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Giant landslides in the foreland of the Patagonian Ice Sheet

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ABSTRACT

Quaternary glaciations have repeatedly shaped large tracts of the Andean foreland. Its spectacular large glacial lakes, staircases of moraine ridges, and extensive outwash plains have inspired generations of scientists to reconstruct the processes, magnitude, and timing of ice build-up and decay at the mountain front. Surprisingly few of these studies noticed many dozens of giant ($\geq 10^8$ m^3) mass-wasting deposits in the foreland. We report some of the world's largest terrestrial landslides in the eastern piedmont of the Patagonian Ice Sheet (PIS) along the traces of the former Lago Buenos Aires and Lago Puyerredón glacier lobes and lakes. More than 283 large rotational slides and lateral spreads followed by debris slides, earthflows, rotational and translational rockslides, complex slides and few large rock avalanches detached some 164 ± 56 km^3 of material from the slopes of volcanic mesetas, lake-bounding moraines, and river-gorge walls. Many of these landslide deposits intersect with well-dated moraine ridges or former glacial-lake shorelines, and offer opportunities for relative dating of slope failure. We estimate that >60% of the landslide volume (~96 km^3) detached after the Last Glacial Maximum (LGM). Giant slope failures cross-cutting shorelines of a large Late Glacial to Early Holocene lake (“glacial lake PIS”) likely occurred during successive lake-level drop between ~11.5 and 8 ka, and some of them are the largest hitherto documented landslides in moraines. We conclude that 1) large portions of terminal moraines can fail catastrophically several thousand years after emplacement; 2) slopes formed by weak bedrock or unconsolidated glacial deposits bordering glacial lakes can release extremely large landslides; and 3) landslides still occur in the piedmont, particularly along postglacial gorges cut in response to falling lake levels.

1. Introduction

The study of giant landslides ($\geq 10^8$ m^3) in mountain regions offers many opportunities for testing the concept of paraglacial landscape response, mostly so in terms of how rapidly and widespread rock-slope stability responds to disappearing glaciers (Korup et al., 2007; Cossart et al., 2008; Prager et al., 2008; Hewitt et al., 2008; McColl, 2012; Schleier et al., 2015; Pánek et al., 2016a). Few studies, however, have explored glacier forelands in this regard (Ballantyne et al., 2002). Yet both rock and debris-covered slopes bordering outlet glaciers or lakes can fail, triggered by lake-level changes, permafrost degradation or rapid river incision (Klimeš et al., 2016; Moreiras, 2017). This latent instability can be problematic if requiring that moraine ridges record the largest past glacier advances in an undisturbed way. For example, inferring past glacial histories from cosmogenic exposure dating of boulders lodged in moraine deposits hinges on the assumption that the boulders maintained their position (Heyman et al., 2011). Simple diffusion models can simulate the slow decay of moraine ridges over time, but may be inappropriate if sudden slope failure is involved. We show that landslides may be much more widespread in glacial forelands than previously acknowledged, and demonstrate this for the eastern outlet of the Patagonian Ice Sheet (PIS), where some of the largest moraines on Earth formed during the Pleistocene (Fig. 1; Glasser et al., 2008). The region around the Lagos Buenos Aires (LBA) and Puyerredón (LP) offers one of the longest (~1 Ma; Singer et al., 2004) terrestrial records of Quaternary glaciations and is among the best studied in terms of its glacial chronology and environmental changes in the Southern Hemisphere (Caldenius, 1932; Singer et al., 2004; Kaplan et al., 2005; Glasser and Jansson, 2005; Douglass et al., 2006; Glasser et al., 2008, 2016; Hein et al., 2009, 2010, 2017; Smedley et al., 2016). Much work also addressed the Holocene history of LBA and LP that once formed a larger “glacial lake PIS” at the front of the PIS (Turner et al., 2005; Bell, 2008; Bourgois et al., 2016; Glasser et al., 2016). Well preserved terminal moraines, glacial lineations and trimlines

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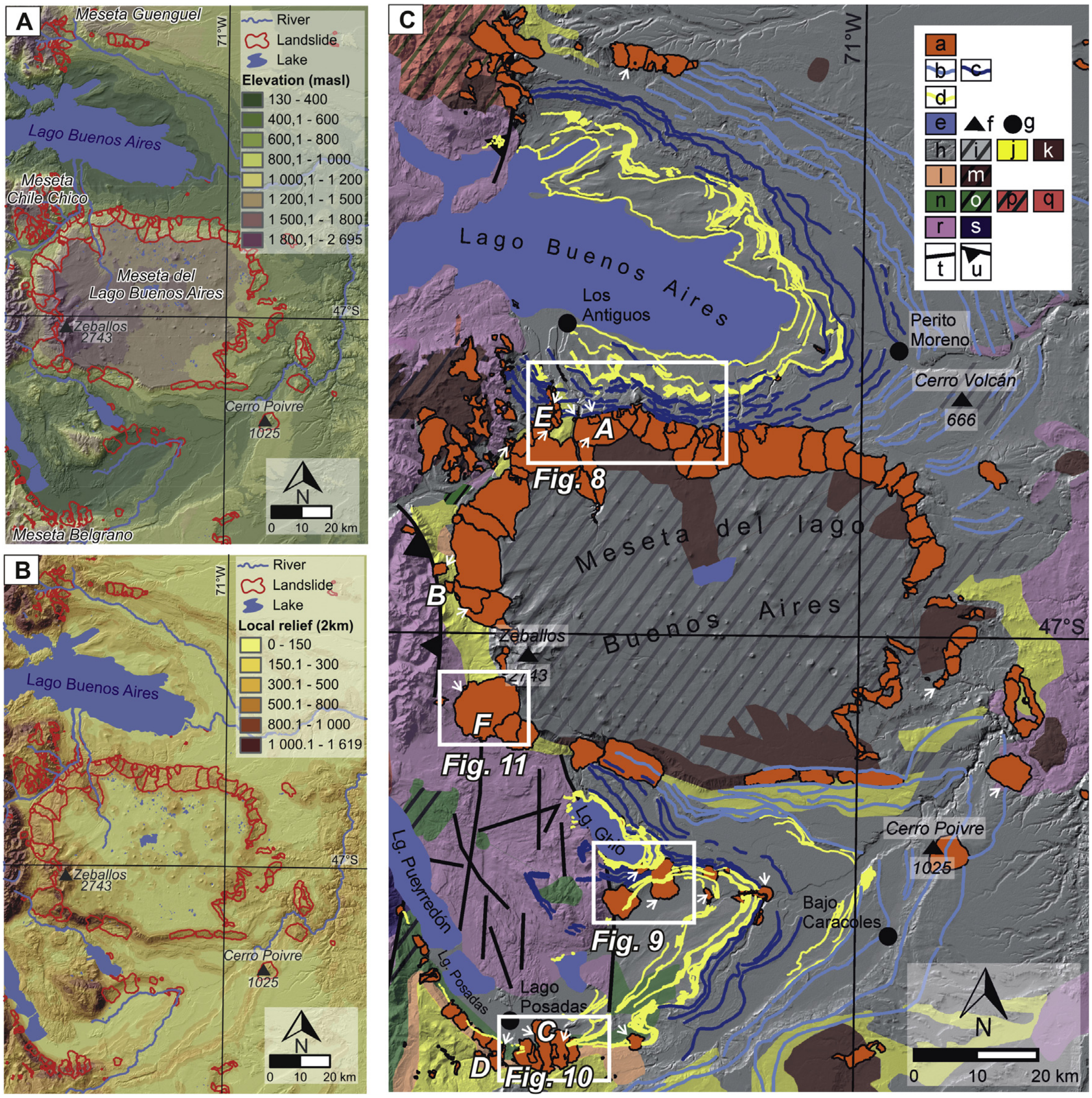

Fig. 1. Study area. A. General topography. B. Local relief as the maximum elevation difference in a moving 2-km radius. C. Geological sketch with selected Quaternary sediments and landforms (partly based on Bendle et al., 2017). Symbol captions: a – landslides, b – pre-LGM moraines, c – LGM moraines, d – lake shorelines, e – lake, f – summit, g – town or settlement; geology: h – Quaternary, i – Plio-Pleistocene basalt, j – Neogene continental sediments, k – Neogene basalt, l – Paleogene marine sediments, m – Paleogene basalt, n – Cretaceous continental sediments, o – Cretaceous marine sediments, p – Cretaceous volcanites, q – Cretaceous pluton, r – Jurassic volcanites, s – Eopaleozoic metamorphic basement, t – faults, u – thrust. Letters A-F are locations of landslides in Fig. 2. Landslides studied in the field are denoted by white arrows.

together with glaciofluvial and -lacustrine sediments offer insights into the extent, timing and rates of the PIS (Glasser and Jansson, 2005), as well as underlying climate changes in mid-latitude South America (Boex et al., 2013; Glasser et al., 2016).

Before this background, we provide evidence that the late Quaternary history of LBA and LP glacier lobes and their glacial lakes was connected to pronounced mass wasting, forming one of the largest clusters of giant landslides worldwide. Detailed maps of the glacial geomorphology of the PIS and its surroundings (Glasser et al., 2008; Horta et al., 2013; Bendle et al., 2017) hardly feature any of the numerous large landslides affecting ice-marginal slopes, glacial moraines, and dried floors of former glacial lakes. Only few of these landslides are marked on geological maps (Escosteguy et al., 2003; Hein et al., 2010; Bourgois et al., 2016). We take this opportunity to systematically analyse the distribution and characteristics of giant landslide deposits in this area. Our objectives are to document and analyse the regional distribution, characteristics, and relative age of landslides in the eastern foreland of the PIS with respect to its well-established late Quaternary chronology of glaciations and lake phases.

2. Regional setting

Our study area surrounds the LBA and LP in the eastern piedmont of the Patagonian Andes between ~46 and 48°S and ~72–72.5°W in the foreland of the PIS up to ~100 km east of the modern North Patagonian Icefield (Fig. 1). Average elevation and topographic relief decrease eastward from >2500 m a.s.l. along the border between Chile and Argentina to ~300 m a.s.l. in the Rio Deseado valley (Fig. 1A and B). The modern lake levels of LBA and LP are at 200 and 155 m a.s.l., respectively. The climate is semiarid, largely dominated by the southern hemisphere westerly winds that