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Glacial chronology and production rate cross-calibration of five cosmogenic nuclide and mineral systems from the southern Central Andean Plateau

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ABSTRACT

Glacial deposits on the high-altitude, arid southern Central Andean Plateau (CAP), the Puna in northwestern Argentina, document past changes in climate, but the associated geomorphic features have rarely been directly dated. This study provides direct age control of glacial moraine deposits from the central Puna (24°S) at elevations of 3900–5000 m through surface exposure dating with cosmogenic nuclides.

Our results show that the most extensive glaciations occurred before 95 ka and an additional major advance occurred between 46 and 39 ka. The latter period is synchronous with the highest lake levels in the nearby Pozuelos basin and the Minchin (Inca Huasi) wet phase on the Altiplano in the northern CAP. None of the dated moraines produced boulder ages corresponding to the Tauca wet phase (24–15 ka).

Additionally, the volcanic lithologies of the deposits allow us to establish production ratios at low latitude and high elevation for five different nuclide and mineral systems: ^{10}Be, ^{21}Ne, and ^{26}Al from quartz (11 or 12 samples) and ^{3}He and ^{21}Ne from pyroxene (10 samples). We present production ratios for all combinations of the measured nuclides and cross-calibrated production rates for ^{21}Ne in pyroxene and quartz for the high, (sub-)tropical Andes. The production rates are based on our ^{10}Be-normalized production ratios and a weighted mean of reference ^{10}Be production rates calibrated in the high, tropical Andes (4.02 ± 0.12 at g^{-1} yr^{-1}). These are, $^{21}Ne_{qtz}$: 18.1 ± 1.2 at g^{-1} yr^{-1} and $^{21}Ne_{px}$: 36.6 ± 1.8 at g^{-1} yr^{-1} (En_{88-94}) scaled to sea level and high latitude using the Lal/Stone scheme, with 1σ uncertainties. As ^{3}He and ^{26}Al have been directly calibrated in the tropical Andes, we recommend using those rates.

Finally, we compare exposure ages calculated using all measured cosmogenic nuclides from each sample, including 11 feldspar samples measured for ^{36}Cl, and a suite of previously published production rates.

1. Introduction

The southern Central Andean Plateau (CAP) is a high-altitude, internally drained orogenic plateau between the Eastern and Western Cordilleras of the Andes in northwestern Argentina (Fig. 1, e.g., Allmendinger et al., 1997). The southern CAP is referred to as the Puna and is located to the south of the Altiplano (northern CAP). Climatically it sits within the Arid Diagonal, a zone of aridity stretching from coastal Peru in the northwest to the Argentine Pampas in the southeast. Although the Puna is a critical region in the Andean climate system (e.g., Baker and Fritz, 2015), paleoclimate data is scarce.

Records of mountain glaciations provide constraints on paleoclimatic conditions, and a growing body of work has concentrated on dating glacial features in the tropical and subtropical Andes, as well as farther south in the temperate Andes (e.g., Blard et al., 2014; Zech et al., 2009), summarized in Jomelli et al. (2014). Glacial features have been documented on the Puna, but rarely directly dated (e.g., Haselton et al., 2002). Here, we present the first glacial chronology for the central Puna, using cosmogenic nuclide based surface exposure ages from moraine boulders from two volcanic complexes (Fig. 1).

An essential input for determining exposure ages is the local production rate (e.g., Balco et al., 2008). Production rates differ

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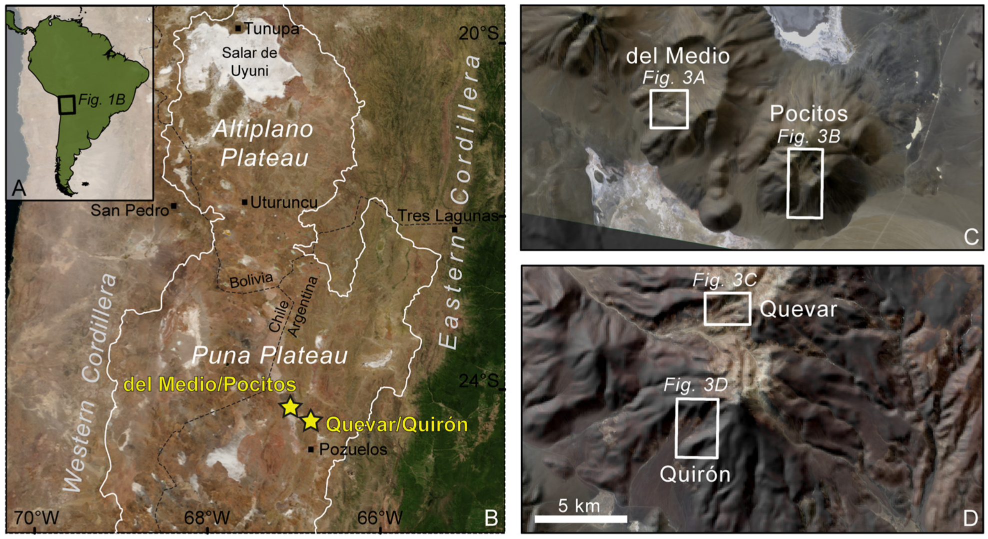

Fig. 1. Location of sampled moraines. Moraines were sampled from four different valleys on volcanoes on the Puna Plateau. (A) Location of the Puna Plateau, the arid southern extension of the internally drained central Andean Plateau. The Altiplano is the northern part of the central Andean Plateau. (B) Yellow stars show the locations of moraines sampled in this study, black squares mark other study areas mentioned in the text. White line indicates the internal drainage boundary derived from an SRTM DEM, black dashed lines are international borders. (C) Sampled valleys on Pocitos and del Medio volcanoes. (D) Sampled valleys on Quevar Volcano, which includes the Quirón site. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

for each nuclide and target mineral, and also change with time, latitude, and altitude, due to the strength and geometry of the Earth's magnetic field and the thickness of the atmosphere. Therefore, estimated production rates at the study site and the resulting exposure ages depend not only on the calibration site where the reference production rate was established, but also on the scaling method, geomagnetic field history, and atmospheric model used.

One strategy to reduce uncertainty in the production rate based on the choice of scaling model is to use a calibration site that is close to the target sampling site in distance, elevation, and time (Balco et al., 2008). However, high-quality production rate calibration sites do not yet exist for all nuclides in all parts of the world (Borchers et al., 2016). Different cosmogenic nuclides are produced at a certain ratio, which may also vary geographically to a small extent. If this ratio is known, it can be combined with a locally calibrated production rate for one nuclide to calculate production rates for other nuclides (e.g., Amidon et al., 2009; Goethals et al., 2009a). The volcanic composition of the sampled boulders allows us to determine the production ratios between five different nuclide and mineral systems: ^{10}Be, ^{26}Al, and ^{21}Ne in quartz and ^{3}He and ^{21}Ne in pyroxene.

The majority of cosmogenic nuclide exposure dating studies use only one or two nuclides, based on the lithology of the samples. When considering ages calculated at different localities with different nuclides, as is often done in review studies, it is largely assumed that these ages are directly comparable (e.g., Jomelli et al., 2014). However, this assumption has seldom been tested. Our samples and nuclide combination provide the additional possibility to directly compare exposure ages calculated from six different nuclide/mineral systems from the same samples: the five listed above and ^{36}Cl from feldspar.

In summary, our study addresses three main goals: (1) Establish the first glacial chronology for the central Puna; (2) Determine production ratios between five different cosmogenic nuclide/target mineral pairings at high elevation and low latitude; and (3) Directly compare ages calculated from each nuclide system from the same sample to test the assumption that they are equivalent.

2. Geologic, climatic, and geomorphologic setting

Uplift of the CAP began between 15 and 20 Ma, with magmatism beginning during the late Oligocene (∼26 Ma) (Allmendinger et al., 1997). In the late Miocene, eruptions occurred along NW–SE striking fault systems, producing the basaltic–andesitic to dacitic del Medio, Pocitos, and Quevar volcanoes that host the moraines we sampled. These stratovolcanoes have K–Ar and Ar–Ar ages ranging between 8 and 5 Ma (Matteini et al., 2002).

Precipitation on the CAP is dominated by summer moisture brought in through the South American Monsoon System (SAMS) (e.g., Garreaud et al., 2003). The semi-arid study area receives <500 mm yr^{-1} of precipitation, at least 70% of which falls during the austral summer between December and February (DJF) (Castino et al., 2016).

The geomorphologic shapes of the studied moraines tend to be smooth, with boulder heights ranging from several tens of centimeters up to ∼2 m (Fig. 2, see Supplementary Materials for further detail). We sampled five moraines from four valleys: del Medio, Pocitos, Quirón M1 and M2, and Quevar (Fig. 3, see Figs. A1–A4 for additional detail). These range in elevation from 3900–5000 m, with the lowest moraines occurring on the del Medio and Pocitos volcanoes and the highest on Quevar (Table 1).

Moraine sequences are best preserved in the Quirón and Pocitos valleys. At Quirón, the lowest lateral moraine (M1) displays broad and flat morphology. The M2 frontal moraine stratigraphically predates the M1 moraine and is rounded. Up-valley of the M2 moraine, complex till covers the valley floor. In the Pocitos valley, hummocky terrain covers the floor of the cirque, and some small (∼2 m high) moraine features occur near the valley walls. Boulder samples from these moraines did not produce dateable material. Two rounded lateral moraines characterize the lower section of the valley – the lowest of these was dated. Farther downstream, large boulders cover an alluvial fan at the mouth of the valley and may be remnants of earlier glacial advances, but have likely been re-transported.

At del Medio and Quevar, we took a similar approach of sampling the lowest lateral moraine from the respective valleys. At Quevar, we also observed large boulders farther downstream, which, similarly to Pocitos, may be related to earlier glacial advances.