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Petroleum system concepts for assessing mineral resources in Andean fold and thrust belts of Peru

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1. Abstract

The fold and thrust belts of northern Peru show concomitant petroleum and mineral systems. Regardless of the source rock of the ore deposits, the characterization of the components of the petroleum system is a valuable tool for assessing the mineral resources. In this study, we examine the potential of the petroleum-mineral system approach in three types of sediment-hosted ore deposits along a crustal-scale cross-section through the Andes of northern Peru.

Keywords: sediment-hosted oil and ore deposits, Andean tectonics

Resumen

Las fajas plagadas y corridas del norte de Perú presentan sistemas petrolíferos y minerales concomitantes. Independientemente de la roca fuente de los yacimientos, la caracterización de los componentes del sistema petrolero es una herramienta potente para evaluar los recursos minerales. En este estudio examinamos el potencial del enfoque del sistema petrolero-mineral en tres tipos de depósitos minerales alojados en sedimentos a lo largo de una sección estructural de escala cortical a través de los Andes del norte de Perú.

2. Introduction

In the Western and Eastern Andean cordilleras and in the Subandean basins of Peru, significant ore deposits (Cu, Pb, Zn, Au, Ag...) are concentrated in sedimentary reservoirs of fold and thrust belts (Fontboté, 2018; Noble and McKee E.H., 1999; Hannanmetals, 2019; Vallance et al., 2023). In this contribution, we explore and develop the hypothesis that there are strong interactions between mineralizing fluids (of both magmatic and sedimentary origin) and petroleum systems (oil shales and fluid reservoirs, structural traps, timing

of deformation and fluid migration). Indeed, ore and oil deposit types can both be found in the same fold and thrust belts, involving similar processes and timing of fluid migration and storage in sedimentary reservoirs and structural traps, controlled by the same geodynamic events. Both can be described and characterised in the same way. Here, we show the potential of the petroleum system approach to mineral exploration along a crustal-scale cross-section through the Andes of northern Peru.

3. The northern Peruvian Andes thrust system and hydrocarbon-ore deposits

The crustal-scale cross-section used in this work has been constructed - thanks to numerous studies realized in cooperation with Peruvian institutions - to better understand structural architecture, crustal thickening and hydrocarbon-ore deposits genesis. Abundant industrial seismic data provided by Perupetro S.A. allowed to properly constrain the geometry of the forearc and retro-foreland basins (Baby et al., 2018; Prudhomme et al., 2019). Deep crustal structures and Moho geometries were constrained by a recent teleseismic receiver function study (Condori et al., 2017). Globally, the current structural architecture highlights the complex propagation of eastward crustal thrust systems, which could result from a total amount of horizontal shortening of almost 220 km evenly distributed between two orogenic periods occurring during (1) the late Cretaceous-early Eocene and (2) the Neogene. Ore deposits located along the balanced cross-section (Figure 1) are related to petroleum and thrust systems developed successively during these two orogenic periods.

In the Western Cordillera, the well-known Marañon fold and thrust belt (MFTB), which developed during the first Andean orogenic period (late Cretaceous-early Eocene), hosts representative gold deposits in an overmature Jurassic-Cretaceous petroleum system composed of marine black shales and fluvio-deltaic sandstones.

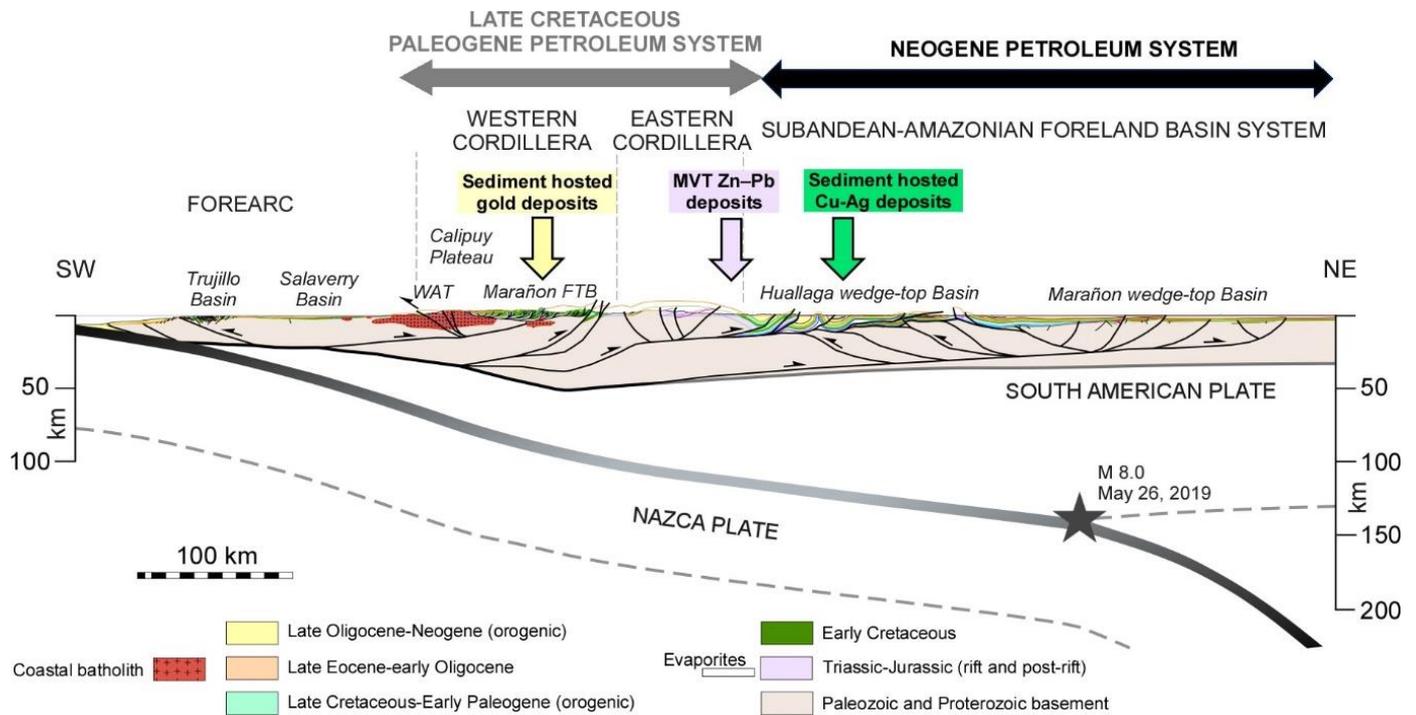


Figure 1. Crustal-scale structural cross-section through the Andes of northern Peru. (5°- 8°S) with location of the three types of ore deposits hosted in fold and thrust belts (modified from Baby et al., in preparation).

The eastern border of the Eastern Cordillera is characterized by world-class Mississippi valley-type (MVT) Zn–Pb deposits (Fontboté and Gorzawski, 1990; de Oliveira et al., 2020) hosted in the marine carbonate Pucara petroleum system (late Triassic-early Jurassic) and associated with the Andean inversion of the Triassic rift.

Finally, the Subandean Huallaga Basin, which corresponds to the modern fold and thrust belt of the eastern front of the orogen, is currently considered a new frontier area (Hannanmetals, 2019) with the discovery of sediment-hosted copper-silver deposits in an active petroleum system.

4. Petroleum and Mineral system components

In this section, we use the petroleum system concept defined by Magoon and Dow (1994) to document the mineral systems. For each type of ore deposit presented above and located in the northern Peru cross-section (Figure 1), we define and discuss essential elements, processes, temporal and spatial aspects, and their relationship with the associated petroleum systems.

4.1. Sediment-hosted gold deposits of the MFTB (Eastern Cordillera)

We focus here on the MFTB-hosted Shahuindo gold deposit recently studied in detail by Vallance et al. (2023), and located in our cross-section (Figure 1). In Shahuindo, mineralization is hosted by sandstones involved in anticlinal traps. Gold reserves are located in the supergene zone, while in the primary mineralization the metal is found as “invisible” gold in arsenian pyrite.

In the Shahuindo mineral system, the main source rock (metal source) corresponds to the Miocene igneous stocks that intruded the Paleogene folded structures. Other possible source rocks could correspond to the black shales of the late Jurassic-Cretaceous petroleum system (Chicama and Santa Formations). Indeed, in various ore deposits located in sedimentary basins (e.g. Carlin and MVT), organic-rich black shales are considered to be the source of the metals (Fuchs et al., 2016; Large et al., 2015; Saintilan et al., 2019). In the case of Shahuindo, the black shales are currently thermally overmature. Hydrocarbons and possibly gold were expelled during the late Cretaceous-Paleogene and are now absent from the black shales.



The main gold host rocks (second essential element) are the Cretaceous sandstone reservoirs of the petroleum system (Chimu, Carhuaz and Farrat Formations) deformed by thrusts propagation during the late Cretaceous-lower Eocene. This first compressive event (also the first process of the petroleum-mineral system) allowed the formation of structural traps sealed by several levels of shale. These are currently at the surface as a result of modern tectonic uplift probably during the late Neogene (second tectonic process), which allowed the formation of a supergene zone but prevented the preservation of hydrocarbons.

The second fundamental process in petroleum or mineral systems is the generation-migration of fluids and accumulation of hydrocarbon or ore. Considering the magmatic origin of the gold of Shahuindo, this process occurred during the Miocene dacitic intrusions (15-16 Ma; Vallance et al., 2023). In the case of a possible sedimentary origin (Chicama and Santa black shales), petroleum modelling shows that gold may have been transported during the gas generation-expulsion phase at a temperature above 200°C during the late Cretaceous-Paleogene (Van De Vyver, 2021). In both cases, structural traps of the MFTB were present to allow the accumulation of ore deposits.

4.2. MVT Zn–Pb deposits of the eastern border of the Eastern Cordillera

For MVT systems, we use the data of the Bongara-Florida Canyon and Bongara-Mina Grande sulfide and nonsulfide Zn-Pb deposits (Arfè et al., 2017; de Oliveira et al., 2020), which are nearest to our cross-section (Figure 1).

Both deposits are associated with the inversion of the Triassic rift and are distributed along faults or on the crest of anticlines of inverted structures. The host rocks correspond to dolomitized strata of the Chambara and Condorsinga formations (also reservoir rocks of the Pucara petroleum system), which are sealed by the red shales of the late Jurassic Sarayaquillo Formation.

The metal sources are still under debate. Like in the case of the San Vicente MVT deposit, most authors consider the Precambrian Marañon Complex and the Triassic Mitu red beds as the favourite source rock candidates. But the presence of bitumen in the Pucara metal host rocks could mean that liquid petroleum and associated water may have carried Pb and Zn as

shown by Saintilan et al. (2019) in the world-class Laisvall MVT deposit in northern Sweden.

Rb–Sr dating of sphalerite from the Florida Canyon indicates that the Zn–Pb sulfide ore formed between 86 and 83 Ma (de Oliveira et al., 2020). It is probably during the same period that the Pucara petroleum system started to function as the inversion of the Triassic rift began. This oil kitchen was probably located to the west in the deepest part of the rift basin. This period corresponds to the critical moment of the mineral and petroleum systems and generated favourable structural traps that could focus sufficient fluid to produce ore deposits. Like in the MFTB of the Eastern Cordillera, late Neogene tectonics has been responsible for the uplift of the ore deposits, allowing the formation of supergene zones but destroying the petroleum system.

4.2. Sediment-hosted copper-silver deposits in the Western Huallaga Fold and Thrust Belt (FTB)

The Huallaga Subandean FTB is mainly known for its petroleum potential (Calderon et al., 2017). In its western part, the current discovery of Cu-Ag deposits (Hannanmetals, 2019) in petroleum reservoirs (late Jurassic fine sands of the Sarayaquillo Fm., sands of the Cretaceous Cushabatay Fm.) shows once again a strong correlation between mineral and petroleum systems. There are no known magmatic intrusions in this region, and the origin of the Cu-Ag is likely to be found in the pre-Andean sedimentary fill.

Hannanmetals (2019) proposes the early Triassic red beds of the Mitu Group as the main source rock. However, our whole-rock chemical analyses of black calcareous mudstones from the Triassic Aramachay Formation (a proven petroleum source rock) in the eastern border of the Eastern Cordillera show that they contain more than 10 ppm Cu (Quinteros, 2022), indicating a clear potential as source rock for copper ore.

Therefore, we propose a second mineral system at the origin of the Cu deposits in the western Huallaga FTB. The organic-rich Aramachay sediments acted as a petroleum and Cu source rock. Petroleum modelling (Calderon et al., 2017) shows that hydrocarbon generation-migration and accumulation occurred since the middle Eocene in the transition zone between the Eastern Cordillera and the Huallaga foreland basin, which corresponds to the inverted border of the Triassic



rift where a significant thickness of the Aramachay black shales was deposited (>300m). Liquid hydrocarbons and associated water may have carried Cu and accumulated in structural traps containing the Sarayaquillo and Cushabatay sand reservoirs during the early Miocene, which is the period of development of the first major thrusts of the western Huallaga FTB (Baby et al., 2018). As in the previous cases, late Neogene Andean tectonics uplifted and eroded the structural traps, allowing ore deposits to rise near the surface. The Triassic evaporite level of the Huallaga Basin, which formed the main detachment for the thrusts system, is an excellent fluid pathway from source to deposit. Indeed, Cu mineralization and still active oil seeps can be observed in the Huallaga evaporites.

5. Conclusions

The Paleogene and Neogene fold and thrust belts of northern Peru show concomitant petroleum and mineral systems. Regardless of the source rock of the ore deposits (magmatic or sedimentary), the characterization of the components of the petroleum system is a valuable tool for assessing the mineral resources. Hydrocarbon and ore deposits are found in the same sedimentary reservoirs and structural traps and are driven by the same tectonic processes. The fluid pathways and fluid migration periods are also often the same.

As with the petroleum system, the mineral system components must be explored on a basin scale by correctly defining the structural and sedimentary architectures using techniques such as balanced sections, and where possible seismic reflection data. Given the importance of the organic matter in the formation of sediment-hosted ore deposits, oil source rocks need to be further investigated to define the period of the expulsion-migration of hydrocarbons and the possible initial metal content in their thermally immature form.

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