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Glacial geomorphology of the Torres del Paine region (southern Patagonia): Implications for glaciation, deglaciation and paleolake history

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ABSTRACT

The processes affecting paleoclimate variability and Pleistocene glacial landscape development in the southern mid-latitudes remain poorly understood, in part because of the scarcity of comprehensive, well-studied records. Glacial landforms are invaluable for reconstructing past ice-sheet, climate, and associated environmental changes along the southern Andes, but there are significant spatial and temporal gaps in existing data. In this paper, we present new geomorphic and sedimentologic analyses, including surficial maps, for the Torres del Paine region (51°S, 73°W), southern South America. Our findings provide a new framework for understanding changes in the regional glacier history and Pleistocene landscape development. Glacial extent during the local last glacial maximum (LGM) remains unknown but new chronological data supported by geomorphic evidence afford evidence for a larger ice sheet at Torres del Paine than previously assumed. Deglaciation from the local LGM was underway by 17,400 ± 200 (1σ) cal. yr. BP. As opposed to previous suggestions, we have found that most of the moraines fringing the lakes in the Torres del Paine national park were deposited during a late-glacial expansion that occurred between 14,100 and 12,500 cal. yr. BP. Late-glacial advances also have been documented recently for the Última Esperanza and Lago Argentino basins to the south and north of Torres del Paine, respectively, suggesting an overall regional ice response to a climate signal. The Tehuelche paleolake accompanied each of the ice-sheet fluctuations in Torres del Paine. New data document at least three main phases of this paleolake, which drained eastward to the Atlantic Ocean, while the Andes gaps were blocked with ice. During the late phase of glacial lake formation, when water levels reached 125–155 m a.s.l., the lake likely merged with paleolake Consuelo in the Última Esperanza area at the end of the last glaciation. Lake Tehuelche in Torres del Paine had drained into the Pacific Ocean by the late-glacial period, suggesting that ice southwest of Torres del Paine may have retreated back into the mountains by this time.

1. Introduction

Despite the fact that the northern and southern mid-latitudes are influenced by opposing insolation intensity signals, ice-core and marine records from both hemispheres appear to display broadly similar glacial–interglacial climate cycles at orbital timescales (EPICA community members, 2004; Lisiecki and Raymo, 2005; Jouzel et al., 2007). In addition, several investigators have used dated moraine records to argue for (near) synchronous global glacial activity during the global last glacial maximum (LGM) (Denton et al., 1999; Clapperton, 2000; Sugden et al., 2005). Yet southern hemisphere glaciers apparently advanced in the face of unfavorable summer insolation intensity, a problem Mercer (1984) referred to as “the fly in the ointment of the Milankovitch theory”. What then are the drivers of southern hemisphere glaciations? Precisely dated glacial and climate records from both hemispheres afford a means for isolating the causes behind the ice ages, but are relatively scarce in the southern hemisphere. In order to address the problem of the cause of southern hemisphere glaciations, we have begun a program of geomorphic mapping and chronology in the Torres del Paine region (51°S), southern South America, which has well-preserved sets of moraines that are suitable for direct dating with the exposure-age dating method (Fogwill and Kubik, 2005; Moreno et al., 2009a; García et al., 2012). Also, minimum-limiting ^{14}C data for moraine age formation can be obtained, mainly from peat bog cores (Marden and Clapperton, 1995; McCulloch et al., 2000; Hall et al., 2013). Southern Patagonia receives insolation intensity that is opposite to that of the North Atlantic region. Moreover, it is

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located in the core of the southern westerly wind belt, which is a main component of present-day climate (Cerveny, 1998; Markgraf, 1998) and which is thought to play an important role in glacial terminations (Anderson et al., 2009; Denton et al., 2010).

This paper presents the results of our geomorphological mapping and stratigraphic analyses in the Torres del Paine region and provides the critical foundation for: (1) reconstructing the former glacial and proglacial environments and associated landscape changes in the area; (2) understanding the pattern of deglaciation and associated environmental changes as ice receded back into the Andes; and (3) placing recently obtained chronological data (e.g., García et al., 2012) into a geomorphological framework that will allow us to understand the paleoglaciology and timing and significance of past glacial events in the region, including in the neighboring Lago Argentino and Última Esperanza basins. We address the following questions: How extensive was ice during the last glacial cycle in Torres del Paine? When and how did it fluctuate? What environments existed at the termini of the Patagonian outlet glaciers in Torres del Paine? What was the spatial and temporal extent of paleolakes, and how did they relate to the different glacial and deglacial activity in the area? The details of the chronology are mainly presented in separate papers (García, 2011; Strelin et al., 2011; García et al., 2012); here we only summarize salient aspects of the chronology to help place the timing of the geomorphologic and sedimentologic changes into context. In addition, we present new ^{14}C ages that help define the end of the LGM in this region (Table 1).

2. Regional setting

The former Patagonian ice sheet extended all along the southern Andes between 38 and 56°S (Clapperton, 1993; Glasser et al., 2008). During Quaternary glacial fluctuations, this ice sheet built one of the most striking glacial landscapes on Earth, particularly in its southern part (e.g., Patagonian Andes; Steffen, 1919), where ice was thicker and larger than to the north in the Chilean Lake District (Denton et al., 1999; García, 2012).

For the purposes of this work, the Torres del Paine region (50°45′–51°35′S, 73°30″–71°50′W; Fig. 1) is defined as the area between the Andes Cordillera to the west and the outer terminal moraines deposited to the east in Argentina. Lago Argentino and Última Esperanza basins define the northern and southern limits, respectively, of the Torres del Paine region. During Quaternary glaciations, the Patagonian ice sheet was the main source of ice in the region and, together with the Cordillera Paine alpine system (3248 m a.s.l. at its highest point), nourished eastward-flowing outlet glaciers (Glasser et al., 2008) that, in general, have reached less extensive maximums over time (Coronato et al., 2004; Rabassa et al., 2005; Kaplan et al., 2009).

A cold, temperate climate regime, involving significant thermal and precipitation gradients across the Andes, characterizes the study area. Westerly wind cyclones originating in the Antarctic Frontal Zone are associated with elevated precipitation levels (as much as 10 m per year at high elevations; DGA, 1987) and decreased temperatures (Garreaud, 2007) that directly affect local climate. Most of the study area (Fig. 1) falls in the rain shadow of the Andes and displays a semi-arid steppe. Studies on the present ice fields over the 20th/21st centuries, including instrumental data, document that variations in atmospheric temperature and precipitation, with the former playing the principal role, control glacier mass balance along the southern Andes (Warren and Sugden, 1993; Cassasa et al., 2002; Rivera et al., 2002; Rivera and Cassasa, 2004). Cloudiness and precipitation occur year round over the ice fields (Miller, 1976; Carrasco et al., 2002), to the west of the main field area, and their effect on glacier annual mass balance is less clear (e.g., Rivera et al., 2002).

The moraines to the east of the cordillera, rather than the southern Andes, form the hydrologic divide between the Pacific and Atlantic Oceans in the Torres del Paine region. This condition, along with local bedrock topography, has resulted in the Torres del Paine and adjacent Última Esperanza basins being hydrologically connected. A suite of interconnected rivers and lakes in the Torres del Paine region forms a complex hydrological network that ultimately drains to Fiordo Última Esperanza through Río Serrano. Thus, the paleolake histories of the two regions should also be related (Fig. 1).

3. Previous work

Nordenskjöld (1898), Hauthal et al. (1905) and Caldenius (1932) produced the first glaciological observations and physiographic maps that included glacial landforms from the Torres del Paine region. Caldenius (1932) defined four main moraine belts, from outer to inner: 'Initioglacial', 'Daniglacial', 'Gotiglacial' and 'Finiglacial', with the latter enclosing some of the present-day lakes in Torres del Paine National Park (i.e., Laguna Azul, Lago Sarmiento and Lago del Toro; Fig. 1). Because of the freshness and preservation of landforms, Caldenius (1932) suggested that all four moraine belts dated to the last glaciation and assumed that they were analogous to the Scandinavian glacial record. Marden (1993, 1997) and Marden and Clapperton (1995) subsequently separated the 'Finiglacial' moraines of Caldenius (1932) into four distinct belts (A–D), which they thought were deposited during the LGM (B–D moraines) and Marine Isotopic Stage 4 (MIS 4; A moraines). The same authors delineated two additional ice-marginal positions (E and F) from less distinct and discontinuous landforms proximal to the D moraines and linked them to the late-glacial period, or post-'Finiglacial' in Caldenius' (1932) nomenclature. Fogwill and Kubik (2005) and Moreno et al. (2009a) further modified the mapping and dated to the late-glacial the inner D limit of Marden and Clapperton (1995) near Lago Nordenskjöld and along Río Paine. Recent work (García et al., 2012) determined that B, C and D moraines all formed ca. 14,100 ± 520 cal. yr. BP, during the Antarctic cold reversal (ACR, Monnin et al., 2001; Jouzel et al., 2007) chronozone rather than during the LGM as previously thought. To avoid confusion with sites elsewhere in southern South America that use similar labels to refer to different glacial events (i.e., Clapperton, 1993; Sugden et al., 2005), García et al. (2012) renamed the inner Torres del Paine A–D moraines sets accordingly: A = TDP I, B = TDP II, C = TDP III, and D = TDP IV (TDP = Torres del Paine). An outer moraine belt was termed the "Río de Las Viscachas" (RV) by Caldenius (1932) (his 'Gotiglacial' moraines), here differentiated as RV I and RV II.

In addition, a lobe of the Patagonian ice sheet just south of Torres del Paine built another moraine belt, the Arroyo Guillermo (AG) (Fig. 1). The position of this latter moraine belt suggests that it is correlative with the RV I moraines (e.g., Caldenius, 1932). There are no direct ages for the RV moraines but their deposition during MIS 2–4 cannot be ruled out.

4. Materials and methods

One of the primary goals of our research was to produce the first high-resolution, georeferenced geomorphologic maps for the Torres del Paine region (Figs. 2–6). We constructed the maps first from stereoscopic analysis of aerial photographs (Vuelo Geotec 1998, 1:70,000), which cover most of the study area. We then checked our preliminary mapping during five field campaigns between 2007 and 2012. We focused on ice-marginal positions, as defined by glacial and proglacial features (e.g., moraine ridges, glaciofluvial and glaciolacustrine landforms), built during the last glacial period and transition to the Holocene. We delineated the TDP moraines based on morphostratigraphic position and morphology, following Marden (1993). The final map was created in a geographical information system (GIS) software at a scale of 1:50,000. We used hand-held global positioning systems (GPS) to measure the elevation of glaciolacustrine terraces multiple times (±5–10 m). We complemented these measurements with Shuttle Radar Topography Mission (90 m horizontal resolution; vertical uncertainty <15 m) and Google Earth elevation data. We analyzed stratigraphic sections associated with different landforms wherever possible. We divided stratigraphic sections into discrete sediment units based on physical characteristics,