Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 252 (2006) 275 – 288
EPSL
www.elsevier.com/locate/epsl

Monsoonal forcing of Holocene glacier fluctuations in Ganesh Himal (Central Nepal) constrained by cosmogenic ^{3}He exposure ages of garnets

E. Gayer [a,b,*], J. Lavé [c], R. Pik [a], C. France-Lanord [a]

[a] Centre de Recherches Pétrographiques et Géochimiques, CRPG, CNRS-UPR 2300, BP 20, 54 501 Vandoeuvre-Lès-Nancy Cedex, France
[b] Department of Earth and Planetary Sciences, Harvard University, Cambridge, 02138 MA, USA
[c] Laboratoire de Géodynamique des Chaines Alpines, LGCA-UMR 5025, Maison des, Géosciences, BP 53, 38041 Grenoble, France

Received 7 March 2006; received in revised form 25 September 2006; accepted 26 September 2006
Available online 9 November 2006
Editor: M.L. Delaney

Abstract

In the Himalayas, the late Pleistocene glacier oscillations have produced spectacular glacial landforms. Detailed reconstructions of the chronology and extent of these oscillations are essential to document the sensitivity of the Himalayan glaciers to past and future climatic changes. In this paper, we present a new cosmogenic helium 3 ($^{3}He_{c}$) dating on garnets, that were sampled on moraine blocks and ice-scoured surfaces in a small glaciated valley of the Central Nepal (the Mailun valley), and that provided a detailed chronology of Himalayan glacier fluctuations during the Holocene. Soon after the Younger Dryas, the glacier of the Mailun valley underwent a significant retreat around 10 ka. This retreat was followed by relative stability of the extent of the glacier between ~8.5 and ~7.5 ka. A second phase of rapid retreat occurred at ~7 ka, but rapidly slowed down at ~5–6 ka. Finally, a last phase of re-advance occurred between 0 and 1 ka. The interpretation of the Equilibrium Line Altitude (ELA) variation, deduced from this chronology (for the Holocene period) and carbon 14 (^{14}C) dating (for the Pleistocene period), shows that the early history of the Mailun valley deglaciation (late Pleistocene) is in good agreement with the global paleoclimatic records. The main extent of the glacier and the major ice volume drop are in phase with the global Last Glacial Maximum (25–17 ka) and with the major worldwide temperature increase following the Younger Dryas, respectively, indicating that the Mailun glacier was primarily driven by temperature oscillations during the late Pleistocene. In contrast, the glacier chronology during the Holocene suggests that the Mailun glacier was modulated by the variation in annual precipitation, and is asynchronous relative to most glaciers of the Northern Hemisphere. The significant sensitivity of the Himalayan glaciers to precipitation might explain the striking lack of synchronism of the Himalayan glaciers both along and across the Himalayan arc.

Keywords: ^{3}He; ^{10}Be; cosmogenic nuclide; garnet; himalaya; glaciation; monsoon; glacial chronology

1. Introduction

In the Himalayas, climatic variations during the late Quaternary produced successive glaciations recorded in

* Corresponding author. Department of Earth and Planetary Sciences, Harvard University, Cambridge, 02138 MA, USA. Tel.: +1 617 384 9335; fax: +1 617 496 6958.
E-mail address: egayer@eps.harvard.edu (E. Gayer).

0012-821X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2006.09.040

spectacular glacial landforms. Detailed reconstructions of the chronology and the extent of these glaciations provide a proxy for the quantification of regional and global climatic changes, and particularly for studying the monsoon response to Quaternary climatic oscillations in Himalayan regions [1]. In addition, these reconstructions can bring new insights into the sensitivity of the Himalayan glaciers to climatic changes, which are required to understand the potential evolution of these glaciated regions in response to global warming (particularly in terms of natural hazards and hydrologic balance).

Previous studies have suggested that Himalayan glaciers advanced and receded asynchronously with those of the Northern Hemisphere [1,2], emphasizing the role of the summer monsoon as a major force in driving glaciations throughout the Himalaya, by increasing snowfall at high altitude. However, it is not evident whether the monsoon, through its control on the moisture flux, is the primary agent regulating glaciation on the Tibetan plateau and in its bordering mountain ranges, or has only a secondary role relative to global temperature changes. Furthermore, the degree of asynchronism with the Northern Hemisphere or even at the scale of the Himalayan regions, is still unclear. The apparent non-synchronous preservation of the Himalayan moraines could indeed either result from synchronous advances but with large differences in the amplitudes, or from a completely different timing of the glaciers' advances.

In order to quantify the timing and extent of glaciations in the central Himalayas we conducted a detailed study in the upper valley of the Mailun Khola (Paldor region, Ganesh Himal) in central Nepal. We mapped both glacier moraines and ice-scoured surfaces, and measured exposure ages using cosmogenic helium 3 ($^{3}He_{c}$) in garnets [3]. This new dating method for surface exposure age is complemented with cosmogenic beryllium 10 ($^{10}Be_{c}$) in quartz and carbon 14 (^{14}C) in organic soils. In contrast to previous studies dedicated to glacial chronology in the Himalayan range [1,2,4–6], and which studied large debris-laden outlet glaciers, our goal was to study a small, clean, snowfall-fed glacier, and to use the very well preserved glacial landforms (moraines and ubiquitous striated surfaces) to reconstruct, as precisely as possible, the advance and retreat chronology of this highly sensitive glacier. The evolution of the glacier since the Last Glacial Maximum (LGM) and the associated variations of past Equilibrium Line Altitude (ELA) are then interpreted in terms of climatic changes and compared to other regional paleoclimatic proxies.

2. Geological and geomorphic settings

The Ganesh Himal is located in the central part of Nepal (Fig. 1), between the Manaslu Himal and the Langtang Himal. This mountain range includes peaks higher than 7000 m and glaciers located above 5000 m. The Paldor peak, 5828 m, supports several glaciers. Two glacial snouts flow southward and drain the Mailun Khola, a tributary of the Trisuli river. This N–S oriented valley is located on the southern flank of the High Himalaya and is subject to abundant precipitations during summer monsoon (~2300 mm/yr at Paigutan at 4100 m a.s.l. Fig. 1, ~700 mm/yr of which is snowfall). Geologically, the studied area, which covers ~25 km^2 of the upper Mailun valley (Fig. 1), belongs to the highly deformed and metamorphosed Lesser Himalayan units in the vicinity of the Main Central Thrust. Garnet-rich micaschist represents the dominant lithology of this area.

The upper Mailun valley is today occupied by two small and clean (with little or no supraglacial debris) glaciers, whose areas are 3 and 1.5 km^2 respectively. However, in the past, these two glaciers coalesced into a single ice tongue that built several sets of dumped moraines down to 3600 m and carved a typical U-shaped valley that can be followed down to 3200 m near the village of Somdan. We identified three main sets of moraines according to their types, locations and degree of preservation (Fig. 1):

- A small and poorly preserved remnant of an old moraine (M0) close to the terminus of the U-shaped upper valley that we attribute to the Last Glacial Maximum extent of the Mailun glacier.
- Several sets of nested lateral and terminal moraines (M1–5) in the vicinity of the Paigutan mine, between 3600 and 4700 m a.s.l.. The third set (M3) is sharp crested (Fig. 2), in contrast with the four other sets. They are all dotted with numerous meter-sized boulders, and vegetated by sparse grass and shrubs, except below 3900 m where the vegetation is more extensively developed (bushes, small trees).
- A set of two unvegetated moraines with sharp crests (M6) deposited by the last glaciers advance and located ~2 km in front of the present snouts. Compared to the oldest moraines, these two youngest moraines, in particular the one built by the eastern glacier, represent an impressive volume of debris.

The U-shaped valley is also characterized by ubiquitous ice-scoured features. Numerous striated rocks, *roches moutonnées* and *whale backs* can be