Structure of the Cordillera de la Sal: A key tectonic feature for the Oligocene-Neogene evolution of the Salar de Atacama basin, Central Andes of Northern Chile.

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Abstract. The Salar de Atacama basin is the main topographic low in the Preandean Depression of the Central Andes of Northern Chile. The integration of seismic reflection and surface structural data along the basin allows constrain the Oligocene and Neogene tectonic activity of the Salar de Atacama. A key element to unravel the Neogene to recent history of the basin is found along the Cordillera de la Sal which comprises more than 3,000 m of continental sedimentary successions belonging to the San Pedro Formation. Detailed analysis of the seismic information shows that large depocenters involving distal alluvial facies and evaporitic members of the San Pedro Formation were accumulated in close relation with Oligocene extension. Extension was controlled by a first order normal fault located along the western flank of the basin. The rise of the Cordillera de la Sal ridge involved compression and sinistral strike slip in its south domain, in combination with salt diapirism in its north domain, this transition is related to a change in the depth of the detachment level from 4000 to 6000 m south to north, this detachment is mainly associated with the evaporitic lower members of the San Pedro Formation.

Keywords: Salar de atacama, Cordillera de la sal, San Pedro Formation, salt tectonics, Neogene.

Introduction

The Salar de Atacama basin is located along the driest region on Earth, the Atacama Desert, within the Central Andes of northern Chile, and represents one of the best examples of salt tectonics occurring in collision zones (Hudec & Jakson, 2007). Crustal thickening, tectonic shortening and magmatism have occurred in this region due to an almost uninterrupted subduction of the oceanic Nazca plate beneath continental South America plate at least since Jurassic times (Isacks, 1988). In this plate boundary near-orthogonal convergence is registered at a rate of 50–150 mm/yr since ca. 50 Ma (Somoza, 1998; Pardo-Casas and Molnar, 1987). Neogene shortening has concentrated mostly in the back-arc region (Baby et al., 1997; Arriagada et al., 2008, and references therein); although there is evidence of moderate active tectonics in the forearc of the Central Andes (Farias et al., 2005; Riquelme et al., 2003).

The Salar de Atacama basin is the largest and widest topographic low of the Preandean Depression, a roughly N-S trending array of basins and depressions located in the forearc between 22º and 27º S, flanked to the east by the current volcanic arc (Western Cordillera) and to the west by the Cordillera de Domeyko (Chilean Precordillera) (Fig. 1). Many of these basins are internally drained (endorheic) as a consequence of tectonics and arid climate (Chong Díaz, 1988; Reutter et al., 2006).

In spite of the numerous models that explain the geologic evolution of the Salar de Atacama (Macellari et al., 1991; Flint et al., 1993; Wilkes & Görler, 1994; Muñoz et al., 2002; Pananont et al., 2004; Arriagada et al., 2006; Jordan et al., 2007; among others), there is no consensus about the internal structure of the basin. Several studies have been focused in the Cretaceous-Tertiary tectonic evolution of this part of the Andes, however, the origin of the Cordillera de la Sal and its relation with evolution of the Atacama basin is still a matter of debate. The Cordillera de la Sal, reaching 200 meters above the western side of the Salar de Atacama represents a large structural high exposing a notable en echelon array (Fig. 1); this ridge shows strongly folded and faulted Tertiary strata. Here we analyze the internal structure of the Oligocene-Neogene deposits belonging to the Cordillera de la Sal based on seismic reflection and surface data. A 3D model of the ridge has been produced in order to better constrain the structural evolution of the Atacama basin.

Geology of the Cordillera de la Sal

The Cordillera de la Sal is composed by evaporites and terrigenous Oligocene-Miocene rocks of the San Pedro Formation, unconformably overlain by the upper Miocene-Pleistocene Campamento Formation and the Pleistocene-Pleistocene Vilama Formation, in Southern and Northern Cordillera de la Sal, respectively (Fig. 1). These Tertiary units include several series of sedimentary evaporitic and terrigenous-siliciclastic rocks.

According to the nature of the structures within, the Cordillera de la Sal can be subdivided in two domains (Fig. 1). Southern domain is characterized by extensive array of anticlinal and synclinal folds. Transversely, this system varies geometrically from an overturned fold (eg, La Paciencia anticline), at the western end, and a slightly symmetric open fold at the eastern end of the Cordillera de...
la Sal (e.g., Los Vientos anticline). The Los Vientos anticline, in both east and west, limbs exposes the upper terrigenous members of San Pedro Formation unconformably overlain by the Campamento Formation, while the La Paciencia anticline exposes lower evaporitic members of the San Pedro Formation acting as a salt core, and a back limb to the east that exposes the overlying members, the upper contact with the Campamento Formation is unconformably too. Both flanks of the Cordillera de la Sal in its southern domain are flanked by inverse faults, La Paciencia fault to the west and Los Vientos fault to the east.

**Data base and methods**

We studied the internal architecture and stratigraphy of the Cordillera de la Sal based on detailed geological mapping (1:100.000; according to Becerra et al., 2014 and Henriquez et al., 2014), new seismic reflection data and previously published (Muñoz et al., 2002; Pananont et al., 2004; Arriagada et al., 2006; Jordan et al., 2007) and structural cross sections. We constructed our model with the 3D-modelling software 3D-Move (© Midland Valley Exploration Ltd) by creating structural surfaces which represent key stratigraphic horizons like the top or bottom of members of the San Pedro, Campamento and Vilama Formations. To better constrain the 3D model, seven cross sections were constructed through the Southern Domain of the Cordillera de la Sal (see Fig. 1). Main structural features as faults and detachment levels well shown in seismic information were key elements to create the 2D sections. Finally, to build the three-dimensional surfaces, lines from each cross section were collected and linked together using de “Spline” interpolation algorithm of the 3D-Move software.

The restoration of the structure was performed using the Fault Parallel Flow method, this algorithm models hanging wall deformation in response to fault movement and geometry, this deformation is accommodated by fault-parallel shear of the beds over a fault surface (Kane et al., 1997). One of the most important advantages of this 3D restoration algorithm is that allows trans-tensional, transpresional or entirely strike slip movements to be modeled so the kinematics of the main thrusting events in the Cordillera de la Sal can be better constrained.

**Extensión and inversion structures**

Several authors have proposed that extension or transtension occurred in the Salar de Atacama during the Oligocene (Flint et al., 1993; Pananont et al., 2004; Jordan et al., 2007). Pananont et al. (2004) shown up to 5 km slip of normal faulting controlled the accumulation of the San Pedro Formation in the northwestern part of the Salar de Atacama, acting as a boundary of the basin during the Oligocene (see Fig. 7 in Jordan et al., 2007). In the southern part of the Cordillera de la Sal, evidence of syntectonic accumulation can be found along a 3 km slip measured at depth on a normal fault. The syn-extensional growth strata are well correlated with the San Pedro Formation while the thickness increases to the west and to the north of the basin (Fig. 2). Probably the normal fault recognized by Pananont et al. (2004) is part of the same fault system that we have found in the southern Atacama basin, which imply that the western border of the basin was controlled by a major extensional border during the Oligocene.

Compression took place in the Salar de Atacama during middle to upper Miocene (Wilkes & Görler, 1994; Pananont et al., 2004; Reutter et al., 2006; Jordan et al., 2007). Shortening was mostly accommodated in the Cordillera de la Sal, raising the ridge in different styles from south to north as described above; much of this inversion was accommodated by salt-cored folding and diapirism rather than slip along the former extensional faults, this is in agreement with the salt-related deformation models from Letouzey et al. (1995). From seismic data and the 3D model it is possible to visualize a main west dipping detachment at 4000 m (1-2 s TWT) depth in southern Cordillera de la Sal (Fig. 2), allowing the idea of a main vergence towards the east for the Cordillera de la Sal ridge (Muñoz et al., 2002; Reutter et al., 2006), although the La Paciencia antcline shows a clear sense of transport to the west, the tendency to form pop up structures induced by a symmetric stress system is a common feature in salt tectonics (Letouzey et al., 1995). Diapirism in northern Cordillera de la Sal occurred between 17 and 10 Ma (Pananont et al., 2004).

**Controls on the structural styles of the Cordillera de la Sal**
The transition from the South Domain to the North Domain of the Cordillera de la Sal coincides with deepening of the detachment level; this feature can be followed through the Llano de la Paciencia and Cordillera de la Sal in seismic sections from southern to northern Cordillera de la Sal, reaching depths from 4000 m to 6000 m, respectively (Fig 3). This detachment is associated with evaporitic levels of the Paleocene Naranja Formation on its South Domain (Muñoz et al., 2000; Arriagada et al., 2006), and with the Oligocene lower San Pedro Formation to the North (Muñoz et al., 2002), this feature also coincides with the increasing thickness of the Oligocene deposits to the north (Wilkes & Görl, et al., 1994; Muñoz et al., 2002; Pananmont et al., 2004; Jordan et al., 2007). These antecedents validate the idea of the Neogene deformation being controlled by the mechanical stratigraphy of the basin fill (Muñoz et al., 2000, 2002).

3D restoration parameters of the Los Vientos anticline through the Fault parallel flow can be seen in Table 1. Restoration of Los Vientos Anticline to a horizontal plane equivalent to the footwall east of the range was successfully performed (Fig. 4). Our results suggest that the tectonic inversion in the Salar de Atacama and the rise of the Cordillera de la Sal involved sinistral transpression; this could be controlled by the orientation of the pre-existing normal fault planes in relation with the regional stress field during compression (Letouzey et al., 1990).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Transport Plane</th>
<th>Slip (m)</th>
<th>Shear</th>
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<tr>
<td>Los Vientos Anticline</td>
<td>Azimuth 95</td>
<td>Dip 15°N</td>
<td>1000</td>
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Table 1: Parameters of restoration of the Los Vientos Anticline.

**Conclusions**

Tectonic inversion in the Salar de Atacama during the Oligocene-Neogene period in the evolution of the basin is described for the first time. Extension was controlled by a first order km-scale normal fault in its western border, while in the eastern border the Tertiary units were deposited in onlap on the basement. The north increase in the thickness of the Oligocene synextensional evaporites of the lower San Pedro Formation play a key role in the development of the Neogene Cordillera de la Sal. According to 3D retrodeformation performed in the South Domain, this ridge was uplifted through sinistral transpression. The Cordillera de la Sal changes its deformation mechanism from south to north in response to a deepening of the main detachment; this level is associated with the evaporites of the basin fill and shows the structural control of the evaporite layers in this major example of salt tectonics in the Central Andes. The inversion of this salt-floored basin could be an attempt to understand the development of the Preandean Depression, a still controversial morphostructural unit in the Central Andes.

**References**


Figure 1: Left: Elevation model of the Salar de Atacama basin, showing the structural features and the location of the structural cross sections. Right: Geology of the Cordillera de la Sal.