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Geomorphology on geologic timescales: Evolution of the late Cenozoic Pacific paleosurface in Northern Chile and Southern Peru

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ABSTRACT

The Atacama Desert on the western margin of the Central Andes is one of the driest and oldest deserts in the world. It is defined by a distinct and ancient surface, known as the Pacific Paleosurface (PPS) or Atacama Paleosurface. The age of this surface is determined as the time at which sediment deposition ceased, and the surface was effectively abandoned. Early studies suggested that this abandonment took place between 14 and 10 Ma, and was related to both the uplift of the Andes and the onset of hyperaridity in the region. Here we provide a regional re-examination of the PPS, compiling existing work on the underlying geology, sedimentology, surface exposure dating, and seismic profiling. We also present new multispectral satellite maps of the PPS and 45 new cosmogenic ^{3}He and ^{21}Ne surface exposure ages in order to constrain the formation age, and the preservation and incision history of the paleosurface. We conclude that the PPS is not a single paleosurface, but instead is a mosaic of smaller surfaces that were formed by aggradational and degradational processes over 19 million years (or more) and should be termed collectively as the Pacific Paleosurfaces. The time at which individual paleosurfaces formed is related to regional climate, where the location of each is controlled by regional tectonic activity. Cosmogenic surface exposure ages suggest that the surfaces are a record of regional scale climate events.

1. Introduction

The Pacific Paleosurface (PPS) stretches for over 1200 km along the western margin of the Central Andes in northern Chile and southern Peru (Evenstar et al., 2009). Previous names include the Atacama Pediplain (e.g. Galli-Olivier, 1967), El Diablo-Altos de Pica Paleosurface (Hoke et al., 2007) and Atacama Bench (Armijo et al., 2015). It is located between the Coastal Cordillera to the west and Andean Precordillera and Western Cordillera to the east (Fig. 1a). It is 50 to 70 km wide, it has an average westward tilt of 3–4°, and is approximately coincident with the top of the Longitudinal Valley. For decades it has been believed to be largely erosional in origin (Segerstorm, 1963) but is locally covered by Middle Miocene age alluvial gravels, termed the "Atacama gravels" (Mortimer, 1973). In northern Chile, the surface is incised by ≤ 1700 m-deep rivers ('quebradas') that flow west from the Andes to the Pacific Ocean.

The exceptional preservation of the PPS is a result of the long-lived regional persistent arid climate, and provides a unique opportunity to examine the development of regionally extensive geomorphic surfaces over geologic time-scales at a classic destructive plate margin. By understanding how and when the PPS formed and how it has evolved, we can place new constraints on how tectonic processes and climate change have shaped the modern landscape of the Central Andes. The PPS is also of economic interest since supergene enrichment of porphyry copper deposits ceased across the region during its development (e.g. Segerstorm, 1963, Hollingworth, 1964, Hartley and Rice, 2005). This implies that the controls on these two events may be related.

The formation of a paleosurface can occur by two mechanisms; cessation of active deposition on a surface, or the end of active erosion. In both cases, the surface is "abandoned" and only undergoes superficial modification. The time at which the PPS formed is debated. A widely held view is that the entire PPS formed and was incised during a relatively narrow time interval between 14 Ma and 10 Ma, triggered either by a regional increase in aridity or rapid uplift of the Andes (e.g. Galli-Olivier, 1967, Tosdal et al., 1984, Alpers and Brimhall, 1988, Farías et al., 2005, Hoke et al., 2007, Cooper et al., 2016). More recently, the PPS has been interpreted as a composite paleosurface that

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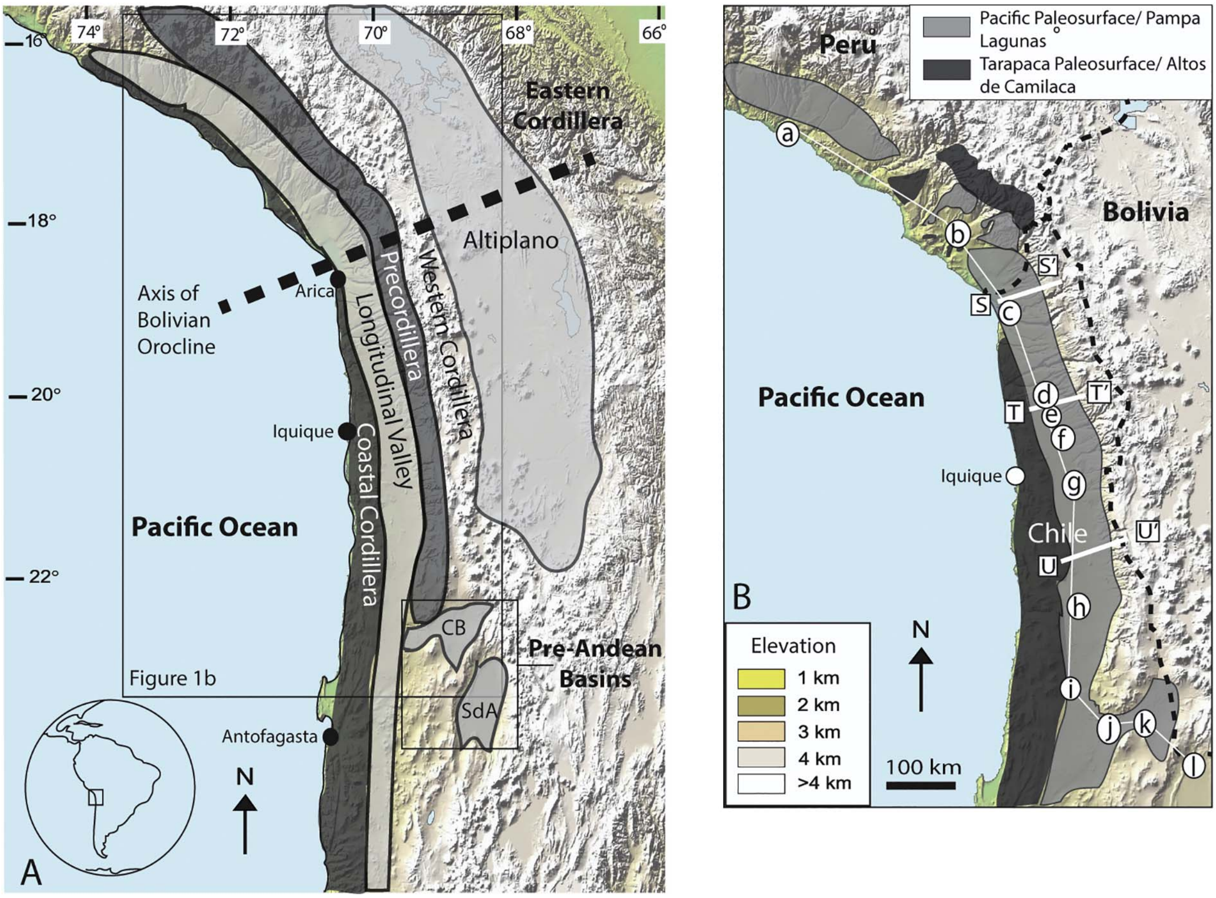

Fig. 1. (A) Digital elevation model of the Central Andes showing the five morphotectonic provinces. Pre-Andean Basins; CB: Calama Basin, SdA: Salar de Atacama. (B) Mapped extent of the two major paleosurfaces in the region: the older Tarapaca/Altos de Camilaca Paleosurface, which lies within the Coastal Cordillera and Precordillera (Mortimer and Saric, 1972, Mortimer and Rendic, 1975, Tosdal et al., 1984, Quang et al., 2005) and the younger Pampa Lagunas/Pacific Paleosurface, which lies predominantly within the Longitudinal Valley (Galli-Olivier, 1967; Mortimer et al., 1974, Tosdal et al., 1984, Hoke et al., 2007, Quang et al., 2005). Locations of N-S and E-W stratigraphic transects through the Longitudinal Valley presented in Figs. 3 and 8.

developed from the Miocene (Evenstar et al., 2009) to the Pleistocene (Jordan et al., 2014).

The lack of good chronological constraints reflects the fact that previous studies have concentrated on relatively small sections of the PPS (e.g. Quang et al., 2005; Evenstar et al., 2009; Jordan et al., 2014). Here we present a synoptic view of the entire surface. We combine regional multispectral satellite mapping and field observations to constrain the spatial extent and internal complexity of the PPS with new cosmogenic ^{3}He and ^{21}Ne surface exposure ages of four key surfaces within it. Our results are integrated with previously-published surface exposure ages, sediment analyses and seismic studies to demonstrate that the PPS formed diachronously from the start of the Miocene to the Pleistocene. The observations allow us to reconstruct the evolution of this complex landscape and use it to infer how both tectonic and climatic processes have interacted along the western margin of the Central Andes and how these processes vary from north to south along the Longitudinal Valley (Fig. 1A).

2. Geological setting

2.1. Morphotectonic provinces

The Central Andes can be divided into five main morphotectonic provinces. From west to east these are the: Coastal Cordillera, Longitudinal Valley, Precordillera, Western Cordillera, Altiplano, and Eastern Cordillera (Fig. 1A).

The Coastal Cordillera rises abruptly from the Pacific Ocean to reach over 3000 m in elevation, with a maximum width of 60 km near the Rio Loa (22°S; Fig. 1A). The elevation and width of the range decreases northwards until it disappears completely at the Bolivian Orocline (18°30′S; Fig. 1A), before reappearing again at 18°15′S in southern Peru, where it increases in elevation and width northwards. The Coastal Cordillera is a Jurassic-Early Cretaceous magmatic arc dissected by a series of faults (Allmendinger et al., 2005). Following a period of extension in the Early Cretaceous, the extensional basins are infilled with Late Oligocene to Early Miocene volcaniclastic sediments (Coira et al., 1982). During the Late Oligocene, large-scale sedimentation ceased within the Coastal Cordillera forming a relict paleosurface termed the Coastal Tarapaca Pediplain (Mortimer and Saric, 1972) (Fig. 1B).

To the east of the Coastal Cordillera lies the Longitudinal Valley (also referred to as the Pampas del Tamarugal or Central Basin/Central Depression in northern Chile, and the Llanuras Costaneras in southern Peru), a deep forearc basin. For simplicity, we refer to the entire region from northern Chile to southern Peru as the Longitudinal Valley. Along its length, the basin varies in width from 30 to 70 km and at the Bolivian Orocline, where the Coastal Cordillera is absent it ranges in elevation from sea level to 2000 m on its eastern margin. To the north and south of the Bolivian Orocline, the elevation of the basin gradually increases.

The Longitudinal Valley is infilled with up to 1500 m of Eocene to Pliocene age sedimentary deposits that originate from the Precordillera to the east (Mortimer and Rendic, 1975; Hartley et al., 2000; Hartley and Evenstar, 2010; Jordan et al., 2015). It is thought that the PPS formed when sediment deposition ceased, which we will show a posteriori occurred in pulses and ceased diachronously across the