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Development of a Pleistocene calcrete over a sequence of marine terraces at Tongoy (north-central Chile) and its paleoenvironmental implications

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ABSTRACT

The importance of the Norte Chico region in north-central Chile has long been recognized for the paleoclimates recorded in its soils. This area lies in an extreme climate gradient between the hyper-arid Atacama Desert in the north and a Mediterranean climate in the south, which has made it very sensitive to past climate changes. Nevertheless, few paleoclimate studies have been undertaken in the region, and these were mostly concentrated on the Holocene. We studied Pleistocene climate changes recorded in soils that formed over a series of marine terraces near Tongoy about 60 km south of La Serena. The calcrete and soil development took place on four marine terraces associated with Marine Isotope Stages MIS 11, MIS 7e, MIS 5e, and MIS 1. The different types of calcretes that developed on the three oldest terraces containing calcareous material indicate that they developed during different periods, and that climatic conditions favorable for the development of these soils existed in the area at least from MIS 11 (412 ka) until post-MIS 5e (125 ka). The calcrete horizons show well-defined development stages recording cyclic climate changes varying between arid and more humid during the late Pleistocene. These climate changes recorded in the Tongoy soils are reflected by sedimentological, geomorphological and pedogenic processes. Climate cycles have only been recorded previously for the post-MIS 5e stage in the area, this study being the first to include climate variations reaching MIS 11.

1. Introduction

The Norte Chico region in north-central Chile lies in a transition zone between the hyper-arid Atacama Desert to the north and the Mediterranean climate of central Chile to the south, which makes this region sensitive to Quaternary climate changes (Miller, 1976). However, paleoclimate studies in this region have concentrated mainly on the Holocene, with very little data on the Pleistocene (Grosjean et al., 1997, 1998; Lamy et al., 1998, 2000; Maldonado and Villagrán, 2002, 2006; Veit, 1996; Villagrán and Varela, 1990). Up to now, paleoclimate studies of the area have only gone back to approximately 120,000 yr BP (Lamy et al., 1998).

Despite controversies about the exact timing and duration of paleoclimate changes in the region, all published records show an alternation of wet and dry periods (Latorre et al., 2007). These are associated with latitudinal shifts of the climate zones along the South American Pacific margin linked to north–south displacements of the Southern Westerlies (Lamy et al., 2000).

Soils with carbonate accumulation are common in Mediterranean semi-arid regions (Yaalon, 1997) and are characterized by calcium carbonates that are known to be important paleoenvironmental proxies (Cerling and Quade, 1993; Durand et al., 2010; Gocke et al., 2011; Tanner, 2010). Such soils commonly develop into calcretes forming sub-profiles within the main soil profiles (Wright and Tucker, 1991). Despite the recognition by several authors of "relict" pedogenic features in the soils of Norte Chico (Casanova et al., 2010; Franz, 1966; Fuenzalida, 1951; Paskoff, 1970; Wright and Espinoza, 1962), only one study combined a pedological interpretation with absolute dating in a paleoclimatic reconstruction of the area (Veit, 1996). However, there are so far no paleoclimatic studies that are based on pedogenic carbonates in the Norte Chico region, even though such studies have been carried out successfully in the Atacama Desert by Berger and Cooke (1997), Latorre et al. (1997), Rech et al. (2003), and Quade et al. (2007).

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The objective of this study is to reconstruct the sequence of events in the development of the Tongoy soil profiles, to which end we examined 20 profiles distributed over four marine terraces, of which seven have been analyzed in detail. This paper presents the complex geomorphological and paleoclimatic history of the Tongoy soils, in an area of great interest to paleoclimatologists, geomorphologists and pedologists.

2. Regional setting and soil forming factors

The study area is located on the north-central Pacific Coast of Chile (Fig. 1) within the area formerly occupied by the Tongoy paleobay (Le Roux et al., 2006). This depression forms part of a Cenozoic basin filled with marine deposits of Mio-Pleistocene age that are known as the Coquimbo Formation (Le Roux et al., 2006). The bayfill deposits include mudstones, sandstones, coquinas and conglomerates that accumulated during a series of transgressions and regressions related to tectonic movements combined with global sea level variations, studied in detail by Olivares (2004) and Le Roux et al. (2006). Variation of the relative sea level combined with continental uplift generated a series of wave-cut marine terraces since the middle Pleistocene in the area, which have been studied by several authors (Benado, 2000; Brüggen, 1950; Chávez, 1967; Darwin, 1846; Domeyko, 1848; Heinze, 2003; Herm, 1969; Ota et al., 1995; Paskoff, 1970; Pfeiffer, 2011; Radtke, 1989; Saillard, 2008). Ota et al. (1995) identified four marine terraces in the area of Altos de Talinay and three terraces in the Tongoy paleobay, which they designated TII, TIII and TIV in order of decreasing age. The TI terrace only appears in the Altos de Talinay area, so that the TII terrace is the oldest for the Tongoy area (Fig. 1). Radtke (1989) made an unsuccessful attempt to determine the chronology of the four terraces at Tongoy by Electron Spin Resonance (ESR) and U/Th disequilibria on marine shells, obtaining a wide range of ages for similar geological and topographic conditions, which he explained as being a result of deposit mixing during the different marine transgressions that reoccupied the same terrace. This conclusion was also reached by Hsu et al. (1989). However, at the Bay of Coquimbo north of the present study area, Radtke (1989) successfully dated marine terraces using U-series on marine shells. These data were used by Ota et al. (1995) to assign ages to the Tongoy terraces based on geomorphological correlation with the Coquimbo Bay terraces, which are almost continuous with those at Tongoy. According to this study, the relative ages of the terraces are Plio-Pleistocene for TI, middle Pleistocene for TII, MIS 9 for TIII and MIS 5e for TIV. The Holocene level was later assigned to TV by Benado (2000), incorporating the present beach as a terrace level, which was previously studied and dated by Ota and Paskoff (1993). The latter authors recognized a series of beach ridges that correspond to a Holocene marine regression episode, in which the oldest beach ridge has a ^{14}C age of 5400 yrs BP and the youngest a ^{14}C age of 910 yrs BP. Saillard (2008) undertook U–Th dating on marine shells of the TII and TIV terraces and assigned them to MIS 11 and MIS 5e, respectively. The TIV terrace age of Saillard (2008) coincides with ages proposed by Ota et al. (1995) and Benado (2000). The TII terrace age poses some questions: many authors agree that there is a geomorphological correlation between the Tongoy and Altos de Talinay terraces, the latter having been dated by Saillard et al. (2009) using ^{10}Be, based on which the TII level was assigned to MIS 9. Regard et al. (2010) proposed that this terrace, extending almost continuously between 15°S and 30°S, formed due to repeated superimposed highstands during a prolonged period of uplift, in which the latest marine transgression corresponds to MIS 11. Terrace TIII is assumed to be of the same age in the Tongoy and Talinay areas according to geomorphological correlation (Table 1), having been dated and assigned to MIS 7e by Saillard et al. (2009). The gap from MIS 11 to MIS 7 existing between the TII and TIII terraces at Tongoy, could be explained by slow uplift after MIS 9 that reoccupied the MIS 9 level during MIS 7 in the Tongoy area. A similar process was described by Saillard et al. (2009) for the Talinay area. In this study we used the terrace ages proposed by the authors mentioned in Table 1.

The soil profiles show two parent materials that are clearly separated by a discontinuity: a marine substrate and an overlying eolian sand, (Herm, 1969; Paskoff, 1970; Pfeiffer et al., 2011). The marine deposit is composed of (i) coarse, sandy *Balanus* coquina of the

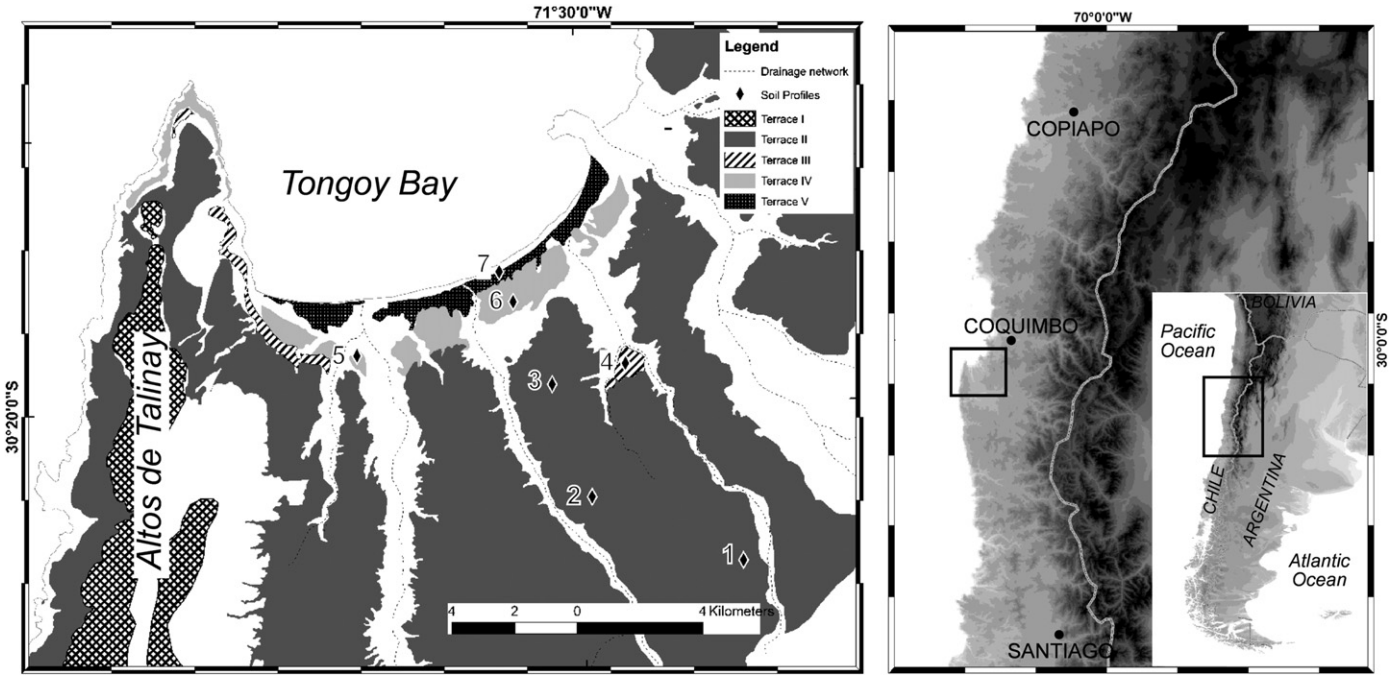

Fig. 1. Location of the study area and distribution of soil profiles over marine abrasion terraces at Tongoy. Numbers represent soil profiles: 1, Maitencillo; 2, La Montosa; 3, Alamito; 4, Almendros; 5, El Rincón; 6, Las Lomas; 7, Beach.