Fast-flowing outlet glaciers of the Last Glacial Maximum Patagonian Icefield.

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Abstract

Glacial geomorphology around the Northern Patagonian Icefield indicates that a number of fast-flowing outlet glaciers (the continuation of ice streams further upglacier) drained the icefield during the Last Glacial Maximum. These topographically controlled fast-flowing glaciers may have dictated the overall pattern of Last Glacial Maximum ice discharge, lowered the ice-surface profile, and forced the ice-divide westward. The influence of the fast-flowing outlet glaciers on icefield behavior also helps to explain why the configuration of the Patagonian Icefield at the Last Glacial Maximum is not accurately represented in existing numerical ice-sheet models. Fast-flowing outlet glaciers would have strongly influenced ice discharge patterns and therefore partially decoupled the icefield from climatically induced changes in thickness and extent.

The Northern Patagonian Icefield

The Northern Patagonian Icefield, covering an area of 4200 km$^2$, is situated in Chile, South America (Aniya, 1988). Its existence in temperate latitudes (47°S) is sustained by abundant precipitation over the icefield (2 to 11 m of water equivalent per yr) generated as the Southern Westerlies are forced over the Andes (Casassa et al., 2002). The existence of the Northern Patagonian Icefield at the very limit of glacierization of the Southern Hemisphere and the strong climate gradients that exist across South America at this latitude create an icefield extremely sensitive to climatic change (Kerr and Sugden, 1994; Rignot et al., 2003). This sensitivity to climate makes the icefield an ideal location for investigating the relative importance of climate and ice dynamics on icefield behavior, including expansion and contraction and changes in ice discharge patterns. Variations in the behavior of the glaciers draining the Patagonian icefields provide valuable information on the forcing mechanisms of global climate change (e.g., Denton et al., 1999; Hajdas et al., 2003), including the latitudinal migration of the precipitation-bearing Southern Westerlies and associated ocean currents (Lamy et al., 2001).

Here, we build on the pioneering work of Caldenius (1932) by presenting a detailed regional map of glacial landforms around the Northern Patagonian Icefield. We use these data to make inferences concerning the behavior of the former Patagonian Icefield during the Last Glacial Maximum. The motivation for this study is the need to identify climatic and non-climatic effects on former ice sheet dynamics. Our data suggest that the Last Glacial
Maximum icefield was strongly controlled by fast-flowing outlet glaciers inherited from ice streams further upglacier. These topographically controlled fast-flowing outlet glaciers may have dictated the overall patterns of ice discharge, lowered the ice-surface profile, and forced the ice-divide westward. This study builds on previous valley-scale geomorphological mapping and glacier-fluctuation dating studies (e.g., Clapperton and Sugden, 1988; Kaplan et al., 2004; Wenzens, 2002), studies of Quaternary stratigraphy (e.g., Caldenius, 1932; Hajdas et al., 2003) and paleoenvironmental reconstructions (Bennett et al., 2000) which have significantly increased our understanding of the environment surrounding the Patagonian Icefields.

Methods

*Satellite images and digital elevation model (DEM)*

Visual interpretations of the glacial geomorphology were compiled from four Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite images as infrared false color composites with a spatial resolution of 30 m, and 13 Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images with a spatial resolution of 15 m in visible near-infrared (Bands 1, 2 and 3N). This combination of satellite imagery allowed us (1) to obtain complete coverage of the land area surrounding the icefield, (2) to duplicate coverage in areas where images contain cloud cover, and (3) to perform an independent verification of landform mapping between the two image types. Landsat 7 ETM+ infrared false color images were used because they provide the greatest contrast between ice, bedrock, and vegetation. Topographic elevation data are derived from the Shuttle Radar Topography Mission (SRTM) with data resampled from 90 to 200 m horizontal resolution. The criteria used in landform identification are listed in Table 1.

*Landform analysis*

Mapped glacial lineations were stacked into flow sets, which are map representations of coherent landform systems inferred to record distinct phases of ice flow. The outline of a flow set is determined on the basis of the spatial continuity of landforms and/or the resemblance to a glaciologically plausible pattern (Boulton and Clark, 1990; Kleman and Borgström, 1996). Glacial lineations are assumed to have formed synchronously over the flow-set area, which indicates that they therefore reflect true flow lines (Clark, 1999; Kleman and Borgström, 1996).

*Ice thickness calculations*

Ice thickness was estimated using the equation $h^2 = 2 h_0 S$, where $h$ is the elevation of the ice surface, $h_0$ is 11 or 2.7 m calculated on a basal shear stress of 25 kPa in the inferred fast-
flowing outlet glacier corridors at the Last Glacial Maximum and 100 kPa in intervening areas (Nye, 1952; Paterson, 1994) and \( s \) is the distance along a flow line from the ice margin.

Table 1 Criteria used in identifying landforms from satellite imagery

<table>
<thead>
<tr>
<th>Landform</th>
<th>Identification criteria</th>
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<tr>
<td>Ice-scoured bedrock</td>
<td>Widespread exposures of bare or lightly vegetated bedrock. Numerous small lake basins and open joints visible.</td>
</tr>
<tr>
<td>Glacial lineations</td>
<td>Parallel features indicating ice-flow direction. Formed in bedrock by glacial erosion or by sediment accumulation.</td>
</tr>
<tr>
<td>Terminal moraines</td>
<td>Prominent cross-valley single or multiple ridges with positive relief. Linear, curved, sinuous or saw-toothed in plan.</td>
</tr>
<tr>
<td>Delta/ice contact deposits</td>
<td>Flat-topped sediment accumulations above the present day valley floor, commonly with a steep delta front.</td>
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\[
h_0 = \frac{\tau_o}{\rho g}, \text{ where } \tau_o = \text{yield stress, } \rho = \text{ice density and } g = \text{gravitational acceleration.}
\]

Calculations of ice thickness require the following assumptions: the ice mass overlies a flat bed, is in steady-state, flows by internal deformation and is isothermal. The assumption of a flat bed is realistic, as witnessed by the topography outside the icefield (Fig. 1). Ice flow from the icefield almost certainly involved processes such as basal sliding and deformation of subglacial material, but we have no detail concerning the distribution of areas dominated by these modes of ice flow. The assumption of isothermal ice is an over-simplification but, in the absence of any data on the three-dimensional temperature distribution in the icefield, it remains a necessary assumption. We consider it more meaningful to employ this simple model, which can be constrained by our data, than try to incorporate simple data into a complex model with numerous unquantified parameters. We note that a model taking frozen patches into account would generate a steeper ice-surface profile in places. On the other hand, incorporating basal sliding and deformation of subglacial material would generate an ice field with a lower profile than suggested in this paper.

Northern Patagonian glacial geomorphology

The primary features of the landscape on the eastern side of the Northern Patagonian Icefield are corridors of ice-scoured bedrock, in areas of high relative relief, associated with glacial lineations and large lobate moraines with related meltwater channels at the eastern foot of the Andes (Fig. 1). Large bodies of sediment, interpreted as ice-contact deposits or deltas, are present at the confluence of the principal west–east trending valleys and their tributary valleys. These deltas generally slope into the west–east valleys from the tributary
valleys. Areas of ice-scoured bedrock (Fig. 2) indicate widespread glacial erosion beneath wet-based, sliding ice (Sugden and John, 1976). The presence of highly attenuated drumlins and flutes (Fig. 2) in these ice-scoured corridors (mean length/width ratios of approximately 15:1 and 25:1 beneath the Cochrane and Lago Buenos Aires outlet glaciers, respectively) indicate formation by fast-flowing ice (Boyce and Eyles, 1991).

Figure 1. Glacial landforms of the area surrounding the Northern Patagonian Icefield. The map was compiled by interpretation of Landsat 7 ETM+ and Terra ASTER satellite images. Background color shows topography derived from the Shuttle Radar Topography Mission (SRTM) and black box shows the outline of Fig. 2. White pixels within areas of generally higher topography indicate gaps in the SRTM data set. The inset table shows satellite image data and the inset map shows the location of the study area within South America. NPI = Northern Patagonia Icefield; SPI = Southern Patagonia Icefield; LGM = Last Glacial Maximum. Dates for terminal moraines around Lago Buenos Aires/Lago General Carrera are from Kaplan et al. (2004).
Figure 2. Terra ASTER sub-scenes showing the Cochrane fast-flowing outlet glacier corridor marked by scoured bedrock (Sb) and glacial lineations (white and black lines), together with associated features such as ice-contact deposits and deltas (D), terminal moraines (lobate features) and meltwater channels (blue lines). Insets show (A) glacial lineations formed in sediment and (B) glacial lineations in bedrock. The glacial lineations have a mean length/width ratio of approximately 15:1. Scale bar is 10 km.

Glacial lineations of similar distribution and characteristics can be stacked into flow-sets (Boulton and Clark, 1990; Kleman and Borgström, 1996), which are inferred to represent former flow lines of the Northern Patagonian Icefield. All major flow-sets east of the Northern Patagonian Icefield are characterized by a narrow main trunk with sharp lateral boundaries, parallel conformity between individual glacial lineations, convergent head areas and attenuated glacial lineations. We therefore infer that these flow-sets (Fig. 3) indicate the presence of fast-flowing outlet glaciers inherited from ice streams further upglacier within the former ice mass (Stokes and Clark, 1999, 2003), and that the large lobate moraines on the low-relief terrain at the eastern foot of the Andes mark the termini of these outlet glaciers.

The eight identified ice stream/outlet glaciers (the Nireguao, Simpson, Balmaceda, Lago Buenos Aires, Cochrane, Belgrano, Nansen and Chico Glaciers; Fig. 3) appear to be strongly related to the underlying topography and clearly drained large portions of the eastern Northern Patagonian Icefield during the Last Glacial Maximum. Radiometric dating indicates that the innermost terminal moraines deposited by the Lago Buenos Aires Glacier (Fig. 1) represent a phase of glacier expansion between 23,000 and 15,600 yr ago (Kaplan et al., 2004). The presence of large deltas and ice-contact deposits at the confluence of the west–east trending valleys and their tributary valleys suggests that sediment was supplied to lakes in the main valleys from the tributary valleys. Although the timing of the operation of the remaining seven outlet glaciers is undated, their extent and similarity in terms of landforms
developed suggest that they also mark Last Glacial Maximum terminal positions. The western side of the Northern Patagonian Icefield is dominated by large tracts of scoured bedrock on the flanks of the main valleys. Bedrock-carved glacial lineations are also present, with lineations generally aligned parallel to valley axes. The identification of the terminal positions of former outlet glaciers to the west of the icefield is difficult because here glaciers descended steeply to sea level to form tidewater fronts and did not generally produce terminal moraine ridges.

**Northern Patagonian Icefield dynamics**

Low surface slopes, low driving stresses (b25 kPa) and rapid velocities characterize ice streams and fast-flowing outlet glaciers (Alley and Whillans, 1991). Low driving stresses are normally attributed to basal motion in glaciers overriding deformable sediments (Kamb, 1991). The outlet glaciers reported in this paper were topographically controlled and rested on beds composed of bedrock and, in places, possibly also paleo-lake sediments. We suggest that the driving stresses for these glaciers were higher than previous estimates of 2–7 kPa for the low-gradient ice streams of the eastern Laurentide Ice Sheet (Kaplan et al., 2001). We therefore assumed a driving stress of 25 kPa to calculate ice surface profiles for the outlet glaciers using the solution proposed by Nye (1952). For other areas, we assumed a yield stress of 100 kPa (Paterson, 1994). The reconstruction of the Northern Patagonian Icefield at the Last Glacial Maximum (Fig. 3) shows, in agreement with the pattern of scoured bedrock (Fig. 1), that the ice-divide was situated further west and that the ice was thinner than previously indicated by numerical ice-sheet models (Hulton et al., 2002). The absence of scoured bedrock in the central area of the former Northern Patagonian Icefield is in line with previous suggestions that non-erosive conditions prevail beneath ice divides (Boulton and Clark, 1990).

We suggest that the difference in ice thickness and configuration reported here and those predicted by numerical models (Hulton et al., 2002) can be explained by the existence of the fast-flowing outlet glaciers that developed on the eastern part of the Northern Patagonian Icefield at the Last Glacial Maximum. In the light of recent results showing that ice streams and fast-flowing outlet glaciers are responsible for 90% of the ice discharge from the West Antarctica Ice Sheet (Joughin and Tulaczyk, 2002) and the documented outline and size of the glaciers reported in this study (Fig. 3), we suggest that the Northern Patagonian Icefield fast-flowing outlet glaciers strongly influenced patterns and rates of ice discharge and ice mass configuration (cf. Payne and Donglemans, 1997) at the Last Glacial Maximum. Therefore, numerical ice-sheet models that do not account for fast-flowing outlet glaciers inherited from ice streams further upglacier fail to reflect accurately the former ice limits established by field investigations (Wenzens, 2002).
Figure 3. Reconstruction of the fast-flowing outlet glaciers draining the eastern portion of the Northern Patagonian Icefield. The reconstruction is based on mapped landforms and shows flowlines (defined by flow-sets) and ice surface topography of the icefield at the Last Glacial Maximum. Ice thickness was estimated using the equation $h^2 = 2 h_0 s$, where $h$ is the elevation of the ice surface, $h_0$ is 11 or 2.7 m calculated on a basal shear stress of 25 kPa in the inferred fast-flowing outlet glacier corridors at the Last Glacial Maximum and 100 kPa in intervening areas (Nye, 1952; Paterson, 1994).

This study demonstrates that geomorphologically constrained reconstructions of ice mass dynamics are required to be able to better understand, by further numerical modeling, the
relationship between former ice masses, climate and sea-level change (Bentley, 1998; Fastook and Prentice, 1994).

Implications

The lack of a detailed regional reconstruction of the Patagonian Icefield during the Last Glacial Maximum has hampered comparisons with numerical modeling results (e.g., Hulton and Sugden, 1997). Numerical models (Hulton et al., 2002) show that glaciers west of the Andes at the Last Glacial Maximum terminated in deep water, which implies that model results are not testable against the terrestrial landform record in this western sector. Landforms created by the terrestrial glacier termini in the eastern sector of the Northern Patagonian Icefield, on the other hand, allow verification of the output from numerical models. Previous estimates of the configuration and volume of the Northern Patagonian Icefield at the Last Glacial Maximum from numerical models have not proved capable of matching these landform data (Wenzens, 2002). Such inconsistencies represent a major obstacle to understanding the dynamics of glacier expansion and contraction, and their paleoclimatic significance.

Conclusions

Glacial geomorphological mapping of the area surrounding the Northern Patagonian Icefield shows that topographically controlled fast-flowing outlet glaciers inherited from ice streams further upglacier developed around the icefield during the last glacial maximum. These glaciers may have dictated the overall patterns of Last Glacial Maximum ice discharge, lowered the ice-surface profile and forced the ice-divide westward. The fast-flowing outlet glaciers would have strongly influenced ice discharge patterns and therefore partially decoupled the icefield from climatically induced changes in thickness and extent. The influence of the fast-flowing outlet glaciers on icefield behavior may explain why the configuration of the Northern Patagonian Icefield at the Last Glacial Maximum is not accurately represented in existing numerical ice-sheet models.

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References


