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Can glacial erosion limit the extent of glaciation?

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ABSTRACT

In southern South America, the maximum areal extent of ice during the Quaternary Period, the Greatest Patagonian Glaciation (GPG, [Mercer, J.H., 1983. Cenozoic glaciation in the southern hemisphere. Annual Reviews of Earth and Planetary Science 11, 99–132.]), occurred at 1.1 Ma and subsequent glaciations were overall less extensive. The GPG preceded global minimum temperatures and maximal volume of ice, which occurred in the last ~800 kyr, as recorded in the marine $\delta^{18}O$ record. Significant modification of the drainage morphology of the southern Andes from a non-glaciated to glaciated landscape occurred throughout the Quaternary Period. We infer a non-climatic relationship between glacial modification of the mountains and the decreasing extent of ice and we discuss processes of landscape development that could have caused the trend. Specifically, these include modification of valleys, such as development from a V- to a U-shape, and lowering of mass-accumulation areas. Such changes would strongly affect glacial dynamics, the mass balance profile and mass-flux during succeeding glaciations, especially for low-gradient outlet glaciers occupying low areas. Other areas around Earth (at least where ice has been warm-based) also may exhibit a non-random trend of decreasing extent of ice with time, ultimately because of glacial erosion in the Quaternary Period.

1. Introduction

In southern South America, chronologic data indicate that the greatest areal coverage of ice (Greatest Patagonian Glaciation: GPG) occurred prior to 1 Ma and, overall, succeeding glaciations have been less extensive (Figs. 1 and 2). The trend exists for >1500 km along the southern Andes, it is not particular to any individual valley, and the successions contain several moraines of different ages (Mercer, 1983; Rabassa and Clapperton, 1990; Singer et al., 2004a). Gibbons et al. (1984) showed that the expected preservation is only 2–3 moraines for a random succession of advances, given that subsequent glacial advances remove previously deposited moraines. More than three moraines (from different glaciations) are observed in various areas studied along the Andes (Meglioli, 1992; Clapperton, 1993; Rabassa et al., 2000; Singer et al., 2004a; Kaplan et al., 2005), pointing to a non-random explanation for the overall trend. The pattern is observed along most of Patagonia despite differences in tectonic setting and modern climate (Prohaska, 1976; Ramos, 2005). Determining whether this trend in decreasing ice extent occurs because of climate and/or other effects, such as topographic changes or tectonic processes, is relevant to understand the general history of the Andes.

The decreasing trend of coverage of Patagonian ice does not mirror Southern Ocean temperature changes over the last 1 Myr (e.g., Hodell et al., 2002; Carter and Gammon, 2004). Although much work remains to be done in documenting the paleotemperature of the Southern Ocean over this time, no known observed trend (in records that resolve glacial–interglacial cycles) is consistent with the decreasing extent of Andean ice over the last 1 Myr. In addition, decreasing coverage of Patagonian ice differs from a key feature of the benthic $\delta^{18}O$ record, which suggests that volumetrically, the ice on the planet (i.e., in the Northern Hemisphere) reached a maximum after 0.8 Ma or in the Middle to Late Quaternary (Fig. 3), >200 kyr after the GPG. The most extensive ice in southern South America occurred before the 100 kyr Milankovitch periodicity was the dominant pacing of the largest volume (and areal?) changes of the Northern Hemisphere ice sheet. Perhaps the greatest volume of Andean ice occurred over the last ~800 kyr, coincident with the global volume of ice, but differed from the maximum areal extent during the GPG. Our focus here is on changes in areal extent of glacial ice.

If climate change is not an obvious cause of the GPG and subsequent less extensive Andean ice, then other explanations need to be invoked. In the Quaternary, glaciers have substantially modified the landscape (Sugden and John, 1976), especially in temperate middle latitude areas such as Patagonia where basal conditions have been warm-based. Here we argue for a connection between the phenomena of glacial erosion and the pattern of the extent of ice over time in southern South America, which builds upon prior discussions of the topic (e.g., Rabassa and Clapperton, 1990; Singer et al., 2004a). We focus on the records of glacial landforms in the Andes and possible changes in paleoglaciology, in

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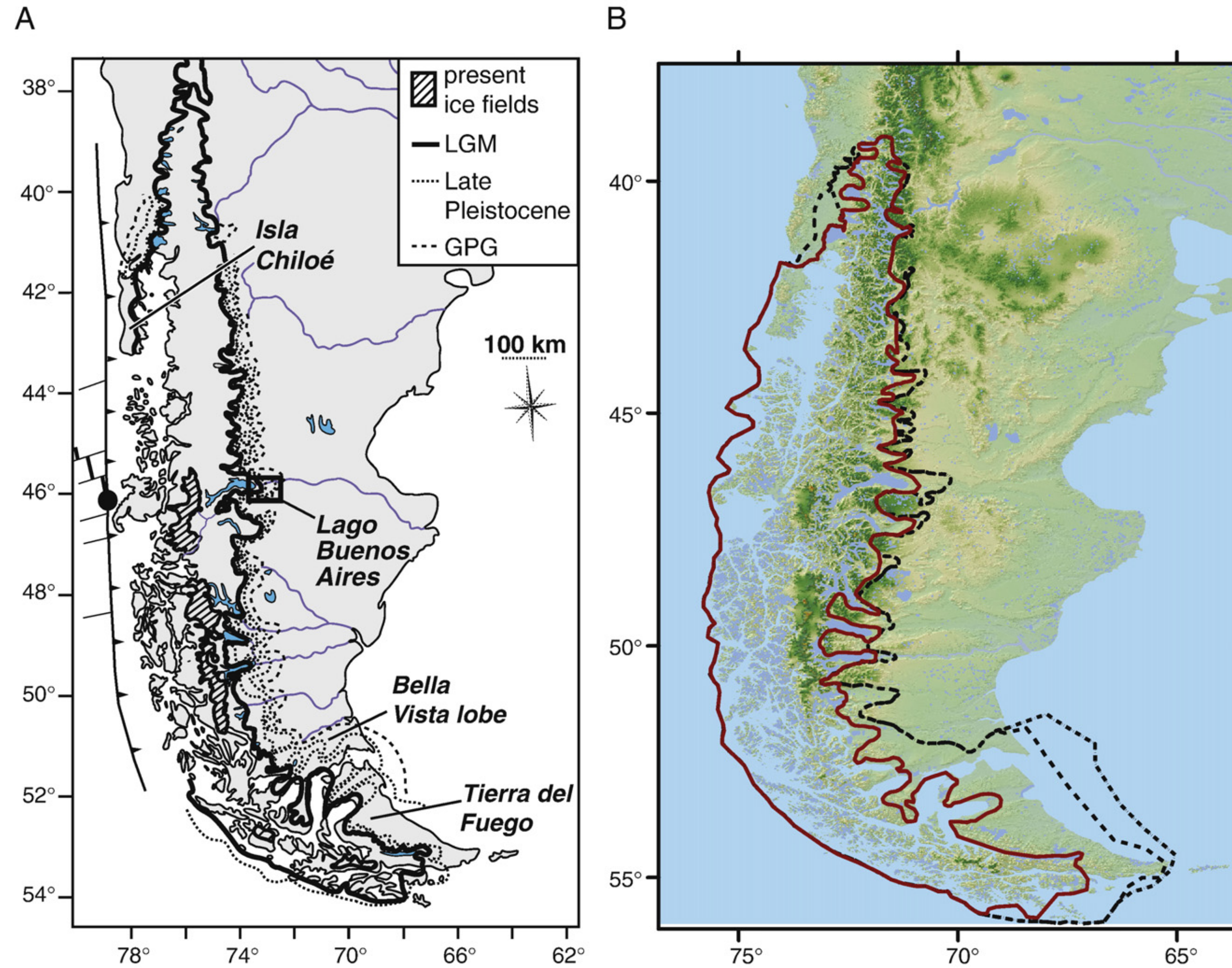

Fig. 1. (A) Map of southern South America showing schematic outlines of Quaternary glaciations, including the Greatest Patagonian Glaciation (GPG) and the last glaciation, and of the tectonic setting, including the Aysen Triple Junction (black circle) just south of 46°S. From Singer et al. (2004a), Clapperton (1993), Hollin and Schilling (1981), and Caldenius (1932). (B) Digital elevation map (ETOPO 30) as a base with the limits of ice during the GPG (in black) and last glacial maximum (in red). The limits are based on the mapped extent of ice along Patagonia, south of ~38°S, from references cited in this paper. 38°S is arbitrarily chosen as the northernmost limit of digitized ice extent and the findings and conclusions of this paper are not affected by the extent of glaciers north of this latitude. The GPG covered between 558,000 and 542,000 km^2; the difference mainly results from whether the extent of ice is arbitrarily placed at the 50 m (inner black dashed line) or 100 m (outer black line) bathymetric contour east of Magellan and Tierra del Fuego (cf., A). The last glacial maximum ice covered ~422,000 km^2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

comparison to other papers on the subject of glaciations and landscape development (e.g., Harbor, 1992; Small and Anderson, 1998; Whipple et al., 1999; MacGregor et al., 2000; Montgomery et al., 2001; Thomson, 2002; Tomkin and Braun, 2002). We propose that a 'self-defeating mechanism' (MacGregor et al., 2000, p. 1033), glacial erosion of the landscape, causes less extensive coverage of ice over time, and plays a key role in the development of the Andes, and perhaps elsewhere.

2. Decreasing ice extent in Patagonia

We focus on southern South America to observe long-term changes in the extent of ice because (in places) it contains one of the best-dated, longest glacial moraine (i.e., frontal position) records on Earth, ~1 Myr (Mercer, 1983; Rabassa and Clapperton, 1990; Clapperton, 1993). From 40°S to 55°S latitude, moraines and till sheets clearly show that glacial expansions have been less extensive in general since the GPG, at 1.1 Ma (Caldenius, 1932, Rabassa and Clapperton, 1990; Mercer, 1983; Meglioli, 1992; Singer et al., 2004a; Coronato et al., 2004a; Rabassa et al., 2005). Lava flows interbedded with glacial deposits allow a multi-chronologic approach to dating the record; radioisotopic and cosmogenic nuclide data provide quantitative ages on at least a broad chronologic framework for the last 1 Myr (Singer et al., 2004a,b; Kaplan et al., 2005).

The GPG and successive glaciations are best dated in two areas of southern Patagonia. At Lago Buenos Aires, Argentina (Figs. 1 and 2), glacial events over the last 1 Myr are defined in age with $^{40}Ar/^{39}Ar$, K–Ar, ^{10}Be, ^{26}Al, ^{3}He, and radiocarbon data (Singer et al., 2004a; Kaplan et al., 2005; Douglass et al., 2006). The oldest glacial deposit, underlying the Arroyo Telken Flow (Fig. 2), is the local representative of the GPG and is dated to >1.016 Ma (Singer et al., 2004a). The $^{40}Ar/^{39}Ar$ and K–Ar chronology (Singer et al., 2004a) of three lava flows (Fig. 2) indicates that at least six Telken moraines (informal names) were deposited between 1016 and 760 ka, five Deseado/Moreno moraines between 760 and 109 ka, and six Fenix moraines after 109 ka. Cosmogenic nuclide data further define the ages of the five Moreno/Deseado moraines between 760 and 109 ka; at least two of the moraines date to ~150–140 ka, and the other older three are likely >300 ka (Douglass, 2005; Kaplan et al., 2005). Kaplan et al. (2004) and Douglass et al. (2006) define further the youngest innermost set of moraines adjacent to the lake to between ~23 and 14 ka or marine isotope stage 2. At Lago Buenos Aires, the GPG deposit is ~50 km farther east than the last glaciation stage 2 moraines (Fig. 2). The GPG and successive glaciations are also well-dated, at least for the purposes of this study, in southernmost Patagonia (e.g., for the Bella Vista lobe), where $^{40}Ar/^{39}Ar$ ages of 1.168 and 1.07 Ma locally provide maximum and minimum ages of the GPG (Meglioli, 1992; Singer