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Isotopic characterization of late Neogene travertine deposits at Barrancas Blancas in the eastern Atacama Desert, Chile

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ABSTRACT

Here we explore the potential of spring-related, surface and subsurface carbonates as an archive of paleoenvironmental change at Barrancas Blancas, located in the broadest and driest sector of the Atacama Desert at 24.5°S. From these deposits we present a new stable isotopic record of paleoenvironmental conditions over portions of the past ~11.5 Ma. U-Pb dates from the carbonates, both surface and subsurface, demonstrate that springs have discharged at this location over much of the last 11.5 Ma, attesting to the exceptional geomorphic stability of the central Atacama. Many of the sampled vein systems line vertical fissures, and formed within the aquifer before groundwater discharged at the surface. Carbonates in such circumstances should not undergo off-gassing and kinetic fractionation prior to formation, simplifying the interpretation of their isotopic composition. Oxygen isotopic compositions of carbonates are generally high (> −5‰VPDB), and using paleospring water temperatures of 3–13 °C reconstructed from clumped isotopes, point to strongly (up to 50%) evaporated water isotope values, like those associated with the hyperarid core of the Atacama Desert today. Carbon isotopic compositions are also high (≥ +3‰ PDB), reflecting a recharge area essentially devoid of plants and dominated by volcanic CO_2, as is the case today. Our isotopic results are very similar to those from the Calama Basin to the north, suggesting that the western face of the Andes between 21 and 25°S has been highly evaporative and nearly plantless when these springs discharged over the last 11.5 Ma. The spring carbonates at Barrancas Blancas strongly resemble those found at Devils Hole and Furnace Creek in Death Valley, USA, and as such warrant further exploration as potential archives of climate change.

1. Introduction

Spring deposits are receiving increasing recognition as significant archives of paleoenvironmental change in the Atacama Desert (Betancourt et al., 2000; Rech et al., 2002; Quade et al., 2008) and elsewhere (Winograd et al., 1992; Pigati et al., 2014). Springs are fed by meteoric water that falls on the local catchment area, and clastic and mineral deposits associated with springs fed by this rainfall record changing environmental conditions averaged across that recharge area. The stable isotope ratios of oxygen from mineralized spring deposits are useful in reconstructing changes in rainfall sources and air temperature, whereas those of carbon reflect on the nature and extent of plant cover. Other rare combinations of the isotopes of oxygen and carbon ("clumped isotopes") in carbonates can be used to reconstruct paleotemperatures at the point of mineralization.

Travertine is probably the most common of spring-related mineral deposits, and it forms by the precipitation of carbonate minerals in cold and thermal springs and streams in a wide range of climatic settings (Dictionary of Geological Terms, 1962). Many studies have examined the isotopic systematics of actively forming travertines, often with a view of exploiting their potential as paleoclimate archives (e.g. Usdowski et al., 1979; Amundson and Kelly, 1987; Matsuoka et al.,

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2001). Nearly all this work has focused on the surficial travertines, that is, travertine that formed at the surface or downstream of the point of spring discharge. After reaching the surface, spring water can evaporate and off-gas CO_2, sometimes leading to kinetic enrichment of ^{13}C, ^{18}O, and ^{2}H in residual water. This results in well-documented increases in the $\delta^{13}C$ and in some cases the $\delta^{18}O$ values of carbonate that precipitate downstream of the discharge point (Usdowski et al., 1979; Matsuoka et al., 2001). The rates of non-equilibrium loss of isotopes species are controlled a number of factors, such as water temperature, humidity, pCO_2 in the water and air, distance from the discharge point, water turbulence, and so forth. These factors are largely unknowable in the past, compromising the use of oxygen and carbon isotopes in surface travertines for paleoclimate reconstruction.

Far less recognized in the published record are carbonates that form in the subsurface, cementing the conduits that feed spring discharge at the surface. Here the circumstances of carbonate formation are quite different. By definition the conduits lie in the saturated zone, and as such do not experience the kind of rapid losses into the gas phase (i.e. evaporation and CO_2 off-gassing) experienced by spring water at the surface. These types of subsurface travertines or vein carbonates are recognized globally (e.g. Avigour et al., 1990; Uysal et al., 2007; De Filippis et al., 2012) but are perhaps best characterized in several localities in Death Valley USA, namely at Devils Hole and Furnace Creek (Winograd et al., 1985, 1992). There, carbonates cement the walls of the conduits in the aquifer systems that fed and still feed the springs in this area. They have accreted evenly and slowly (0.7 mm/1000 yrs) through glacial and interglacial cycles during the last several million years. The slow rates of accretion in a saturated underwater environment ensure equilibrium conditions of formation, to the extent that the subsurface vein carbonates at Devils Hole have been used by some studies to test and define equilibrium fractionation factors for the oxygen and carbon isotope systems (Coplen et al., 1994; Coplen, 2007; Kluge et al., 2014). This has permitted the reconstruction of changes in vegetation cover and recharge conditions in the high elevation catchment of the Devil's Hole system. These features of subsurface carbonates make them excellent potential paleoclimate archives (Winograd et al., 1985, 1992).

In this paper we present results from travertines at Barrancas Blancas that formed at the western foot of the Andes in the Atacama Desert of Chile (Fig. 1). This sector of the Atacama Desert between 18 and 26°S is arguably the driest region of the world, in its hyperarid core receiving < 10 mm/yr of precipitation below 1500 masl. The causes of this aridity are well known and include a mid-latitude position (18–30°S) south of subtropical Hadley circulation; orographic blockage of dominantly easterly moisture sources by the high-standing Andes (Houston and Hartley, 2003); continentality; decreased evaporation from the nearby Pacific Ocean by cold coastal currents (Hartley et al., 2005); and thermal inversion over the Pacific Ocean, thus inhibiting convection, and confining moisture to < 1000 m (Garreaud et al., 2010). Most of these features have probably characterized this latitude of South America since at least the early Cenozoic (Marty et al., 1988; Randall, 1998; Hartley et al., 2005; Canavan et al., 2014). However, interpretation of various proxies has led to a range of estimates from Oligocene to Quaternary for the onset of hyperaridity that characterizes the climate of the Atacama today (Sillitoe and McKee, 1996; Hartley and Chong, 2002; Dunai et al., 2005; Rech et al., 2006; Amundson et al., 2012; Sáez et al., 2012). Moreover, some research suggests that hyperarid conditions in the mid-Miocene gave way to wetter conditions in the Pliocene (Sáez et al., 2012; de Wet et al., 2015; Evenstar et al., 2015) in possible response to strengthening of El Niño-like conditions at that time (i.e. warmer coastal waters decrease the thermal inversion, which in turn favors advection of moisture inland – see Garreaud et al., 2010). Isotopic records from subsurface and surface carbonates such as at Barrancas Blancas can potentially address the many questions surrounding the temporal and spatial variability of hyperaridity in the Atacama, provided that the carbonates are datable and their isotopic systematics are well understood. Our ultimate goal is to reconstruct long-term hydroclimate in the recharge area (the neighboring high western Andes and Puna Plateau) of the Barrancas Blancas paleosprings. Here we present our initial survey, dating, and stable ($\delta^{13}C$, $\delta^{18}O$, Δ_{47}) isotopic characterization of all types of travertine from several key locations, but with particular emphasis on the cements from the subsurface vein systems.

2. Description of the springs and spring deposits

Barrancas Blancas is situated in the southeast quadrant of the Salar de Punta Negra basin, ~200 km southeast of the coastal city of Antofagasta (Fig. 1). The Cordillera Domeyko borders the western side of the valley, and the loftier western Cordillera of the Andes on the east side. Volcán de Llullaillaco (6739 m), 35 km northeast of Barrancas Blancas and one of the world's highest volcanoes, has one of the highest snowlines in the world at ~6500 m, further testimony to the hyperaridity of the region. Large alluvial fans descend steeply down the west flank of the Andes south of Llullaillaco, and onto the margins of Salar de Punta Negra (Fig. 1), a large phreatic playa in the valley bottom.

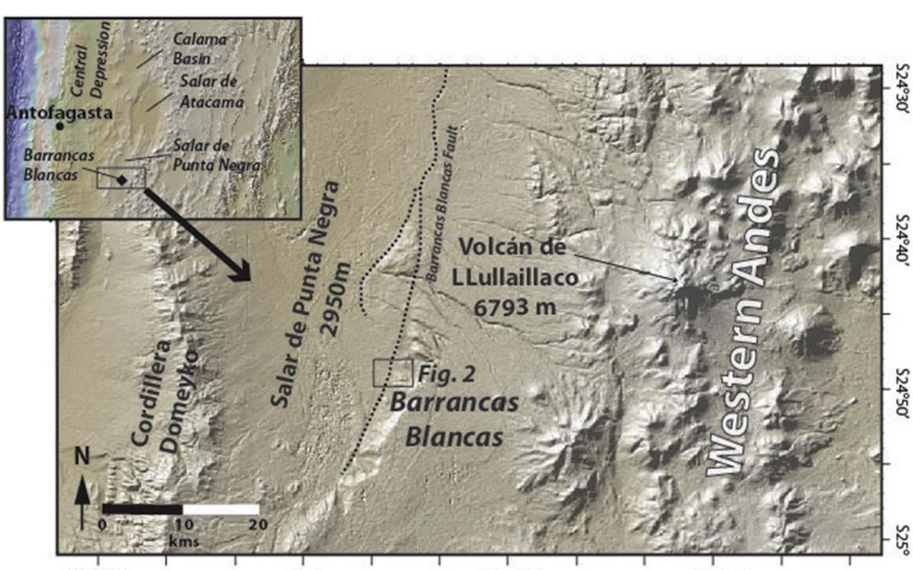

Fig. 1. Location of the study area at Barrancas Blancas at the foot of the western slope of the Andes. The springs at Barrancas Blancas are fed by recharge from the western Andes, including the towering Volcán de Llullaillaco (6739 m). The regional inset shows the major basins mentioned in the text and the coastal city of Antofagasta.