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Rates and geochemical processes of soil and salt crust formation in Salars of the Atacama Desert, Chile

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ABSTRACT

The hyperarid Atacama Desert contains numerous local basins with surficial salt crusts, known as salars, where evaporation of shallow groundwater drives the major soil processes. We examine chemical and isotopic profiles in two soils of differing ages from the Salar Llamara to determine the geochemical processes involved in their formation. Evaporation, which provides salts to the soils through mineral precipitation, decreases with increasing salt crust thickness, and average ~ 0.03 mm m^{-2} d^{-1} over geological time frames. Salt distribution varies predictably with depth and soil age, with the most soluble compounds concentrated nearest to the land surface, indicating the direction of fluid flow. $\delta^{34}S$ values of mineral sulfate tend to decrease with decreasing soil depth, following a pattern indicative of Rayleigh-like fractionation as solute-rich waters migrate toward the land surface. $\delta^{13}C$ and $\delta^{18}O$ values of carbonate suggest that the uppermost halite layers, which contain very small amounts of carbonate, have a strong biological signature. In contrast, carbonate-rich layers deeper in the profiles consist of largely unmodified lacustrine carbonate that formed in highly evaporitic lake conditions. The continuous upward evaporation of water and dissolved solutes creates a rugged and physically dynamic halite crust composed of rounded salt nodules. The crust undergoes deliquescence as atmospheric relative humidity rises from marine air intrusions, and we found that the halite nodules on the surface of the Salar Llamara are nearly always at or above deliquescence relative humidity. The interiors of these nodules are therefore able to buffer the large diurnal changes in atmospheric relative humidity allowing for the survival of halophilic microbial communities in an otherwise very dry environment. Radiocarbon measurements of occluded organic C in the surface crusts indicate that C cycling occurs at differing rates depending on local micrometeorological conditions, and that a given salt crust feature may persist for thousands of years once formed.

1. Introduction

Geochemical processes in the Atacama Desert are limited by water. Most of the region consists of uplands and alluvial fans dependent on sparse rainfall (<2 mm y^{-1}) to drive soil and geochemical processes. However, the region also contains closed basins that receive both surface runoff and subsurface flow from the adjacent High Andes. Once a lake or wetland is desiccated, the evaporation of shallow groundwater by capillary flow promotes an upward movement of solutes, a direction that is the reverse of the normal water trajectory of most desert soils (Finstad et al., 2014). Studies of soil formation in these geological settings are very limited, and none have been conducted in northern Chile.

In Chile, salt covered evaporitic basins are called salars and are distinguishable by the hard salt crusts commonly found on their surfaces (Chong, 1984; Ericksen and Salas, 1990). Approximately half of the salars in northern Chile contain halite (NaCl) crusts, an area of >4000 km^2 (Stoertz and Ericksen, 1974). Most of the salars are located in the Andes, with only a handful in the Central Depression near to the Pacific coast. Salars in this region of the world are of growing significance. First, they contribute to an understanding of climate and hydrologic change, providing insight into both regional environmental changes and patterns of occupation by early hunter-gatherers and agriculturalists (Latorre et al., 2013). Second, fluid migration and chemical fractionation have locally deposited economically viable concentrations of iodine, boron, and other salts (Boschetti et al., 2007; Perez-Fodich et al., 2014; Chong et al., 2000). Finally, and somewhat paradoxically, salt crusts on the surface of salars can

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harbor microbial communities persisting on liquid water obtained through the deliquescence of halite (Davila et al., 2013). Presently, there is only a preliminary understanding of the geological evolution of these crusts and on how these processes influence the microbial communities (Artieda et al., 2015).

A pedogenic process-oriented understanding of salar evolution is still lacking. The objectives of this paper are twofold. First, we wished to characterize the resulting chemical nature and properties of the soils from the continuous evaporation of shallow groundwater and calculate rates of long-term water evaporation and salt accumulation. Second, we hoped to develop a conceptual model of surface halite crust formation and assess the capacity of this unique environment to support microbial life. We focused on two sites in the Salar Llamara, one 15,484 cal yr BP and one 19,348 cal yr BP, to examine the chemical and isotopic evolution of these soils at different time steps, with the goal of monitoring the soil environment to provide constraints to process-based models of water and salt movement.

2. Geological setting

The Salar Llamara lies in the Central Depression in northern Chile (Figs. 1 and 2). Since the Miocene the area has been part of an evaporitic basin, one which developed an outlet to the Pacific Ocean sometime in the late Pliocene or early Pleistocene (Pueyo et al., 2001; Saez et al., 1999). In the more recent geological past, the area of evaporite deposits is constrained to an area of approximately 205 km^2. Lakes or wetlands were likely formed during episodes of increased Andean runoff (Gayo et al., 2012; Nester et al., 2007; Rech et al., 2002), and their subsequent drying has formed distinctive salar characteristics. The surface is primarily covered with a dense, rugged salt crust composed of sodium chloride. Rounded features, referred to as salt nodules, are common features of Coastal Range and Central Valley salars, developing from the slow recrystallization of salt on the surface in the absence of precipitation (Stoertz and Ericksen, 1974), influenced by the presence of fog.

One site is located on a young unit of lacustrine origin, mapped as PlHs (undifferentiated Pleistocene-Holocene saline deposits of halite, sulfate, and nitrates). The other site is slightly higher in elevation and is either lacustrine in origin or formed on the distal end of an alluvial fan, and is mapped as PlHa(p) (Pleistocene-Holocene alluvial deposits of antiquity, playa facies) (Quezada et al., 2012) (Fig. 3). For simplicity, we refer to them here as Qh and Qp, respectively. Underlying the halite crust in both locations is a very fine-grained, laminated sediment consistent with a lacustrine or distal alluvial fan depositional environment. Occasional strata of what appear to be freshwater marls are also present in the Qh profile, which indicate the past occurrence of standing water

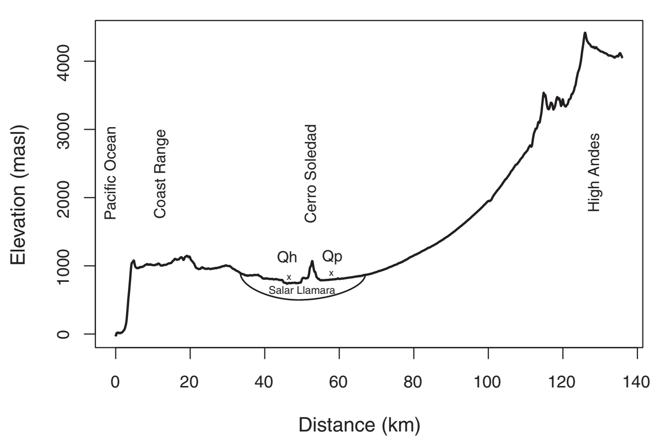

Fig. 1. Elevation profile of the Salar Llamara and field sites. The Salar Llamara sits in the Central Depression created by the High Andes to the east and Coast Range to the west. Digital elevation model (DEM) was taken from GeoMapApp (www.geomapapp.org).

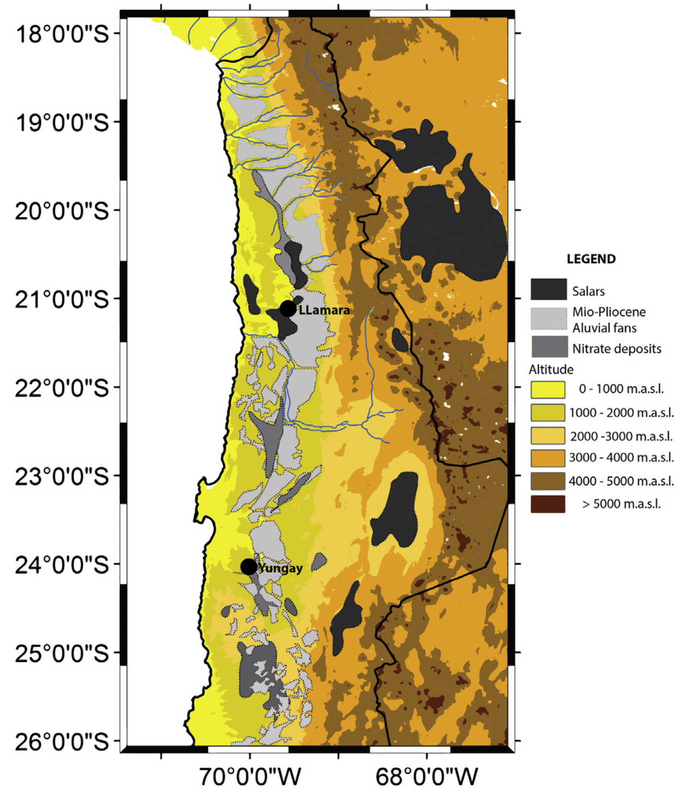

Fig. 2. Location of the Salar Llamara within the Atacama Desert, Chile. Salar deposits are shown in black, nitrate deposits in gray, and Mio-Pliocene alluvial fans in light gray. Figure from Finstad et al. (2014).

in this location. Radiocarbon dating of organic matter within the sediments revealed generally declining ages with decreasing depths, and distinctive age differences between the two sites. The Qh ages range from 12,209–15,484 cal yr BP, and samples from the Qp site range from 19,144–19,348 cal yr BP (Table 1).

Sites for soil excavations were selected for study based on examination of satellite imagery and field observations. A few open pits or stream exposures revealed that our sites appear to be representative of large regions of the landscape. Due to both the cost of sensors and the difficulty of excavation (which requires a jack hammer), we conducted the detailed research on one profile for each landform.

3. Materials and methods

3.1. Site description and soil sampling

Soils were excavated to depths of >1 m with the assistance of a portable jackhammer. Soil features were identified and described using methods outlined in the USDA Soil Survey Manual (Soil Survey Staff, 1999). Bulk soil samples of identified horizons were placed in zip lock bags and transported back to the lab. For the chemical and mineralogical measurements made here, this storage strategy likely had no effect on resulting data. Subsamples were taken in ~5 cm increments from the Bzm horizon of each soil for $\delta^{37}Cl$ analysis (Fig. 4). Three halite nodules from each site were also collected for subsequent study, and a groundwater sample was obtained from a backhoe trench that had been emplaced near the Qh site. Soil, halite nodules, and water samples were collected in June 2013. The chemical and isotopic analyses described below were conducted beginning in August 2013 and continued through February 2016.

Additionally, two radiocarbon ages obtained in 2009 (but previously unpublished) are included in the discussion to further constrain the timing and rates of lake drying and soil formation. This includes a