Correspondence

The 2004 outburst flood at Glaciar Perito Moreno, Argentina

Glaciar Perito Moreno (50°28′ S, 73°02′ W), with a surface area of 259 km^2, is one of the major eastern outlet glaciers of Hielo Patagónico Sur (southern Patagonia icefield). It terminates at an active, grounded calving front some 5 km long and 55–80 m high, with surface velocities reaching 800 $\mathrm{m\,a}^{-1}$ in the pervasively crevassed terminus area (Rott and others, 1998; Chinni, 2004). It flows across and bisects an inner fjord of Lago Argentino, the northern front calving into Canal de los Témpanos and the southern front into Brazo Rico. The eastern point of the terminus intermittently comes ashore onto Peninsula Magallanes. The glacier is well known, partly as one of Patagonia's primary tourist destinations and partly as a result of its 20th-century history of repeated outburst floods. These occur when the terminus advances onto Peninsula Magallanes to form an ice dam which cuts off the southern arms of Lago Argentino from the main body of the lake. Water levels then rise until the eventual failure of the dam precipitates catastrophic drainage. There is no evidence that these periodic advances are related to surge-type behaviour.

The first recorded outburst flood occurred in 1917. This followed at least 18 years of steady advance during a period when all neighbouring glaciers were retreating rapidly from Little Ice Age maxima. Warren (1994) suggested that this early 20th-century advance was a delayed response to Little Ice Age cooling caused by the interplay between calving dynamics and sedimentation. Between 1917 and 1988 there were 16 closures lasting from months to 3 years. Dams typically form in the late winter or early spring, with failure occurring in mid- to late summer (March–April). Water levels in the impounded lake arms of Brazo Rico and Brazo Sur rise 10–26 m, causing extensive flooding and forming a temporarily enlarged lake with a surface area of ~150 km^2. A combination of water pressure and melting eventually creates sub- and/or englacial conduits through the ice dam and these rapidly evolve into a subaerial tunnel as the dam fails. The outbursts then discharge some 3.0–4.0 km^3 of water in the space of several hours to days. During drainage, the tunnel is rapidly enlarged by melting and calving, followed by collapse of the tunnel roof. Outburst floods raise the level of Lago Argentino, a lake some 100 km long, by several metres, inundating farmland, roads and buildings along the shore, and sometimes damaging bridges over Río Santa Cruz, the river which drains the lake at its eastern end.

From 1915 to 1993 the average position of the terminus showed little change (Aniya and Skvarca, 1992; Warren, 1994). This long-maintained stability during a century when almost all Patagonian glaciers consistently retreated (Warren and Aniya, 1999) can be explained primarily by the steepness of the glacier surface near the equilibrium line, which renders the glacier insensitive to climate change, and also by the relatively high ratio of calving flux to net accumulation (Rott and others, 1998). From 1966 to 1988, closures occurred in a quasi-cyclic 4 year pattern, with lake build-up typically taking about 2 years from closure to dam failure followed by 2 years before the formation of the next dam. However, from 1988 to 2003 no closures occurred. Winter advances onto the peninsula did occur, but water continued to drain through subglacial conduits near the shoreline.

The winter advance of 2003 did, however, form an effective dam. The water level in Brazo Rico began rising in November, and by late February 2004 the lake had risen 6.0 m. In the following 15 days, which was a period of warm, sunny weather, the level of the dammed lake rose at a rate of 0.3 $\mathrm{m\,d}^{-1}$ to reach 10.5 m above the pre-impoundment level. By then, as during previous closures, a tunnel had begun to form on the southern side of the tongue, and dam failure was anticipated during April. However, during the afternoon of 11 March, water was observed to be draining underneath the dam and emerging on the northern side. Following rapid enlargement of incipient tunnels on both the northern and southern flanks of the tongue, the dam ruptured on the morning of 12 March. Thunderous water discharge then ensued through a large subaerial tunnel (Fig. 1). The tunnel rapidly grew in size as mechanical and thermal erosion at the waterline undermined the side-walls, initiating frequent blockfalls within and adjacent to the tunnel. By the morning of 13 March, some 50% of the length of the tunnel had been removed and the thickness of the tunnel roof was much reduced, but the southern side of the former dam was little changed. Although the rate of water discharge then progressively decreased, ongoing thermomechanical erosion and calving continued to increase the size of the archway until the tunnel roof suddenly and spectacularly collapsed at 1910 h on 14 March, leaving walls of ice standing either side of a narrow channel (Fig. 2). The outburst flood had impacts all around the shores of Lago Argentino as water levels rose by as much as 4.5 m for several days. Despite the sudden and unexpected onset of the rupture, news of the event spread so rapidly that an estimated 10 000 tourists came to watch the spectacle during the 3 days.

Many facets of this latest outburst event conform with the sequence observed during 20th-century impoundments, including the timing and mechanisms of dam formation and rupture. However, the 2003/04 dam was one of the shortest-lived on record, restricting the magnitude of lake-level rise to much less than has commonly occurred. It is of interest that ruptures at Glaciar Perito Moreno are initiated

Fig. 1. The early stage of dam rupture on 12 March 2004, following the formation of a subaerial tunnel through the ice dam. The image shows the northern side of the former dam, viewed from Peninsula Magallanes, and water flow is from left to right. The calving cliff on the right rises ~50 m above lake level.

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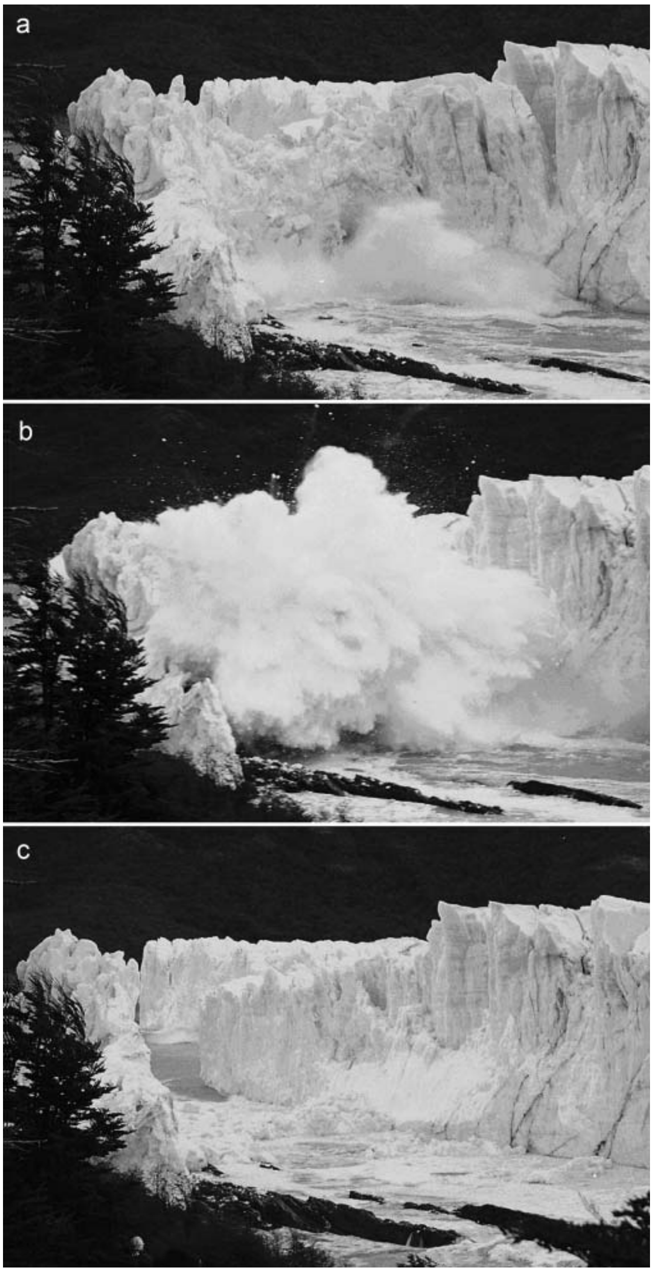

Fig. 2. (a–c) The tunnel collapsing explosively at 1910 h on 14 March 2004, leaving an ice-choked channel and an unstable fragment of tunnel wall standing on the shore of the peninsula.

by subglacial drainage, whereas, when temporary dams formed at Hubbard Glacier, Alaska, USA, in 1986 and 2002, rupture was initiated by water overflowing the dam because the rate of lake-level rise ($0.2\ \mathrm{m\,d^{-1}}$ in 2002) exceeded that of dam growth (Trabant and others, 2003).

The most striking contrast with previous behaviour, however, was the extended interval between the last rupture in 1988 and the formation of the 2003 dam. What combination of glacioclimatic factors interrupted the well-established 4 year cycle, prevented dam formation for 16 years and then caused an impoundment in 2003/04? The cessation of the cycle during the 1990s, combined with indications of negative net mass balance and the strong regional retreat, led to predictions that the glacier might soon retreat off the peninsula into deeper water and commence a catastrophic retreat (Clapperton, 1993; Warren, 1994). The renewed advance and damming is therefore surprising and intriguing. Unfortunately, there are neither sufficient mass-balance nor climatic data with which to address this puzzle, although several climate stations in southern Patagonia show cooling temperatures and increases in precipitation in the last 15–20 years (Carrasco and others, 2002). Since the glacier is thought to be at least as sensitive to precipitation as it is to air temperature (Rott and others, 1998), and given the glaciodynamically important role of calving at this site, the combination of complexity and limited data currently frustrates any attempt to interpret the glacier's recent behaviour or to predict whether outburst floods will once again become a regularly repeating phenomenon at Glaciar Perito Moreno.

Leandro N. Alem 724, Guillermo A. CHINNI
Don Torcuato (1611),
Buenos Aires, Argentina
E-mail: gachinni@yahoo.com.ar

School of Geography Charles R. WARREN
and Geosciences,
University of St. Andrews,
St. Andrews, Fife KY16 9AL, UK

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