacá Basin structure is closely associated by pre-orogenic structures. Spatial and temporal correlation between mineral deposits and long-lived structures presented in this work, permit us to propose a structural exploration model/strategy for post-mineral cover zones along Southern Peru and Northern Chile.

2. Introduction

One of the most fertile metallogenic belts in Southern Peru and Northern Chile is the Paleocene - Eocene porphyry copper belt, that contains world class porphyry copper deposits such as Cerro Verde, Cuajone, Cerro Colorado, Spence and Lomas Bayas (Fig. 1). However, most of the extension is concealed by sedimentary and pyroclastic deposits produced by erosion of the Western Andean Mountain Front, covering ~60% of the total metallogenic belt area (Fig. 1). This scenario increases the difficulty to find new deposits in areas with post-mineral cover and potentially associated to this metallogenic belt. As the market projections for copper (associated to high demand in upcoming efforts towards electro mobility, as well as increasing demand for technology and construction) will surely increase, discovery and determination of new resources is imperative (Kerr, 2014), therefore exploration of covered terrains has become a priority.

First approaches for optimized exploration in concealed zones were related to the understanding of post-mineral cover thickness (García *et al.*, 2017; Labbé *et al.*, 2019), establishing low thickness areas as potential target zones. Also, Fuentes *et al.* (2018) showed main structural arrays and styles that could be considered as conduits for ore-forming fluids. Notwithstanding these advances, it is highly necessary to better constraint these prospective zones.

In order to contribute to this exploration problem, we present a structural exploration model based on structures that exert a high control on secondary permeability and could act as pathways for magmatism and hydrothermal fluids, focusing on the evolution of the pre-orogenic structures (Arequipa-Tarapacá Basin) that could have been reactivated during the evolution of the metallogenic belts.

3. Methods

In order to understand the evolution and along-strike variations of the Tarapacá Basin beneath the Upper Oligocene to recent deposits, we used W-E oriented 2D seismic reflection sections acquired by ENAP (Empresa Nacional del Petróleo) close to 21°S. Seismic interpretation was calibrated by well and drill-hole data and rock outcrops, and validated by restoring the structural sections with the StructureSolver software. Lateral structural variations were investigated using 3D visualization and analysis of geological and geophysical data with Andino 3D and Leapfrog softwares.

4. Results

Based on the seismic interpretation, integrated with well and rock outcrop data, four seismic horizons were correlated with geological units previously established (Fig. 2).

4.1. Geology below post-mineral cover

4.1.1. ***Basement***

Chaotic reflectors characterize the basement, where high amplitude reflectors mark the contact between the basement and the Syn-rift unit. Integrated to rock outcrops and well data, the basement is correlated to the Upper Carboniferous granitoids (Fig. 2).

4.1.2. ***Syn-rift unit***

Semi-continuous to continuous reflectors represent the Syn-rift unit, with variable frequency showing fan patterns close to lateral breaks in the seismic stratigraphy and onlap contact relations against basement. This unit is correlated with the Jurassic to Lower Cretaceous marine and continental sedimentary sequences (Fig. 2).

4.1.2. ***Syn-inversion unit***

Parallel and continuous reflector packages characterize the Syn-inversion unit, with moderate to high amplitude and high frequency reflectors overlying the Syn-rift unit in a low angular unconformity, showing contractional growth strata through anticline folds limbs. This syn-inversion unit is correlated with Upper Cretaceous volcano-sedimentary sequences (Fig. 2).

4.1.2. ***Syn-contractional units***

Parallel and continuous reflectors, with intercalations between moderate to high frequency and amplitude ones represent the Syn-contractional units. The internal tectono-stratigraphic architecture shows fan geometries and growth strata close to anticline limbs, indicating synchronic deposition with compressive deformation. Syn-contractional units are correlated with the Upper Oligocene to recent sedimentary sequences (Fig. 2).

4.2. Structures

Main structures exposed in surface correspond to the Chintaguay and Longacho anticline, affecting the overall syn-contractional units and controlling homonymous hills.

Interpretation of seismic sections reveal that the sub-surface principal structures are west-verging with moderate to high angle inverted faults, developing inversion anticlines in their hanging walls (harpoon shape), affecting syn-rift and syn-inversion units. The Chintaguay and Longacho folds are spatially associated with the propagation of these pre-existing structures located over inversion anticlines.

4.3. Structural evolution and inherited extensional architecture

Extensional and contractional growth strata allow us to establish:

(i) the extensional phase associated to the Tarapacá basin formation, during the Jurassic to Early Cretaceous.
(ii) the inversion phase related to the tectonic inversion of the Tarapacá basin, since the Upper Cretaceous.
(iii) the contraction phase associated to repeated reactivation in a reverse kinematic sense of long-lived inherited structures, during the Upper Oligocene to recent (Fig. 2).

4.4. Along strike variations in the Tarapacá Basin structure

Main structures and syn-rift depocenters present a N-S orientation and along-strike variations are reflected as changes of polarity and vergence. These latitudinal variations were controlled by inherited pre-orogenic structures, implying an original segmented extensional basin.

5. Discussion and final remarks

5.1. Long-lived structures and neotectonics importance in mineral exploration

Recently McCuaig and Hronsky (2014) and Piquer *et al.* (2019), remark the importance of fundamental basement faults in the spatial location of ore bodies. In this applied research, we could recognize several structures active from Jurassic times. In addition, these structures were subsequently reactivated in reverse kinematic displacements since the Upper Cretaceous. In this context, the Tarapacá Basin corresponds to a partially inverted segmented basin, presenting lateral variations and developing accommodation and transfer zones, which could include local transtensional and transpressional areas. These structural features have been widely recognized and established as key features in mineral occurrences (Love *et al.*, 2004; Kyne *et al.*, 2019). Because of subsequent reactivation of these long-lived structures, Neogene deformation has been highly influenced by the pre-existing structural configuration (Tarapacá Basin faults).

In Northern Chile, the Challacollo district (Fig. 1; ~21°S) evidences close relationships between mineral occurrences, veins and intrusive bodies, and long-lived faults affecting the overall syn-rift, syn-inversion and syn-contractional units, and latitudinal variations in the structural features (Fig. 2). Meanwhile in southern Perú, the Incapuquio fault system is one of the most important structural features in Cuajone, Toquepala, Quellaveco and Cerro Verde mineral deposits (Fig. 1; Carlotto *et al.*, 2009; Acosta *et al.*, 2010). These authors have proposed a structural evolution similar to the one recognized in this study, with an extensional phase and subsequent compressive phases since the Upper Cretaceous, including basin inversion.

Following this rationale and taking in account that most of the Paleogene and Eocene metallogenic belt is concealed, new mineral exploration strategies must consider not only the post-mineral thickness distribution, but also the Neogene structural kinematics, spatial location associated to older structures and lateral variations, paying attention in fault tip points and structural intersections.

As expressed, knowledge of the structural configuration and evolution of back-arc basins has several implications for porphyry and epithermal deposits exploration, as well for IOCG and VMS deposits in the Andean tectonic and metallogenic context.

Acknowledgements

We gratefully acknowledge the Empresa Nacional del Petróleo (ENAP) for permission to use seismic reflection profiles and well data. Authors are thankful for financial support provided by Universidad Santo Tomás Regular Investigation Funds. La.Te. Andes S.A., Seequent and Nunns and Rogan LLC kindly provided us Andino 3D, Leapfrog and StructureSolver softwares, respectively.

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Figures

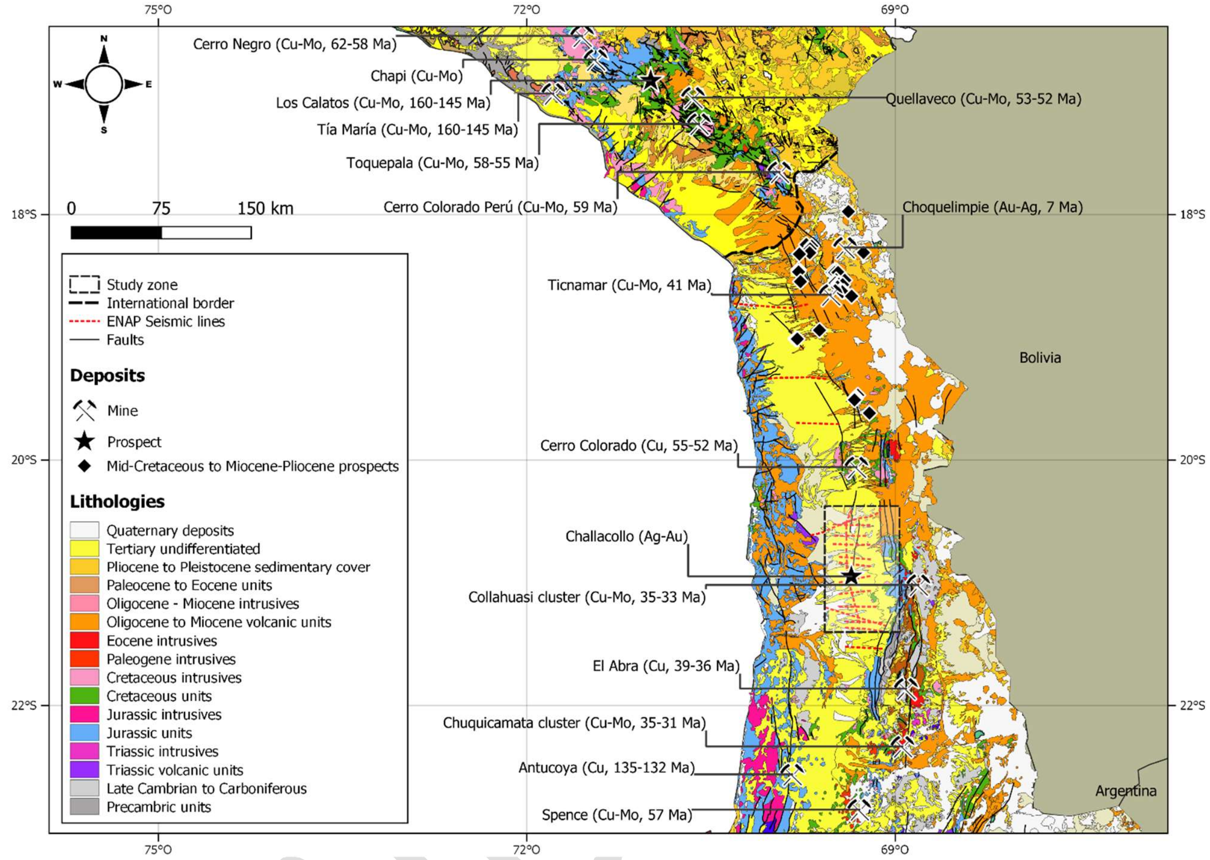

Figure 1. Simplified geological map, showing the main mineral deposits from Southern Perú to Northern Chile. Based on 1:1.000.000 regional map from SERNAGEOMIN (2003), 1:1.000.000 regional map from INGEMMET (2016). Other information from García *et al.*, (2017) and Porter GeoConsultancy Database available on http://www.portergeo.com.au/database/index.asp.

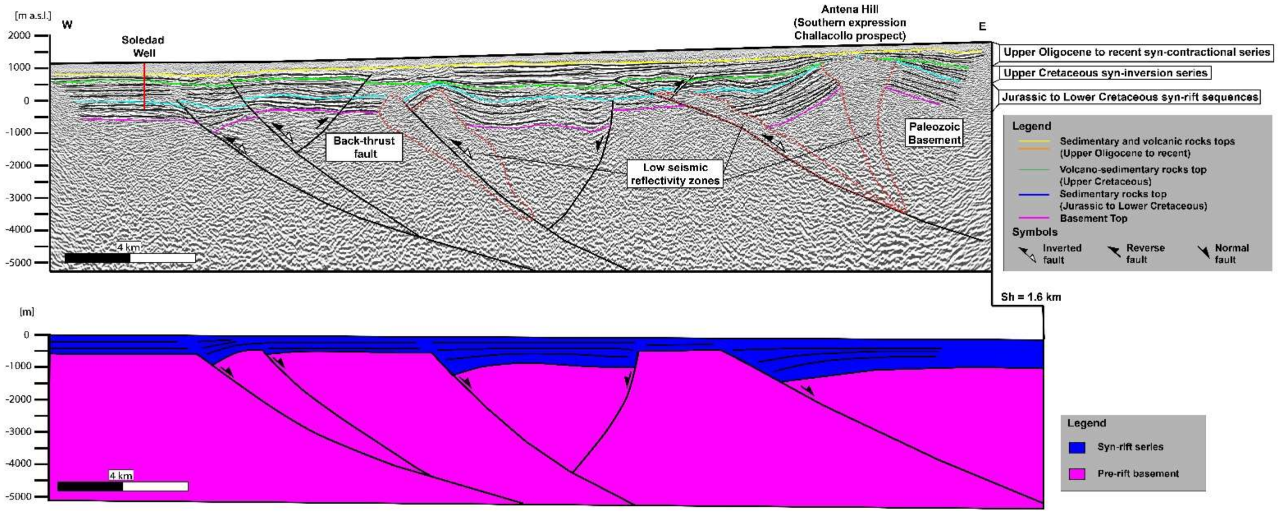

Figure 2. Seismic reflection section 99-9 interpretation (above) and structural restoration previous to tectonic shortening (below). Note the low seismic reflectivity zones (above) potentially associated to igneous intrusions and its relation with structural features.