Available online at www.sciencedirect.com
SCIENCE DIRECT®
Quaternary Research 63 (2005) 206–211
QUATERNARY RESEARCH
www.elsevier.com/locate/yqres

Short Paper

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

Neil F. Glasser[a,*], Krister N. Jansson[b]

[a]Centre for Glaciology, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, Ceredigion SY23 3DB, Wales, United Kingdom
[b]Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden

Received 9 April 2004
Available online 10 December 2004

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.

Keywords: Northern Patagonian Icefield; South America; Last Glacial Maximum; Fast-flowing outlet glaciers; Ice discharge; Glacial lineations; Ice-scoured bedrock

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

* Corresponding author.
E-mail addresses: nfg@aber.ac.uk (N.F. Glasser), krister@natgeo.su.se (K.N. Jansson).

0033-5894/$ - see front matter © 2004 University of Washington. All rights reserved.
doi:10.1016/j.yqres.2004.11.002

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).

Table 1
Criteria used in identifying landforms from satellite imagery

Landform	Identification criteria
Ice-scoured bedrock	Widespread exposures of bare or lightly vegetated bedrock. Numerous small lake basins and open joints visible.
Glacial lineations	Parallel features indicating ice-flow direction. Formed in bedrock by glacial erosion or by sediment accumulation.
Terminal moraines	Prominent cross-valley single or multiple ridges with positive relief. Linear, curved, sinuous or saw-toothed in plan.
Delta/ice contact deposits	Flat-topped sediment accumulations above the present day valley floor, commonly with a steep delta front.

Ice thickness calculations

Ice thickness was estimated using the equation $h^2 = 2h_0 s$, 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. $h_0 = \tau_o/\rho g$, where τ_o = yield stress, ρ = ice density and g = 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