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Relict soil evidence for profound quaternary aridification of the Atacama Desert, Chile

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ABSTRACT

A relict soil on a late Tertiary/early Quaternary gravelly alluvial fan in the southern Atacama Desert was studied to determine if evidence of Quaternary climate change was evident in the profile. Stratigraphic relations of soil morphological features indicated that the initial phase of soil development was extensive chemical weathering with the loss of Si, Na, etc. and the formation of secondary clay. This was then followed by a prolonged period of carbonate accumulation that has discontinuously impregnated the earlier formed argillic horizons. The carbonate accumulation occurred both as fine-grained accumulations that engulfed and expanded the gravelly soil matrix, and as carbonate that formed dense and continuous coatings on gravel bottoms. Overlying the carbonate is a Holocene calcareous sand unit. Stable C and O isotope profiles of the disseminated carbonate show that this material appears to have formed under conditions of low to modest plant cover and significant soil water evaporation, very similar to soils presently found at higher latitudes and altitudes in modern Argentina. Seven transects of the carbonate laminations on the gravels at 10-μm scale reveal that all show a nearly 4‰ increase in δ^{13}C values with time over distances of approximately 150 mm, and variable δ^{18}O values. The shift in C isotope values, which is unlikely to be due to significant changes in C3 vs. C4 vegetation, reflects a profound and prolonged aridification with a corresponding lowering of plant density and soil respiration. The precise beginning of the aridification is unknown due to a lack of carbonate dating methods amenable to the time frame involved. When all changes are considered, this remarkable soil indicates that local rainfall declined from somewhere between 500 to 1000 mm y^{-1} in the late Tertiary/early Quaternary, to the present climate of about 25 mm y^{-1}. Future work will focus on developing more precise geochronological controls, but this initial study reveals the enormous potential that carbonate-bearing relict soils have for understanding climate change.

1. Introduction

Paleosols play an important role in reconstructing terrestrial paleoclimate. Soils integrate climatic and vegetation conditions over extended time periods before burial (10^3 or many more years), and are then separated from adjacent paleosols by sedimentary sequences that may accumulate over time intervals that exceed the initial exposure history of the buried soil. Thus, buried soils are temporally coarse records, and may not capture climatic shifts that occur on the order of 10^4 or even 10^5 years.

Land surfaces that are older than the Holocene all bear soils that have experienced conditions that contrast with those of today. Known as *relict* soils (Fedoroff et al., 2010), these soils have long been recognized as qualitative indicators of climatic shifts, but their utility in quantitative studies has lagged relative to buried soils. Intuitively, the most well-preserved records in relict soils should exist in landscapes that have undergone continuous aridification, since the decline in fluid flow should tend to preserve chemical and mineralogical evidence from previous intervals, and overlay on them mineral assemblages that are environmentally incompatible with those formed in earlier and more humid weathering conditions.

A region where Quaternary climate history is both poorly known and of great interest is the Atacama Desert of Chile. Estimates of the onset of hyperarid conditions range wildly, and land-based observations vary from the Oligocene (Dunai et al., 2005), to the Miocene (Alpers and Brimhall, 1988; Rech et al., 2006), to the Pliocene (Hartley and Chong, 2002; Amundson et al., 2012). Alternatively, off-shore sediments suggest Quaternary oscillations of erosion and sedimentation that generally correspond to glacial cycles (Stuut and Lamy, 2004). The on-set of aridity is of considerable tectonic interest in that the aridification of Andean Altiplano is used by some researchers as evidence of Andean uplift and rainshadow development (Garzione et al., 2008).

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Here we examine a relict soil located at the present southern boundary of the Atacama Desert, where the absolute (plant-less) desert merges, over a distance of ~300 km, into a semi-arid Mediterranean climatic regime. After considering both morphological and chemical soil properties, we conclude that there has been a generally continuous, and severe, aridification of this region during the Quaternary.

2. Materials and methods

2.1. Site selection and information

The site chosen for study is a deep road cut incision into what is mapped as a late Tertiary alluvial fan (Moscoso et al., 1982) by Chilean Ruta 5, the main north–south highway in Chile (−28.1587°S, −70.647°W). The highway incision is perpendicular to an escarpment of the fan created by a local intermittent stream called the Quebrada Algarrobal, a tributary of the Quebrada Carrizal that serves as the watershed's outlet to the Pacific (*quebrada* is Spanish for intermittent stream or ravine) (Fig. 1).

Geographically, the site lies in an interior depression between a low coastal set of mountains (Cordillera de la Costa) on the west, and the Andes to the east. Mortimer (1973), based on mapping at nearby Vallenar, argued that the depression largely consists of Miocene pediments and gravelly sediments, known locally as the Atacama Gravels (Fig. 2). Inset into these landforms are Pliocene and smaller assemblages of Quaternary geomorphic features (Amundson et al., 2012). Based on its relative height above the stream channel and surface features (pavement development, degree of surface clast weathering), the deposit is geochronologically consistent with other Tertiary deposits in the region (Ewing et al., 2006). Mortimer (1973) examined stream long profiles of Quebrada Carrizal, and found that both the Atacama Gravels and younger stream systems had convex long profiles. Mortimer (1973) thus suggested that the watershed, which receives little Andean drainage, has apparently lacked adequate water to maintain stream profile equilibrium since possibly the late Miocene.

The present climatic conditions are very arid. Long-term average conditions for the cities of Vallenar, 47 km to the south, and Copiapo, 93 km to the north, are provided in Table 1. The plant cover, at the time of sampling, was very sparse (and all plants were dead). However, the region responds to periodic intrusions of storm moisture associated with the El Nino phase of the ENSO cycle, leading to what is known as the Desierto Florido (blooming desert) (Gajardo, 1994). Among the species that respond to this moisture are *Skytanthus acutus* and *Atriplex deserticola*, *Encelia canescens*, *Fagonia chilensis*, *Alona rostrata*, *Heliotropium myosotifolium* and *Heliotropium megalanthum*. A number of other forbs emerge during large rainfalls. The most recent blooming event occurred in 1997–1998 (Moreira-Muñoz, 2011).

2.2. Field and laboratory methods

2.2.1. Field

An exposure of the upper 3 + m of the soil was cleared back to fresh soil material from the highway cut (Fig. 3a). Horizons were identified on the basis of visual and tactile properties using common pedological methods (Soil Survey Staff, 1993). Bulk samples were collected in ziplock bags and transported back to the lab, and due to the desiccated conditions, drying was not required. Gravel percentage (>2 mm particle size) was determined in the field by the sieving and weighing (using a spring-loaded scale) of coarse and fine fractions. Soil texture (and clay content) was determined in the field on the <2 mm fraction using the ribbon method (Soil Survey Staff, 1993). While semi-quantitative,

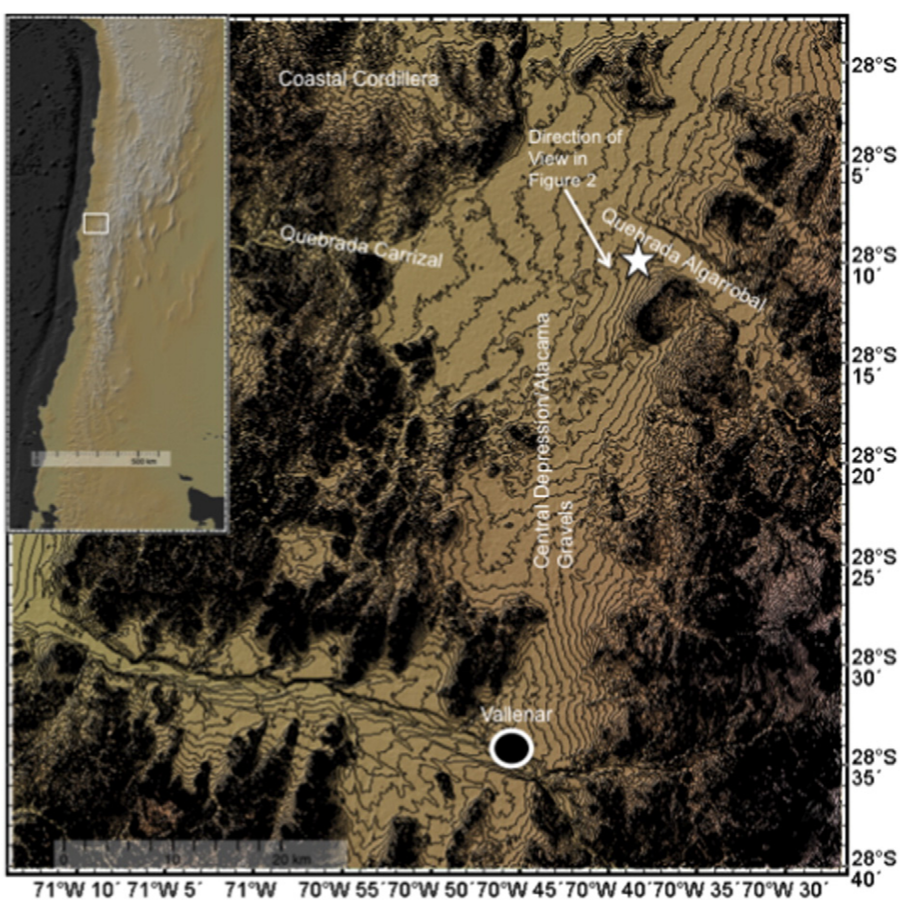

Fig. 1. Location of the field area on a DEM of northern Chile (inset) and a 25 m contour map of the research area (site location is indicated by the white star).