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Early to Middle Miocene climate in the Atacama Desert of Northern Chile

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ABSTRACT

The Cenozoic paleoclimate of the Atacama Desert is not well known. We examined 14 early to mid-Miocene paleosols exposed in the El Tesoro Mine, near Calama, Chile. The paleosols developed on an aggrading alluvial fan system, and lie above the mineralized gravel horizons that host a copper ore body. Soil-forming conditions that oscillated between chemical weathering and clay production (humid: analogous to modern Alfisols) to environments favoring the accumulation of pedogenic carbonate (arid to semi-arid: analogous to modern Aridisols) are indicated. In contrast, the region is presently hyperarid, and soils accumulate sulfates, chlorides, and nitrates. While total chemical analyses clearly show the accumulation of Ca by the carbonate-rich paleosols, none of the soils exhibit significant losses of elements by leaching. The $\delta^{18}O$ values of the carbonates range from -8.79‰ to −3.16‰ (VPDB). The O isotope data, when combined with published data from the region, reveal a significant divergence in the O isotope composition of precipitation in the eastern and western margins of the Andean plateau since the early Miocene, suggesting that simple interpretations of declining $\delta^{18}O$ values of carbonate with increasing elevation may not be appropriate. These paleosols clearly indicate that wetter conditions prevailed in what is now the Atacama Desert during the early to mid-Miocene.

1. Introduction

The detailed climate history of the present hyperarid Atacama Desert of northern Chile is poorly known, but parts of the history can be constructed from a variety of methods. In the Mesozoic, arid conditions are interpreted to have existed based on the presence of evaporite deposits of late Triassic (Suarez and Bell, 1987; Clarke, 2006) to late Jurassic (Hartley et al., 2005) age. In the earlier segments of the Cenozoic, terrestrial cosmogenic nuclide studies of old geomorphic surfaces suggest the preservation of landforms dating from the Oligocene/Miocene boundary (Dunai et al., 2005) or Early/Middle Miocene (Evenstar et al., 2009). The lack of erosion has been interpreted to indicate relatively arid conditions since then, with interspersed pluvial episodes occurring ca. 20 Ma, ca. 14 Ma, and ca. 9 Ma (Dunai et al., 2005).

While it is probable that there is considerable variability in the spatial and temporal patterns of climate conditions in the Atacama, regional climate change during the later part of the Cenozoic is likely linked, in some manner, to the uplift history of the Andes. There is paleosol evidence of hyperarid conditions as early as 13 Ma (Rech et al., 2006). Basin sediments in the northern desert have been interpreted as suggesting a Pliocene onset of hyperaridity (Hartley and Chong, 2002), while a suite of geomorphic evidence indicates a profound aridification in the southern Atacama Desert in the late Pliocene or early Pleistocene (Amundson et al., 2012). A resolution to these seemingly conflicting estimates of the onset of hyperaridity may involve relatively high climate variability throughout the Cenozoic with multiple episodes of aridity separated by wetter intervals (Jordan et al., 2014).

A challenge for understanding the climate history of this region is identifying a long and continuous archive that may capture dynamic climate states, instead of discrete geologic units in disparate locations. Here, we present data from a buried paleosol sequence exposed in an open-pit copper mine in alluvial sediments near Calama, in northern Chile. The sediments appear to have been deposited as alluvial fans along a mountain front, and periodic abandonment of the surface by lateral fluvial migration led to local deposition hiatuses that allowed soil formation. While the geochronology is not precisely constrained, the paleosols likely formed in early to mid-Miocene times. Our observations and analyses illuminate the early Neogene paleoclimate of this region of the Atacama Desert, and suggests that it consisted of periodic oscillations between humid and semi-arid end members, probably spanning millions of years.

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2. Study location and geology

The study was located in the El Tesoro copper mine, ~60 km SSW of the town of Calama (22°57′S, 69°5′W; Fig. 1) and located along the western flank of the Cordillera de Domeyko at a surface elevation of 2290 m above sea level (masl). At this exotic-type copper deposit, gravel sediments >800 m thick strike N–S to NNE–SSW and dip NW at 10°–25° (Fig. 2) (Mora et al., 2004; Tapia et al., 2011). The gravels are divided into two main units, with the upper (Gravas II, Gravas de Caliza of Tapia et al., 2011) unconformably overlying the basal (Gravas I, Gravas de Granito of Tapia et al., 2011) (Fig. 3). Gravas I hosts the copper mineralization horizons that are interpreted to have formed by meteoric waters leaching a porphyry copper ore body and subsequent lateral advection of the mineralized fluids into gravel zones with favorable permeability. Basement faulting associated with the Domeyko fault system subsequently down dropped and isolated the mineralized gravels from any further copper enrichment (Mora et al., 2004). Gravelly sediments continued to accumulate above the mineralization, though interrupted by a depositional hiatus and erosional episode marked by the unconformity between Gravas I and Gravas II. The paleosols studied here occur in the upper part of Gravas I and throughout Gravas II (Fig. 3). The parent material for the paleosols is comprised of mixed igneous and limestone clasts with typical diameters of 1–7 cm, occasionally up to 35 cm or larger. The mode of deposition is interpreted to be high-energy stream and sheet flood events, based on the clast-supported matrix, presence of trough cross lamination sedimentary structures and sub-rounded gravel lithomorphology with gravel provenance from the east and east-southeast (Tapia et al., 2011).

The region experienced considerable uplift, tilting, and faulting since Oligocene times (Jordan et al., 2010). The heads of many Miocene fans are abruptly truncated at ~4000 m by the deep escarpment that descends into the present Salar de Atacama; while paleosol and geomorphic considerations indicate that the eastern end of the fans may have been uplifted ~900 m since the late Miocene (Rech et al., 2006), with a tilting of 1.3° to the west along the N–S monoclinal axis (Jordan et al., 2010). As a result, the present geographical setting differs substantially from that during the alluvial deposition and soil formation recorded by the paleosols.

The mean annual precipitation (MAP) of nearby Calama is 4.2 mm (Houston, 2006), and mean annual temperature (MAT) is 12 °C. Except for stream margins, the region is plant-free. Surface soils are rich in gypsum/anhydrite in the upper ~1 m, and have accumulations of chloride and nitrates at greater depths (Ewing et al., 2006). Presently, carbonate-forming environments begin at ~3200 masl (Quade et al., 2007). The surficial geology consists of expansive dissected alluvial fans of Miocene age that have inset Plio-Pleistocene surfaces. As with much of the Atacama, Quaternary landforms are largely constrained to modern stream channels and washes, and the landscape surface is dominated by Tertiary deposits.

3. Methods

3.1. Paleosol field identification and sampling

In 2010, there were two large open pits at the El Tesoro Mine, and this research was located in the southern mine. The entry road into the mine was oriented in a sub-perpendicular direction to the sedimentary dip, allowing for the observation of ~200 m of stratigraphic section (Fig. 2). The section was walked and the exposures were cleared of dust. The section contained numerous paleosols, each of which is 1 to 3 m thick, separated by many tens of meters of non-pedogenic gravelly sediments. The paleosols were easily identified by reddening, disruption of sedimentary structure, and/or distinctive secondary carbonate—all typical of modern soils. Paleosols varied greatly in degrees of development, from slightly oxidized zones (representing very short durations of exposure), to very distinctive soil profiles. Thus, only the major soils exposed in the mine were logged, described, and sampled, and the sequence ultimately chosen consisted of 14 paleosols. The sampled paleosols were well distributed along the transect and we consider them to be representative of the pedogenic variability along the entire section.

Soil profile thickness was measured from the top of the contact between uppermost horizon and overlying unaltered parent material to the approximate base of pedogenic alteration. Each soil was morphologically described *in situ* (Soil Survey Staff, 1999). The paleosols were sampled by horizon for bulk soil material and carbonate-bearing clasts for geochemical and carbonate stable C and O isotope analyses. All paleosols were lithified to varying degrees, and sample collection usually involved a hammer and chisel. Samples of the overlying non-pedogenic gravel were also collected to represent unweathered parent material or to compare to the weathered material below. Detailed stratigraphic measurement of the non-pedogenic gravels and the gravel package as a whole was not possible due to access and time limitations in the actively producing mine at El Tesoro.

3.2. Laboratory methods

Bulk samples were disaggregated by light crushing in a mortar and pestle or by jaw crusher and then passed through a 2 mm sieve to separate the fine fraction. Munsell soil color value determinations were made on the dry <2 mm fine fractions. Sub-samples of approximately 150 g were taken from the <2 mm fraction to be analyzed for major

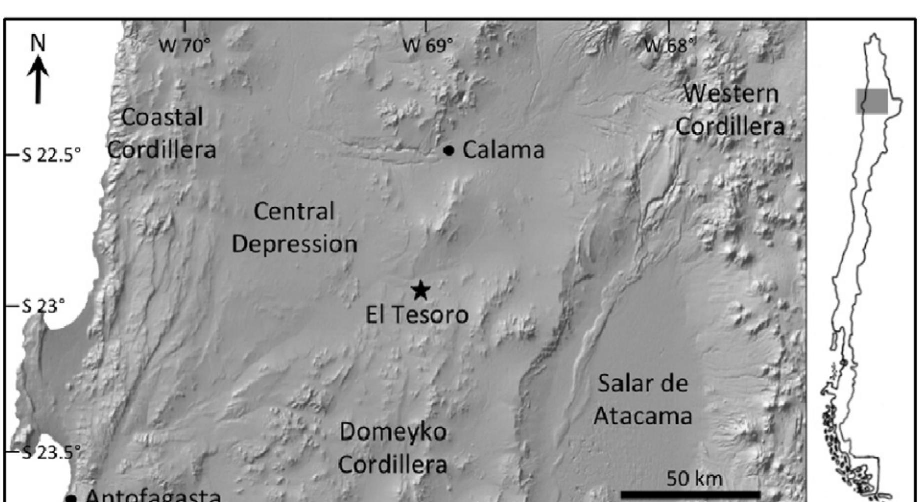

Fig. 1. Map of northern Chile with the El Tesoro mine location marked with star and nearby physiographic features.