Extension of the Late Triassic salt into western Peru: Implications for Andean tectonics and mineral exploration

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1. Introduction

A better understanding of large- and small-scale Andean geological features and timeline can obviously make a difference in exploration. Knowledge of the Andean evolution continues however to be plagued by geological myths and obsolete concepts (such as "compressional tectonic phases" and "ocean-continent collision"), while major key features of this evolution remain underrated.

One of these key features is the "Mitu interval", during which the Peruvian margin was submitted to intense extension starting ~240 Ma. These extensional conditions caused intense back-arc rifting along the margin, and a related thick accumulation of sediments (and subordinate volcanic rocks), ranging from terrestrial clastics (the Mitu Group, 240–~215 Ma) to shallow-marine carbonates (the Pucará Group, ~210–≤170 Ma). This rift basin was also the locus of thick salt accumulation approximately during the ~215–~210 Ma interval (the Pareni Formation, or Pareni Salt), making that western Peru was occupied by a giant salt basin during part of the Late Triassic (Sempere & Cotrina, 2018; Berrospi et al., 2018). Previous attributions of this major salt unit to the Permian are wrong (Sempere & Cotrina, 2018).

Most of the western rim of Amazonian Peru is indeed characterized by abundant salt and other evaporites, as documented both by numerous outcropping diapirs and in seismic information (Sempere & Cotrina, 2018). In the high Andean plateau, where no Permian strata occur, the San Blas salt dome pierces the Pucará limestones southwest of Lake Junín, and gypsum occurs between the Mitu and Pucará groups, being mined at a number of places, such as ~16 km WNW of the city of Tarma. Elsewhere in central Peru, effects of salt tectonics can be detected at least along the Cordillera Oriental (Berrospi et al., 2018).

Sempere & Cotrina (2018) showed that this salt and related other evaporites must have originally represented a considerable volume (>100,000 km^3 as a minimum). Halokinesis vigorously developed during the Jurassic and continued through later times, generating a variety of salt-tectonic deformations (which were generally misinterpreted as resulting from thrust tectonics due to influence of the mainstream compressional paradigm).

In this preliminary paper, we address the issue of the western extension of this giant salt basin, and briefly review the implications of the existence of voluminous salt and other evaporites for Andean tectonics and mineral exploration.

2. Rationale

Salt is notoriously prone to upward and/or lateral migration and withdrawal, and to dissolution (particularly in outcrops and shallow subsurface). These features explain why salt, although abundant in the sub-Andean subsurface, is currently rare in Andean outcrops. The San Blas salt dome (*Figure 1*) proves however that salt was originally deposited at least 100 km west of the present-day sub-Andean belt.

Our ongoing research suggests that most of the other Andean occurrences of salt in southern Peru and Bolivia are likely to be of the same age, and to have caused salt-tectonic deformation in the huge region delineated in *Figure 1*.

In order to outline the original extension of the salt basin, we must therefore rely on a number of features that can be used as proxies for tracing the initial salt. These proxies include the following features:

2.1. Association with other evaporites

In the Late Triassic rift basin, salt accumulated along with other evaporites such as gypsum and anhydrite, as confirmed by a variety of observations (*e.g.*, Benavides 1962/1968; Marocco, 1975). Thus outcrops of these sulfates, especially where they are stratigraphically located between the Mitu and Pucará groups, can be used to outline the original extension of the "salt" basin.

Figure 1. Outline of the possible extension of the salt basin, considering both autochthonous and allochthonous salt. Blurry symbols indicate an imprecise position. Line 1: eastern limit of autochthonous salt (hypothetical in southern part of map); line 2: hypothetical western limit of salt (which is expected to have been in part allochthonous); line 3: position of the magmatic arc during Pucará times (the actual arc was broader than the illustrated line); all lines are hypothetical where thin or blurry. This map does not show the other elements used to construct it, such as the numerous occurrences of other evaporites and the structural proxies detailed in text. This map suggests that the salt basin should be expected to extend into Ecuador, but no corresponding salt has been reported from this country so far (see Baby et al., 2014).

2.2. Structural effects of salt tectonics

The existence of thick salt at a specific stratigraphic position is well known to trigger generally complex and protracted deformation in the overlying strata, referred to as halokinesis and/or salt tectonics, starting when the overburden has become dense enough and an instability is created (*e.g.*, Jackson & Hudec, 2017).

Structural features strongly suggestive of fossil salt tectonics deforming post-Mitu strata crop out nearly all over sub-Andean and Andean Peru. It can be commonly observed that the Pucará Group and younger units (i.e., above-salt units) exhibit atypical folding whereas, in contrast, older, below-salt post-Devonian units were characteristically deformed in a much simpler way. Soft-sediment deformation of the Condorsinga Formation (the Early Jurassic portion of the Pucará Group), as observed along the eastern rim of the Cordillera Oriental of central Peru (Berrospi et al., 2018), confirms that salt tectonics developed as early as the Early Jurassic (Sempere & Cotrina, 2018).

2.3. Weak level used as detachment

The original occurrence of thick salt and other evaporites between the Mitu and Pucará groups implied a significant rheological discontinuity, which must logically have generated a major detachment level during later deformations. This is indeed observed in Andean central Peru: Mégard (1978) described a key outcrop near Matasenca (see Sempere & Cotrina, 2018), and other areas presenting a detachment at the same stratigraphic level are being currently studied (*e.g.*, Berrospi et al., 2018). The occurrence of detachments or décollements at or near the contact between the Mitu and Pucará groups may thus be used as a proxy for original presence of salt (see below).

2.4. Weak level used by magma emplacement

Due to the rheological weakness and high solubility of sodium chloride, the initial existence of thick salt between the Mitu and Pucará groups is logically expected to have provided magmatism with a preferred level of sill emplacement.

One case of such emplacement of magma as a sill at this very stratigraphic location exists in the Río de La Leche valley, near Hacienda Mayascón (~6.411ºS, ~79.557ºW). In the same area, the La Leche Formation (consisting dominantly of carbonates, and partly a time-equivalent of the Pucará Group) displays a deformation style that is suggestive of fossil salt tectonics. This case strongly suggests that the Pareni Salt was also deposited in near-coastal northern Peru (*Figure 1*), which helps to delineate the salt basin and hypothesize its 3-D geometry (see below; *Figure 2*).

3. Implications for mineral exploration

3.1. General considerations

Saline solutions are well known for their high ability to transport metal ions. The protracted occurrence of the thick Pareni Salt, of Late Triassic age, deeply buried within the Peruvian sedimentary pile can be expected to have made possible that basinal fluids be highly saline brines during a long period of time in the considered regions. Subsequent magmatism, where it was active but depending on local geometries, may also have mobilized available sodium chloride into highly saline fluids. We therefore believe that the existence of the Pareni Salt has represented a significant enhancing factor in the complex metallogenic history of Peru.

In this scope, taking into consideration the Pareni Salt may be useful for more accurate mineral exploration of regions where this unit is expected to have been deposited, following the type of reconstruction we have suggested above.

3.2. Pb-Zn MVT deposits

Genetic models of Mississippi-Valley-type (MVT) Pb-Zn deposits favor that evaporite-related structures play a major role in concentrating the flow of metal-bearing fluids (Leach et al., 2010a,b). The original existence of a thick salt unit (the Pareni Formation) just beneath the Pucará Group has significant implications for exploration of both MVT deposits and hydrocarbons in Peru, as subsequent salt tectonics created structural traps for later fluid migrations (Berrospi et al., 2018).

MVT Pb-Zn deposits in Peru are hosted in the ~0.5–2.5 km-thick Pucará Group, which largely consists of organic-rich marine limestones and dolostones and originally overlay the Pareni Salt. These deposits occur in "metallogenic belt XVI" defined by Quispe et al. (2018). In the vicinity of significant MVT Pb-Zn deposits (e.g., San Vicente, Shalipayco, and the Bongará district), unusual and complex structural features are suggestive of salt-tectonics deformation of the Pucará carbonates by motion of the originally underlying Pareni Salt (Berrospi et al., 2018).

4. Conclusions

Identification of the Late Triassic Pareni Salt (and other associated evaporites) and recognition that related salt tectonics must have affected post-Mitu units open a new avenue for exploration, regarding both MVT deposits and hydrocarbons, and probably other issues of academic and economic interest (Berrospi et al., 2018).

From a structural point of view, the existence of thick salt almost invariably generates halokinesis and provides a weak level for any kind of subsequent deformation of the overlying stratigraphic pile. In the wide area delineated in *Figure 1*, it is therefore likely that the deformation observed in Andean Peru has been in some way partly a consequence of the original occurrence of thick salt.

In particular, because halokinesis is documented to have started at least in the late Early Jurassic (Sempere & Cotrina, 2018), tracing Jurassic deformation allows to spot probable areas of coeval salt tectonics. For instance, mid-Cretaceous strata post-date significant deformation (including folding) of earlier units in a broad region of southern Peru (Sempere et al., 2002).

Our ongoing research, which is only outlined in this preliminary communication, strongly suggests that the present-day northern Gulf of Mexico might provide a possible general analog of the *backarc* paleogeography of Peru between the mid-Jurassic and mid-Cretaceous (*Figure 2*).

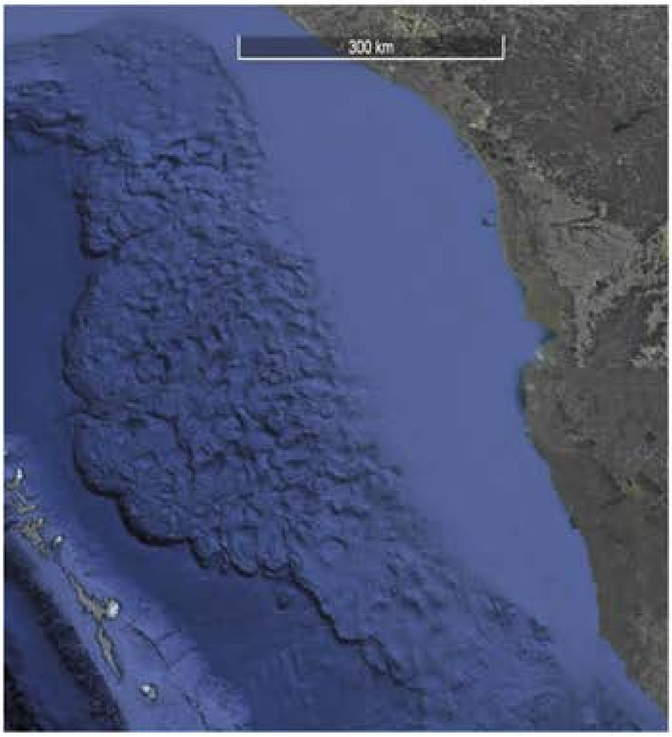

Figure 2. Possible analog of the paleogeography of Peru at some time during the mid-Jurassic to mid-Cretaceous interval, largely inspired by the present-day features of the northern Gulf of Mexico (this comparison is obviously valid only for the coeval backarc region of Peru). The idea of a salt canopy moving downslope, as illustrated by the image, is part of the analogy (ongoing research).

In Bolivia, salt and other evaporites largely crop out in the Altiplano, and at specific localities in the Cordillera Oriental and sub-Andean belt. In particular, rock salt is mined at Entre Ríos, ~60 km east of Tarija in southernmost Bolivia (*Figure 1*), from the Ipaguazú Formation, a unit reliably dated also as Late Triassic (Bertrand et al., 2014). This stratified salt is thus a far-away time-equivalent of the Pareni Salt, a correlation that bears important implications regarding the original extension of this giant salt basin in the Central Andes (*Figure 1*).

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