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Pleistocene uplift, climate and morphological segmentation of the Northern Chile coasts (24°S–32°S): Insights from cosmogenic ^{10}Be dating of paleoshorelines

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ABSTRACT

We present new cosmogenic (^{10}Be) exposure ages obtained on Pleistocene marine abrasion shore terraces of Northern Chile between 24°S and 32°S in order to evaluate the temporal and spatial variability of uplift rates along the coastal forearc. Both the dispersion of cosmogenic concentrations in samples from the same terrace and data obtained in vertical profiles show that onshore erosion rates, following emergence of paleoshorelines, approached 1 m/Myr. Therefore, minimum ages calculated without considering onshore erosion may be largely underestimated for Middle Pleistocene terraces. The elevation of the last interglacial (MIS-5) paleoshoreline is generally between 25 and 45 m amsl, suggesting that the entire coast of the study area has been uplifting during the Upper Pleistocene at rates approaching 0.3 mm/yr. Available ages for Middle Pleistocene terraces suggest similar uplift rates, except in the Altos de Talinay area where uplift may have been accelerated by the activity of the Puerto Aldea Fault. The maximum elevation of Pleistocene paleoshorelines is generally close to 250 m and there is no higher older Neogene marine sediment, which implies that uplift accelerated during the Pleistocene following a period of coastal stability or subsidence. We observe that the coastal morphology largely depends on the latitudinal climatic variability. North of 26.75°S, the coast is characterized by the presence of a high scarp associated with small and poorly preserved paleoshorelines at its foot. The existence of the coastal scarp in the northern part of the study area is permitted by the hyper-arid climate of the Atacama Desert. This particular morphology may explain why paleoshorelines evidencing coastal uplift are poorly preserved between 26.75°S and 24°S despite Upper Pleistocene uplift rates being comparable with those prevailing in the southern part of the study area.

1. Introduction

Many authors, following Darwin (1846), noted that most of the Pacific coasts of South America are uplifting. Brüggen (1950) and Fuenzalida et al. (1965) reported the presence of several marine terraces, partly cut in bedrock and partly filled or veneered with clastic materials along most of the Chilean coasts, particularly between 26°S and 40°S. They observed that the elevation of the highest terraces generally exceeds 150 m above mean sea level (m amsl).

The analysis of the Norte Chico coastal morphology and associated continental and marine deposits evidences periods of coastal uplift alternating with periods of subsidence during Tertiary times (Le Roux et al., 2005). In the Tongoy area (~30°S), for instance, Paskoff (1970) describes a period of subsidence marked by the deposit of the Neogene Coquimbo marine formation. He shows that this episode of subsidence followed a period of coastal uplift during which the paleo Limari River had excavated a deep valley, today preserved 500 m below sea level. Although the particular geological evolution of this area has been affected by fault activity, the same succession of periods of uplift interrupted by episodes of subsidence is registered by geological markers in many places of the Norte Chico coastal area. For instance, in the Caldera region

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(27°S), continental deposits overlain by Miocene marine sediment fill valleys carved in the Paleozoic and Mesozoic basement (Marquardt, 1999; Marquardt et al., 2004).

An active margin coastal area being subject to tectonic uplift or subsidence is not surprising. The question of how subduction drives forearc vertical motions, however, is not clear, and several processes may act together to change the dynamics of the coastal area (e.g., Regalla et al., 2013; Henry et al., 2014; Martinod et al., 2016). In order to constrain the causes of observed motions, it is important to quantify and date the coastal morphological evolution. Scientific questions relative to this issue are listed as follows. When did the present-day coastal uplift begin? Did it occur at constant speed or during short pulses? How does its speed vary laterally? Do periods of uplift and subsidence correlate everywhere along the Chilean coasts, or are they instead controlled by local tectonic settings?

Answers to the aforementioned questions require dating the beginning of the present-day episode of coastal uplift in Northern Chile. Considering published data, Regard et al. (2010) estimate the onset of coastal uplift in Northern Chile and Southern Peru, looking at the elevation of the highest preserved shoreline and supposing that the vertical velocity remained constant since the beginning of uplift. They propose that coastal uplift started in most sectors of Pacific coasts of the Central Andes during the Middle Pleistocene. In many sites however, the uplift velocity is only constrained by a single age, and there is no information on its temporal variability. Moreover, the constant uplift velocity hypothesis adopted by Regard et al. (2010) conflicts with results obtained by Saillard et al. (2009) in the Altos de Talinay area (~30.5°S). Indeed, data presented by Saillard et al. (2009) suggest that Altos de Talinay have been affected by a pulse of very rapid uplift culminating at 1.2 mm/yr between MIS-9 and MIS-7, preceding a severe decrease of the vertical velocity close to 0.2 mm/yr since MIS-5. It implies that the Pleistocene history of coastal uplift may have been much more complex than supposed by Regard et al. (2010) and, in turn, raises the question of how the geodynamic processes operating in the area may explain highly variable uplift rates.

The spatial variability of coastal uplift in the study area is also disputed. Between 32°S and 26°S ('Norte Chico' region) raised shoreline markers are almost continuously preserved above the present-day coastline (e.g., Brüggen, 1950; Paskoff, 1970), whereas between 24°S and 26°S ('Norte Grande') the coast is marked by the presence of a high scarp whose elevation approaches 1000 m, and below which terraces or other structures marking the position of ancient seashores are generally absent (see below). In some places north of Tal-Tal (25.4°S), the ocean is actively eroding the scarp. Does the scarp mark a different tectonic evolution and a different uplift velocity north of 26°S?

In the following, we present new cosmogenic data (^{10}Be) to date Pleistocene shorelines in Chile between 24°S and 32°S. We dated terraces in places where no ages where available, in order to look at the spatial variability of uplift rates. On the other hand, we also dated new paleoshorelines in sites where some terraces had already been dated, in order to evaluate the Pleistocene temporal variability of uplift rates. We confirm that uplift has been active everywhere in the study area during the Middle and Upper Pleistocene. Finally, we show that the morphological signature of coastal uplift in the study area, and particularly the preservation of paleoshorelines, largely depends on climate. Paradoxically, we observe that paleoshorelines are better preserved in the semi-arid Norte Chico than in the hyper-arid Atacama Desert because the coastal cliff, whose preservation is permitted by the hyper-arid climate of Atacama, restrains the formation of wide shore platforms.

2. Coastal morphology of the Norte Chico region, between 24° and 32°S

Both erosional and depositional paleoshores are present in the study area. Erosional paleoshores often consist in staircase marine terraces directly cut in bedrock (abrasion shore platforms). Their formation is related to sea-level highstands associated to the Quaternary glacial/interglacial cycles (e.g., Chappell, 1974; Lajoie, 1986; Pedoja et al., 2014). During sea-level highstands that correlate to odd-numbered Marine Isotopic Stages (MIS), wave action erodes rocky coasts. It results in the appearance of a cliff located above a planar shore platform gently inclined towards the sea. The shoreline angle at the base of the cliff marks the maximum elevation of the ocean during the highstand (e.g., Lajoie, 1986; Jara-Munoz et al., 2016). This erosional surface is abandoned when the sea level falls. If the coast is uplifting, the shore platform is not reoccupied by the ocean, and the bedrock surface morphology is only weakly modified by continental erosion in the semi-arid to hyper-arid environment of Northern Chile. In many places of Northern Chile, the coastal fringe eroded by the ocean corresponds to a 'Rasa', i.e. a polygenic surface in which intermediate shoreline angles marking different highstand levels are difficult to observe (Guilcher, 1974; Regard et al., 2010).

Depositional paleoshores result in terraces where marine deposits accumulated. They are generally covered by beach-ridges, and their presence in Northern Chile is generally restricted to bays where the energy of waves is lower (Saillard et al., 2012).

The morphology of the coast varies significantly depending on the bedrock lithology, the continental slope close to the present-day shoreline, and the considered latitude. We describe below, from north to south, the morphology of this segment of the Chilean Coast. See Fig. 1 for the geographical location of sites cited in the text.

The coast of the northern part of the study area between Caleta El Cobre (24°S) and Caleta Obispito (26.75°S) is particularly steep (Fig. 1). In many segments, it is marked by the presence of a scarp built in Mesozoic volcanic and plutonic rocks whose elevation approaches 1000 m. The distance between the scarp and the present-day coastline is generally ~1 km. Most of the fringe between the coast and the scarp is composed by a single rasa, whose inner edge elevation is often lower than 100 m amsl, and no remnants of Pleistocene marine erosion are preserved at higher elevations. In some places, especially north of Tal-Tal (25.4°S), the coastal rasa totally disappears and the ocean is actively eroding the scarp. In this northern segment (24°S–25.4°S), the rasa at the base of the coastal scarp corresponds to a rough surface in which many ancient seastacks have been preserved, often covered by thick caps of debris fallen from the scarp. In many places, the bedrock is not visible beneath the scarp and the ocean is actively eroding the cap of fallen debris. Very few flat terraces containing marine deposits between sea stacks are preserved north of Tal-Tal. The larger ones are located close to Planta Paposo (25.1°S) and above Punta Piedras (24.75°S) (Fig. 2). The marine terrace located above Punta Piedras is only ~150 m wide per ~300 m long.

The coastal segment located south of Caleta Obispito (26.75°S), in contrast, presents a gentle topography. Between Caleta Obispito and Caleta Sal (27.9°S), Pleistocene paleoshorelines often lie above Neogene marine sediment pertaining to the Bahia Inglesa Formation. Numerous paleoshorelines marked by the occurrence of beach ridges are visible between the present-day coastline and ~220 m amsl (Marquardt, 1999; Marquardt et al., 2004).

Between 27.9°S and 28.8°S (Caleta Sarco), Neogene deposits disappear and Pleistocene terraces are generally built above Paleozoic metamorphic series and Mesozoic intrusives. Large parts of the coastal fringe affected by marine erosion are covered by aeolian deposits, masking the morphology inherited from marine erosion. The width of the coastal fringe affected by Pleistocene marine erosion is roughly 2 km. In Huasco (28.5°S), Cooke (1964) and Fuenzalida et al. (1965) note the presence of several narrow lower terraces. Above lower terraces, the coastal fringe consists of a large upper rasa, whose inner limit is between 130 and 220 m amsl.

The coastal area located between 28.8°S (Caleta Sarco) and 29.35°S (Choros Bajo) corresponds to a wide low elevation area. The basement consists in Paleozoic metamorphic series, Jurassic plutons, covered in