OROGENIC-SCALE GROUND WATER CIRCULATION IN THE CENTRAL ANDES: EVIDENCE AND CONSEQUENCES

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INTRODUCTION

The Salar de Atacama, Chile, accumulated an estimated 3000 km^3 of halite during the last roughly 5 million years. We propose that the principal water supply to the closed drainage salar during that time has been deep ground water (Fig. 1). It is the ground water that transports the Na, Cl, and associated ions to the salar, where evaporation under a hyperarid climate generates evaporite minerals. Precipitation infiltrates in the less arid Altiplano-Puna plateau, located E, N, and S of the Atacama basin, and flows as ground water toward into the Atacama basin. Ground water circulation from the Andean interior to the lowland flanks would have existed since uplift began but, we propose, the halite initiation near 5 Ma marks the time when the magnitude and form of the topography reached states similar to today's.

AGE AND VOLUME OF ATACAMA HALITE

The subsurface geology of the Salar de Atacama is constrained by hundreds of km of seismic reflection data (property of ENAP), a 5000 m deep borehole (Toconao-1) for which cuttings descriptions and wireline logs exist, and tens of cores ranging in length from 40 to 500 m (property of brine-mining company SQM). Direct age constraints come from U-series dates of halite in two SQM cores (Bobst et al., 2001; Lowenstein et al. in review) and a K-Ar date of an ignimbrite horizon in core 2106 in the SE zone of the salar (Bevacqua, 1991).

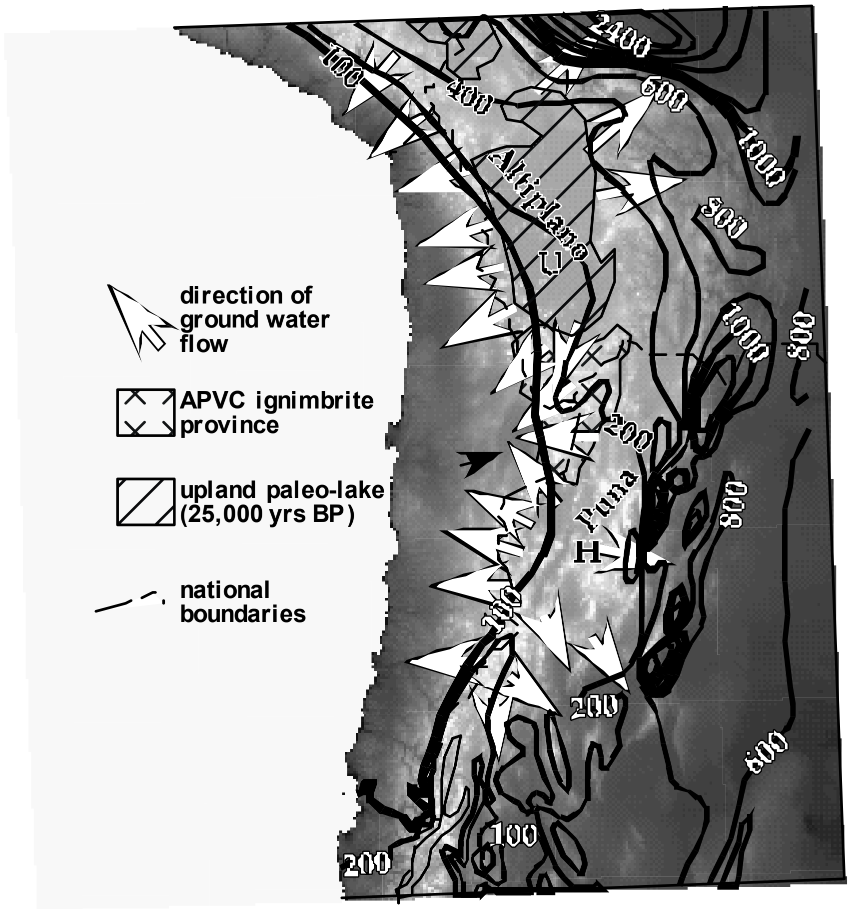

Figure 1. Grayscale topography of the Central Andes, showing location of Atacama Basin and major elements of the hydrology. White to light gray represents high elevations, mostly in the Altiplano-Puna plateau. Salars for which the history of late Pleistocene lakes is well documented are Uyuni (U), Hombre Muerto (M), and Atacama. Contours are mean annual precipitation (mm).

We mapped the base of the Halite Unit, as defined in Toconao-1, throughout the salar subsurface following reflection continuity (Jordan et al., in review). We also mapped 8 stratigraphic sub-sequences within the Halite Unit. Conversion of the seismic travel time to depth leads to the estimate that the volume of the Halite Unit is approximately 3000 km^3.

The ages of two Pliocene horizons are well constrained. First, the dated 3.1 Ma ignimbrite of core 2106 (Bevacqua, 1991) correlates with the 3.1 Ma Patao Ignimbrite and/or 3.2 Ma Tucucaro Ignimbrite, which cover broad regions immediately E and S of the salar (Ramirez and Gardeweg, 1982). We interpret a prominent negative-polarity reflection at the depth of 2106's dated ignimbrite as the seismic signal of ignimbrite. A reflection of similar character, likely also ignimbrite, occurs widely in the eastern periphery of the salar within Stratigraphic Subsequence 4. We correlate that seismically identified ignimbrite (?), which underlies the 3.1 Ma horizon and spans the length of the salar, with the 4.0 Ma Atana - Toconao Ignimbrites. Lindsay et al. (2001) showed that the Atana-Toconao Ignimbrites totaled some 2500 km^3 in volume east of the salar, and are 35 m thick in outcrop only 20 km east of the salar margin. Consequently, the thick and widespread Atana-Toconao Ignimbrite set is anticipated to persist into the salar region. At greater depths in the E and NE, similar reflection characteristics below Stratigraphic Subsequence 4 likely reveal other ignimbrites, but we lack criteria for assigning ages to specific horizons. Comparison of the base of the Halite Unit to the seismically-identified ignimbrites (?) reveals that the base of the Halite Unit is younger than the oldest ignimbrites(?). The oldest exposed ignimbrites are approximately 10 Ma N of the salar, although near the E margin of the salar the oldest exposed ignimbrites are 5.8 Ma (Gardeweg and Ramirez, 1987; DeSilva, 1989; Lindsay et al., 2001). We bracket the base of the Halite Unit as older than 4 Ma and younger than 5.8 Ma or, at greatest, 10 Ma.

GROUND WATER AND NaCl

The majority of halite in the upper 200 m near the center of the salar crystallized a few tens of centimeters beneath the solid top crust of the desiccated salar, at the water table - air interface (Lowenstein et al., in review)). Times during the late Quaternary when Salar de Atacama was a salt lake correlate well with the history of high lake stands in the southern Altiplano (Bobst et al., 2001; Lowenstein et al., in review; Baker et al., 2001) but are markedly out-of-phase with the precipitation history of the Salar de Atacama drainage basin (Betancourt et al., 2000). This is easily reconciled if Salar de Atacama is fed by ground water, rather than by surface water, and if the ground water source is the plateau. A source of the water in the Altiplano is consistent with the isotopic composition of paleo-lake waters trapped as fluid inclusions (Godfrey et al., in review).

The traditional explanation of the upper Neogene halite has been its derivation by dissolution of the Oligocene-lower Miocene San Pedro Formation halite. In contrast, we interpret that the original volume of halite in the San Pedro was much less than the 3000 km^3 in the Plio-Quaternary Halite Unit. Instead, we propose that much of the NaCl must be delivered to the Atacama basin from other sources, including dehydration of the underlying Nazca plate, residual waters distilled from arc magmas, and surface weathering and subsurface leaching of Cl from typical crustal bedrock. For the modern drainage basin we estimate that the sum of NaCl supplied by operation of all of these processes is only a fraction of the halite now in the Atacama basin. However, the volume of halite in the Atacama basin can be accounted for if the source area of the solutes greatly exceeds the surface drainage area of the basin, and if the ground water that feeds the salar circulates deeply.

Deep circulation of ground water sourced in the Altiplano-Puna plateau toward the Chilean lowlands is the average response to the high elevation of the plateau. Indentation of the western slope of the plateau by the Atacama basin focuses flow toward the Atacama basin. Consequently, the Atacama basin receives an enhanced flux of ground water and dissolved ions. Ground water flow through hundreds of km of rock, to depth on the order of 10 km, would mobilize solutes from dehydration and/or magmas, and react with average crustal rock.

We hypothesize that halite came to dominate the Salar de Atacama basin when the topography reached a state similar to today's. An increase in elevation of the western half of the Andes Mountains between 10 and 5 Ma is consistent with major shortening of the upper crust along the Subandean eastern flank of the Andes commencing near 9 Ma (Echavarría et al., in review).

The Altiplano-Puna Volcanic Complex lies between the major late Pleistocene lakes of the Altiplano and the Atacama basin, and many of the largest ignimbrite eruptions were contemporaneous with halite accumulation. Topographically driven ground water flow would pump very large amounts of Altiplano-derived water through the APVC crust, possibly contributing to the wet conditions needed for explosive eruptions (Lindsay et al., 2001).

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