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Preservation of beach ridges due to pedogenic calcrete development in the Tongoy palaeobay, North-Central Chile

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ABSTRACT

At the Tongoy palaeobay in north-central Chile, a series of beach ridges developed during seaward progradation that took place after the MIS 11 sea-level highstand (412 ka). The microrelief left by this succession of beach ridges has been well preserved from erosion due to the development of a calcrete (petrocalcic horizons), which was resistant to the chemical and physical weathering that characterized the area during humid phases of the late Pleistocene and middle Holocene. Macro- and micro-morphological analysis shows that the calcrete is of pedogenic origin and formed during two stages: in the first stage a massive (beta) calcrete developed, followed during the second stage by a laminar (alpha) calcrete. Each event in the development of the calcrete was intimately related to the foregoing process, mainly due to changes in the permeability of the profile horizons. During the first stages of development, organisms played an important role in the precipitation of calcite, which made the calcrete less permeable and favored the accumulation of ponded water during the wet season. As a result of this increased humidity, calcium carbonate with a laminar structure was precipitated. The development of the calcrete was also intimately associated with the evolution of the drainage network, which is characterized by a trellis pattern of tributaries parallel to the beach ridges. This study demonstrates the importance of soil genesis in the geomorphological evolution of landscapes.

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1. Introduction

Soils result from the interaction of factors such as climate, vegetation, topographic setting, parent material, and time (Jenny, 1980; Birkeland, 1999). Because soil development can affect the properties of unconsolidated deposits (Birkeland, 1999) it can influence the hydrological and erosional processes that occur during landscape evolution (Dunne, 1978; Wells et al., 1987; McAuliffe, 1994; Eppes et al., 2002). This is particularly true for indurated horizons such as calcretes (petrocalcic horizons), which increase drainage and runoff due to making the soil profile impermeable, and also diminish erosion rates because of their mechanical resistance. For example, Eppes et al. (2002) discussed the role that soil played in the topographic evolution of the San Bernardino Mountains in California, where the development of a petrocalcic horizon preserved prominent ridges formed by anticlinal folds due to its high resistance to erosion. Another example occurs in the southern Pampean landscape of Argentina, where a petrocalcic horizon constituted a resistant surface that survived a series of erosional cycles and preserved an undulating, early Pleistocene topography (Amiotti et al., 2001; Blanco and Stoops, 2007). More examples of calcrete protection from erosion can be found in Arizona at the Mormon Mesa (Brock and Buck, 2009) and Buckeye (VanArsdale, 1982). Therefore, a close relationship exists between geomorphology and soil development, and soil evolution can elucidate the development of a particular landscape. In this study we examine the relationship between soil formation and the preservation of Pleistocene beach ridges south of La Serena, north-central Chile (Fig. 1).

Pleistocene beach ridges are uncommon features in the stratigraphic record, their preservation occurring mostly in arid climates where the effect of erosion is more limited (Augustinus, 1989; Meldahl, 1995; Otvos, 2000). Along the Chilean coastline, Pleistocene beach ridges are preserved in the hyper-arid Atacama desert (Armijo and Thiele, 1990; Marquardt et al., 2004; Victor et al., 2011), whereas in the more humid

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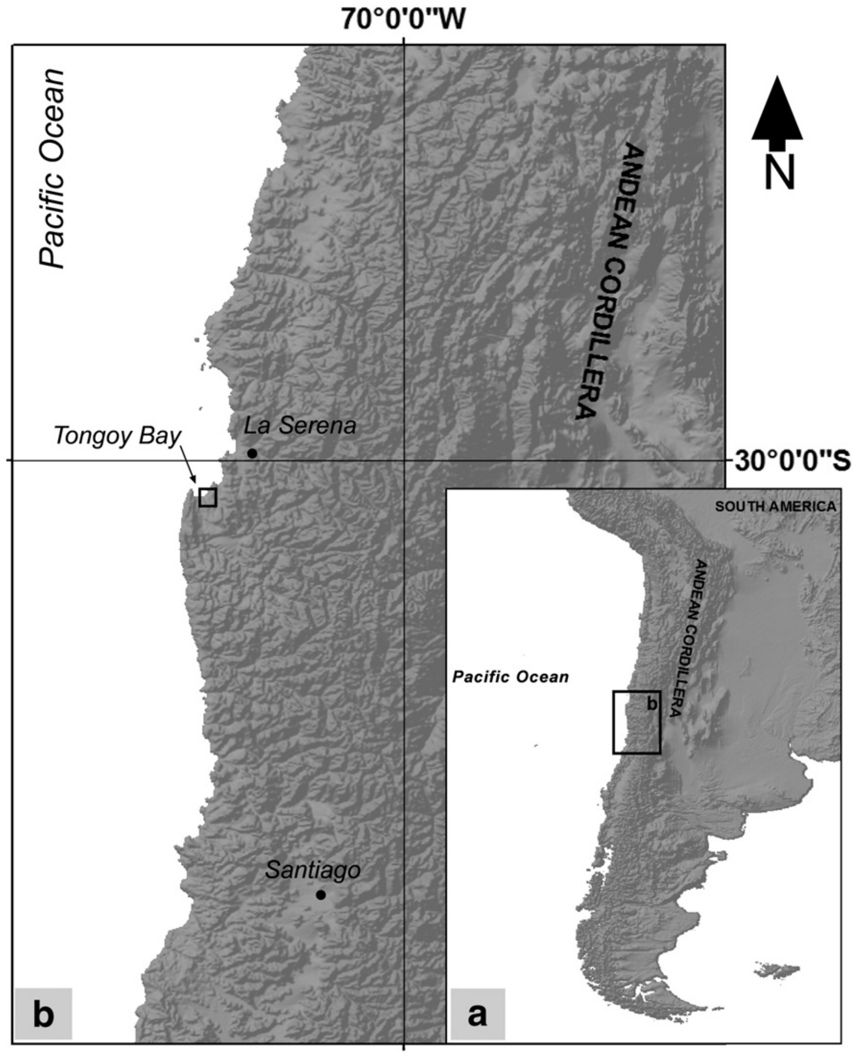

Fig. 1. (a) Location of the study area superimposed on a Digital Elevation Model of southern South America (b) Close-up of rectangle shown in (a), rectangle corresponds to Fig. 2a.

south only Holocene beach ridges have been documented (Nelson and Manley, 1992; Bookhagen et al., 2006; Melnick et al., 2006). In Argentinian Patagonia, Holocene and Pleistocene shoreline sequences are also preserved, but the latter are scarcer because of probable erosion (Schellmann and Radtke, 2010; Pedoja et al., 2011).

In the Tongoy palaeobay, a series of marine terraces described by several authors (Darwin, 1846; Domeyko, 1848; Brüggen, 1950; Chávez, 1967; Herm, 1969; Paskoff, 1970; Ota et al., 1995; Benado, 2000; Heinze, 2003; Saillard, 2008) developed over marine deposits corresponding to the Mio–Pleistocene Coquimbo Formation (Le Roux et al., 2006). One of these terraces reaches more than 30 km in its widest section. It was dated by Saillard (2008) using U-Th dating on marine shells, which yielded an age of around 400 ka corresponding to Marine Isotopic Stage (MIS) 11. Upon this extensive platform a pedogenic calcrete was formed after the marine regression that followed the MIS 11 highstand (Paskoff, 1970; Vera, 1985; Saillard, 2008).

The development of calcrete can be of diagenetic or pedogenic origin (Wright and Tucker, 1991), the latter implying surface processes so that plants and other organisms can participate in their formation. Calcretes normally experience several stages of development that correspond to different environmental conditions (Gile et al., 1966; Machette, 1985; Wright and Tucker, 1991; Alonso-Zarza and Wright, 2010; Gallala et al., 2010). The Tongoy calcrete shows the most advanced stage (VI) of development according to Machette (1985), which implies a series of processes during its evolution. In this paper we propose a model for the development of the Tongoy calcrete, based on micro- and macro-morphological features, soil chemistry and geomorphological analysis.

2. Geographic, geological and geomorphological setting

The study area is located south of the Bay of Tongoy, at 30°18′S 71°33′W, 40 km south of the city of La Serena and 430 km north of Santiago (Fig. 1). Although the climate is semi-arid, prolonged multi-year droughts or extremely rainy seasons occur, with occasional intense rainfall or even debris flow events (Vargas et al., 2006). The area has also been described as having a Mediterranean climate because 85.7% of the average annual precipitation is concentrated in the winter months (May–August), while the summer is very dry; the mean annual precipitation lying between 75 and 100 mm, and the mean annual temperature being 13.6 °C (CIREN, 1990).

The dominant vegetation is composed of steppe forest, i.e. low shrubs, small trees and different herbaceous species adapted to dry conditions (Gajardo, 1994).

The Coquimbo Formation is composed of shallow marine or bayfill deposits including mudstones, sandstones, coquinas and conglomerates that accumulated during a series of transgressions and regressions related to regional and local tectonic movements combined with global sea-level variations (Le Roux et al., 2006). The succession

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