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Late Pleistocene glaciations of the arid subtropical Andes and new results from the Chajnantor Plateau, northern Chile

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ABSTRACT

The spatiotemporal pattern of glaciation along the Andes Mountains is an important proxy record reflecting the varying influence of global and regional circulation features on South American climate. However, the timing and extent of glaciation in key parts of the orogen, particularly the deglaciated arid Andes, are poorly constrained. We present new cosmogenic ^{10}Be and ^{36}Cl exposure ages for glacial features on and near the Chajnantor Plateau (23 °S). The new dates, although scattered due to cosmogenic inheritance, imply that the most recent extensive glacial occupation ended before or during the global Last Glacial Maximum (LGM). We discuss this new record in the context of published glacial chronologies from glacial features in Peru, Bolivia, and northern Chile rescaled using the latest cosmogenic ^{10}Be production rate calibration for the tropical Andes. The results imply regionally synchronous moraine stabilization ca. 25–40 ka, 15–17 ka, and 12–14 ka, with the youngest of these moraines absent in records south of ~20 °S, including in our new Chajnantor area chronology. This spatial pattern implicates easterly moisture in generating sufficient snowfall to glaciate the driest parts of the Andes, while allowing a role for westerly moisture, possibly modulated by the migration of the Southern Westerly Wind belt, in the regions near and south of the Atacama Desert.

1. Introduction

The Andes Mountains are presently glaciated, or have been glaciated in the past, along their entire length, from the Northern Hemisphere tropics (e.g., Jomelli et al., 2014) to the upper southern midlatitudes (e.g., Kaplan et al., 2008). The timing and extent of glaciation varies along the Andes, reflecting the spatial and temporal changes to climate factors that influence glaciation, chiefly temperature and precipitation (e.g., Sagredo et al., 2014). Along the strike of the range, the relative influence of the major global (Hadley) circulation features changes. These larger-scale patterns are modulated by regional systems (e.g., the South American Summer Monsoon; Baker and Fritz, 2015) and by apparent teleconnections with longer-range climatic drivers such as Northern hemisphere Heinrich events (Kanner et al., 2012) or Antarctic polar front migration (Moreno et al., 2009). Accordingly, the history of glaciation along the length of the Andes is germane to understanding linkages between modern climate systems as well as the global progression of regional climate changes during major climate transitions (e.g., periods of glaciation, deglaciation, and abrupt warming; e.g., Rodbell et al., 2009; Denton et al., 2010). However, in many parts of the Andes, the timing and extent of glaciation is poorly constrained.

The arid subtropical Andes, between 18 °S and 27 °S, are presently deglaciated, even on mountains higher than 6 km. A few studies (e.g., Jenny and Kammer, 1996) have documented moraines, glaciated bedrock, and other glacial features between 18 °S and 23 °S, but there is little age control on these features, particularly in the area of the Chilean Altiplano (Zech et al., 2008; Rodbell et al., 2009). It is therefore unknown how the timing of glaciation here relates to the increasingly well-documented timing of glaciation in Patagonia (e.g., Ackert et al., 2008; Kaplan et al., 2011), tropical Peru (e.g., Smith et al., 2008; Jomelli et al., 2014; Kelly et al., 2015), and parts of the Bolivian Altiplano (e.g., Smith et al., 2008; Blard et al., 2009). Given the high precipitation sensitivity of the nearest

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adjacent groups of modern glaciers (Sagredo et al., 2014), and the overall aridity of the region, it is a fair assumption that the former glaciation of the Chilean Altiplano was modulated at least in part by precipitation changes (e.g., Kull and Grosjean, 2000). However, the area is much farther from oceanic moisture sources than the western Peru cordilleras or the glaciated Chilean peaks south of ~30 °S, and far from the eastern Andean foothills and Amazon Basin moisture as well. It is not clear whether past glaciers in the Chilean Altiplano should have responded similarly to glaciers more directly affected by one or another of these moisture sources.

Here, we report unambiguous evidence for the prior presence of a >200 km^2 ice cap on the 5-km-high Chajnantor Plateau (23 °S) and a new hybrid cosmogenic ^{10}Be and ^{36}Cl chronology for glacial features in this arid, presently unglaciated part of the Andes. The new dates and the mapped glacial features suggest that this region last deglaciated early during Marine Isotope Stage 2 (MIS 2: 29–14 ka; Lisiecki and Raymo, 2005) and before the global Last Glacial Maximum (here taken as 21 ka). The Chajnantor Plateau site appears to be located near a transition within regional-scale patterns of glacier response to climatic changes, which we document here by compiling published cosmogenic ^{10}Be and ^{3}He chronologies of latest Pleistocene glacial deposition in the Andes from 10 °S to 30 °S.

2. Field area geology and modern climate

2.1. Geology and geomorphology

The Chajnantor Plateau (23.00 °S, 67.75 °W) is a high (5000 m), arid volcanic plateau in the Andes of northern Chile (Fig. 1) that hosts several astronomical observatories, including the Atacama Large Millimeter/Submillimeter Array (ALMA) radio telescope. Its broad, domelike topography was constructed by late Cenozoic volcanism (Schmitt et al., 2001), and most of the plateau is capped by the 1.3 Ma Cajón ignimbrite (Ramírez and Gardeweg, 1982). Many 5600–5700 m stratovolcanoes and lava domes of the Purico Complex (pyroclastic shield) ornament the plateau (Fig. 2). The active stratovolcano Láscar (5592 m) lies 35 km south of the Chajnantor Plateau. Extending approximately 100 km to the north of the Chanjantor Plateau is the Cordillera del Tatio (Fig. 2), a range of previously glaciated, 5000–5500 m volcanic peaks along the Chile–Bolivia border. The well-known Tatio geyser field lies at ~4300 m on the western flank of these mountains. South of the geyser field, the Cordillera del Tatio includes a pancake-like dacite dome extrusion which we refer to as Cerro Torta; below, we present dating results from moraines near this extrusion in addition to those from the Chajnantor Plateau.

The western flank of the Chajnantor Plateau is onlapped by salt and sediment deposits of the Salar de Atacama, a ~4500 km^2 salt flat at 2300 m elevation that extends approximately 100 km to the south from the north end of the plateau. While much of the ignimbrite shield of the Chajnantor Plateau is a bare bedrock surface, locally thick (>50 m) deposits are preserved in patches below the volcanic peaks. These are commonly diamictic and likely include lahar and debris flow deposits (Ramírez and Gardeweg, 1982; Cesta, 2015), other volcanogenic sediment, and glacial and periglacial deposits. ~60 km farther south is Laguna Miscanti, a shallow (10 m maximum depth), saline lake at ~4500 m on the western flank of the Cordón de Puntas Negras (Grosjean et al., 2001). Regionally, small salt flats, alpine wetlands, and small lakes exist above ~4000 m, in addition to hot springs and geyser fields. These features are related to complex groundwater circulation in the mountain block, recharged by the meager precipitation (Risacher and Fritz, 2009).

2.2. Glacial features

Glacial features have been previously recognized in the subtropical arid Andes, mostly above 4000 m elevation, and many of these were mapped by Jenny and Kammer (1996). Their mapping identifies three main stages of glaciation, with younger, well-preserved "Stage I" and "Stage II" moraines commonly closely nested, and "Stage III" – older moraines, undivided – which are much less well-preserved and in some cases very distal to the Stage I and II moraines. While age assignments for the moraines in this area suffer from a lack of published dates, it is clear that this area was extensively glaciated, with at least Stages I, II, and the latest Stage III moraines interpreted to have formed in the late Pleistocene (<120 ka). While the Chajnantor Plateau deposits that are the subject of this study were not part of their mapping, some of these deposits near Cerro Toco, on the northeastern portion of the plateau, were noted by Jenny and Kammer (1996) and Amman et al. (2001).

Better-known moraines near the Chajnantor Plateau lie about 70 km to the north, among the volcanic peaks above the El Tatio Geysers. These moraines extend ~10 km to either side of the range crest and have been variously assumed to date to the time of the global LGM (Graf, 1991; Grenon, 2007), or to late glacial times (Kull and Grosjean, 2000; Amman et al., 2001). Absolute ages for these features have not been published.

2.3. Modern regional climate

The modern mean annual temperature on the Chajnantor Plateau is between -3° and −4 °C, and a discontinuous 50 cm permafrost layer exists above 5350 m (Grenon, 2007). The modern annual precipitation is too low to support glaciers: the upper elevations of the plateau receive between 200 and 350 mm/yr of water-equivalent precipitation (Grosjean et al., 2001; Grenon, 2007), with high interannual variability (e.g., Garreaud and Aceituno, 2001; Houston, 2006). Much of this precipitation falls during austral summer and is derived from moist air transported from the east, arriving from the tropical Atlantic via the Amazon Basin. This moisture promotes summer rain and snow and occasional damaging floods (Mather and Hartley, 2005; Houston, 2006). Because of the very low humidity, high winds, and high insolation, most of the snow that does fall is quickly swept into depressions, where it sublimates. In most years, any snow cover is gone by August.

The overall aridity of the Altiplano and subtropical Andes is maintained primarily by the large-scale subtropical downwelling and cold oceanic upwelling along the west coast of South America related to the Humboldt Current (e.g., Hartley, 2003). An important component of the regional climate is related to the South American Summer Monsoon (SASM), which promotes heavy rainfall in the central Amazon Basin (e.g. Cook and Vizy, 2006). Latent heating associated with the monsoon induces an upper-level high-pressure system called the "Bolivian High" over the subtropical Andes centered around 19 °S, 60 °W (Lenters and Cook, 1997, Fig. 1). In the modern climate, inter- and intra-annual wet periods in the Altiplano correspond to southward displacements of the Bolivian High (Vuille et al., 1998; Garreaud and Aceituno, 2001). This shifts upper-level easterly winds southward, enhancing moisture transport from the east into the Altiplano and arid Andes (Garreaud, 2000). The basic climatology of the region is also modulated by the El Nino/Southern Oscillation (ENSO), which induces circulation anomalies over South America and is associated with regionally heterogeneous precipitation anomalies (e.g., Vuille, 1999; Garreaud and Aceituno, 2001).