Asynchronous glaciation at Nanga Parbat, northwestern Himalaya Mountains, Pakistan

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ABSTRACT

We present a new glacial chronology demonstrating asynchroneity between advances of Himalayan glaciers and Northern Hemisphere ice-sheet volumes. Glaciers at Nanga Parbat expanded during the early to middle Holocene ca. 9.0–5.5 ka. No major advances at Nanga Parbat during the last global glacial stage of marine oxygen isotope stage 2 (MIS-2) between 24 and 11 ka were identified. Preliminary evidence also indicates advances between ca. 60 and 30 ka. These periods of high ice volume coincide with warm, wet regional climates dominated by a strong southwest Asian summer monsoon. The general lack of deposits dating from MIS-2 suggests that Nanga Parbat was too arid to support expanded ice during this period of low monsoon intensity. Advances during warm, wet periods are possible for the high-altitude summer accumulation glaciers typical of the Himalayas, and explain asynchronous behavior. However, the Holocene advances at Nanga Parbat appear to have been forced by an abrupt drop in temperature ca. 8.4–8.0 ka and an increase in winter precipitation ca. 7–5.5 ka. These results highlight the overall sensitivity of Himalayan glaciation to orbital forcing of monsoon intensity, and on millennial or shorter time scales, to changes in North Atlantic circulation.

Keywords: Himalaya Mountains, Asian monsoon, Holocene, glaciation.

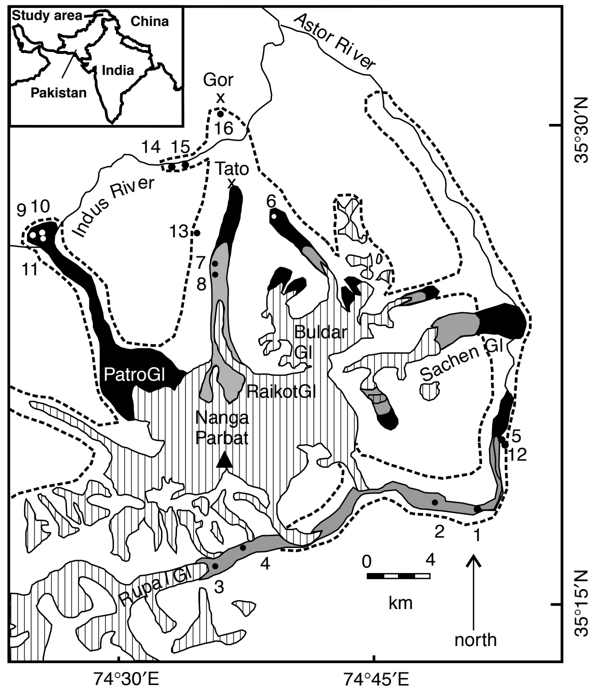

Figure 1. Location of Nanga Parbat showing sites of dated glacial deposits. Numbered samples refer to ^{10}Be and infrared stimulated luminescence ages given in Table 1. Ruled pattern indicates modern glaciers (Gl); black indicates maximal extent of deposits dated as Holocene in this work; shaded area indicates mid-Holocene readvance and/or stillstand; dashed line is maximal extent of glaciers during marine oxygen isotope stage 3 (MIS-3). Glacial geology is modified from Scott (1992), Derbyshire and Owen (1997), and Shroder et al. (1989).

INTRODUCTION

Although the Himalayas contain the largest volume of ice outside polar regions, their glacial history is poorly known. Himalayan glacial deposits have been difficult to date securely because of a general lack of organic material suitable for radiocarbon dating. Previous studies have proposed that Himalayan glaciers advanced and receded synchronously with Northern Hemisphere ice sheets (e.g., Burbank and Cheng, 1991). However, differences of as much as 10–20 k.y. between local Himalayan maximal advances and the global glacial maximum during marine oxygen isotope stage 2 (MIS-2) have been suggested (Gillespie and Molnar, 1995; Benn and Owen, 1998). If such differences are widespread in the Himalayas, then the understanding of climate system operation in a key region of the Earth must be incomplete. Much of the evidence for asynchronous Himalayan glaciation consists of thermoluminescence (TL) ages from the northwestern Himalaya with poor documentation and/or difficulties produced by partial trap saturation and incomplete bleaching (Derbyshire et al., 1984; Shroder et al., 1989, 1993). In addition, silt deposits overlying glacial landforms in the Swat Himalaya are reworked colluvium and yield much younger TL dates than the true age of glaciations (Owen et al., 1992). Conversely, optically stimulated luminescence (OSL) ages from the Nanga Parbat region imply glacial advances during both MIS-2 and MIS-3 (Richards et al., 2000). Radiocarbon ages associated with glacial moraines in the neighboring Tibetan Plateau (Lehukuhl, 1997) and in a few parts of the Himalaya (summarized in Benn and Owen, 1998) suggest that advances occurred during MIS-2. Thus, the extent and even the existence of asynchronous glaciation have been unclear. Here we present 16 new numerical ages of glacial deposits that clearly document for the first time asynchronous Himalayan glacial behavior.

GEOMORPHIC SETTING

At 8126 m, Nanga Parbat is the ninth highest mountain on Earth (Fig. 1). About 70 separate glacier systems covering 300 km^2 occur on this very high massif (Gardner and Jones, 1993), where almost half of the land area is between 4000 and 5000 m (Brozovic et al., 1997). Nanga Parbat is at the approximate present-day boundary between regions dominated by winter westerly circulation and the summer southwest Asian or Indian monsoon. Glaciers are nourished by both sources of moisture. The north

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side of the massif is in a rain shadow, causing present-day glacial equilibrium line altitudes (ELAs) to rise to the north-northwest, away from the monsoon moisture source (Scott, 1992).

Geomorphic mapping and stratigraphic studies indicate three major periods of glacial expansion at Nanga Parbat relative to present-day ice volumes (Scott, 1992; Derbyshire and Owen, 1997; Shroder et al., 1989, 1993). Deformed, partly indurated tills of the Jalipur sequence preserved along downdropped areas of major fault zones have been tentatively identified as the one oldest tills known in the Himalayas (Shroder et al., 1989). However, the age of the Jalipur remains uncertain, because OSL ages suggest that it could be as young as ca. 25 ka (Richards et al., 2000). The middle period of glacial expansion is indicated by remnants of till, stratified drift, and lacustrine deposits on glaciated surfaces at elevations well above present-day valley bottoms. This period represents the local last glacial maximum at Nanga Parbat, when ice volumes were large enough to fill tributary valleys and build moraine complexes into and across the Indus River valley. Further study is needed to determine the number and precise timing of advances represented by the middle period, but at least two major advances occurred. Deposits covering the bottoms of tributary valleys radiating from the summit of Nanga Parbat date from the youngest period of expanded ice. These deposits extend as much as 20 km beyond the limits of modern glaciers but are everywhere less extensive than deposits of the middle period. Detailed stratigraphic study of the younger sediments shows that they represent an advance, partial retreat, and then a readvance or stillstand (Scott, 1992; Derbyshire and Owen, 1997).

TABLE 1. ^{10}Be SURFACE EXPOSURE AGES AND IRSL AGES

Sample	Method	Age* (ka) $\varepsilon = 0$	Age† (ka) ε = 1 mm/k.y.
1	^{10}Be	8.4 ± 1.1	8.5 ± 1.1
2	^{10}Be	6.2 ± 0.7	6.2 ± 0.7
3	^{10}Be	4.7 ± 0.7	4.7 ± 0.7
4	^{10}Be	4.1 ± 0.9	4.1 ± 0.9
5	IRSL	6.6 ± 0.9	6.9§
6	^{10}Be	8.0 ± 0.8	8.0 ± 0.8
7	^{10}Be	5.3 ± 0.6	5.3 ± 0.6
8	^{10}Be	5.4 ± 0.6	5.5 ± 0.6
9	^{10}Be	8.0 ± 2.0	8.0 ± 2.0
10	^{10}Be	7.8 ± 1.6	7.9 ± 1.6
11	^{10}Be	18.9 ± 3.9	19.2 ± 3.9
12	IRSL	34.0 ± 4.7	6.0§
13	^{10}Be	56.4 ± 5.2	59.4 ± 5.5
14	^{10}Be	33.7 ± 3.1	34.7 ± 3.2
15	^{10}Be	54.3 ± 4.6	57.1 ± 4.8
16	^{10}Be	158.8 ± 24.42	185.7 ± 28.3

Note: Errors are 1 σ. IRSL is infrared stimulated luminescence. See GSA Data Repository item (see text footnote 1) for additional sample and analytical data.

*Zero erosion age with production rate of 6.01 ^{10}Be atoms g^{-1} yr^{-1} (Nishiizumi et al., 1989).

†Exposure age with 1 mm/k.y. erosion rate (ε).

§Single aliquot IRSL bleaching parameter (Clarke et al., 1999).

DATING METHODS

We used the buildup of cosmogenic ^{10}Be in quartz from large erratic boulders (Gosse et al., 1995) and infrared stimulated luminescence (IRSL; Clarke et al., 1999) of feldspars in proglacial lake sediments to date the youngest period of expanded ice.[1] Preliminary age estimates for the middle advances were also obtained with the same techniques. Erosion of boulder surfaces and/or exhumation of boulders from till can produce cosmogenic nuclide exposure ages that are younger than the depositional age of the moraine. To minimize this problem, we sampled only very large, stable boulders (intermediate axes >2 m and heights above ground of >1.3 m). Our preferred results (Table 1) assume zero surface erosion. Although this assumption is well justified for the fresh-appearing deposits that we sampled, an erosion rate of 1 mm/k.y. does not significantly alter exposure ages. Our conclusions are also insensitive to the cosmogenic ^{10}Be production rate used. For accurate IRSL ages, the sediment must have been thoroughly exposed to light during deposition. Bleaching parameters (Table 1 [and see text footnote 1]; Clarke et al., 1999) show that the luminescence signal in our samples was fully zeroed prior to deposition. To date a glacial advance, the sediment must be clearly associated with ice. We sampled finely laminated silts with synsedimentary deformation that indicate an ice-contact environment.

RESULTS

Our chronology (Table 1) is best controlled for the youngest deposits. The Rupal Glacier on the south side of Nanga Parbat reached its maximum Holocene extent and was retreating by 8.4 ± 1.1 ka (sample 1; see Fig. 1 for all sample locations). Following retreat, the glacier readvanced or was stationary at 6.2 ± 0.7 ka (sample 2). A lake created by this readvance or stillstand is dated as 6.6 ± 0.9 ka (sample 5). By 4.7 ± 0.7 ka, ice had retreated to within 0.5 km of the present Rupal Glacier terminus (sample 3). This is confirmed by a rockfall deposited onto outwash at 4.1 ± 0.9 ka (sample 4). On the north side of Nanga Parbat, the outermost lateral moraine of the Buldar Glacier was formed at 8.0 ± 0.8 ka (sample 6). The Raikot Glacier retreated from its most advanced Holocene position near Tato to the Fairy Meadows terrace, where it deposited a thick volume of till during a stillstand dated as 5.3 ± 0.6 ka and 5.4 ± 0.6 ka (samples 7 and 8). In the Indus Valley, the Patro Glacier built a large moraine at 8.0 ± 2.0 and 7.8 ± 1.6 ka (samples 9 and 10). A third sample (sample 11) from the same moraine gave a ^{10}Be age of 18.9 ± 3.9 ka that probably reflects nuclide inheritance because it is an outlier with regard to all other ages on Nanga Parbat moraines.

Exposures of older glacial deposits at Nanga Parbat are complex and not yet fully understood. Our preliminary chronology suggests deposition of these sediments during MIS-3 and MIS-4 rather than during MIS-2. Ground moraine associated with lateral moraines preserved ~1000 m above the Raikot Valley floor formed at 56.4 ± 5.2 ka (sample 13). A proglacial lake in the upper Astor valley is dated as 34.0 ± 4.7 ka (sample 12). A large moraine complex built by the combined Raikot and Buldar glaciers in the Indus Valley gave exposure ages of 33.7 ± 3.1 ka (sample 14) and 54.3 ± 4.6 ka (sample 15). The Gor moraine complex deposited by the Raikot and/or Buldar glaciers across the Indus valley yielded a ^{10}Be age of 158.8 ± 24.2 ka (sample 16). This date is unreasonably old given the position in the landscape of the sample, and probably reflects nuclide inheritance rather than the moraine depositional age.

COMPARISON WITH REGIONAL PALEOCLIMATIC RECORDS

The climate of south Asia is dominated by variations in the intensity of the summer monsoon. During global interglacials when Northern Hemisphere summer insolation is high, monsoon activity increases (Clemens et al., 1991) and south Asia is flooded with summer precipitation. A weak summer monsoon occurs during global glacial periods, as differential heating between the Indian Ocean and Asia is reduced. For this reason, global glacial periods such as MIS-2 are dry and cold in south Asia (Overpeck et al., 1996; Liu et al., 1998). Comparison of long records of monsoon intensity from Arabian Sea cores (Clemens et al., 1991; Schultz et al., 1998; Overpeck et al., 1996) with the Nanga Parbat chronology shows that ice volumes expanded during warm, wet climatic optimums when summer monsoon strength was high (Fig. 2). Dates of older deposits cluster around

[1]GSA Data Repository item 200045, Tables A–C, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.

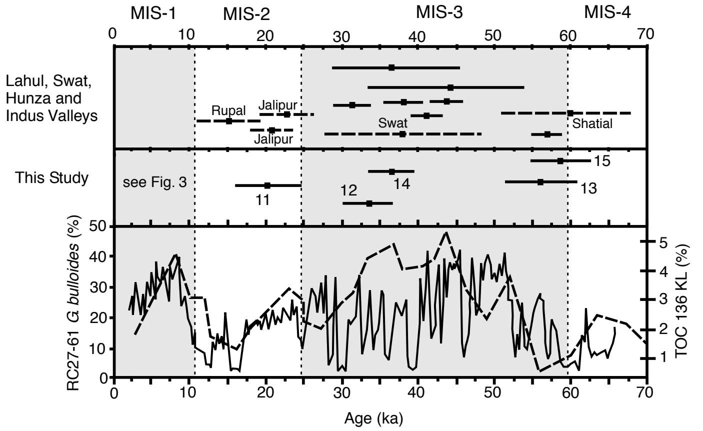

Figure 2. Correlation of Arabian Sea sediment cores with glacial histories from northwestern Himalayas. Relative southwest Asian monsoon intensity is indicated by abundance of upwelling indicator *G. bulloides* (dashed line; Clemens et al., 1991) and biological productivity is shown by total organic carbon (solid line, TOC; Schultz et al., 1998). Hunza, Lahul, and Indus Valley glacial dates are shown with solid error bars (from compilation in Benn and Owen, 1998). Luminescence ages from Swat and Nanga Parbat have dashed error bars (Richards et al., 2000). Numbered ^{10}Be and infrared stimulated luminescence ages from Nanga Parbat refer to samples shown in Figure 1 and Table 1. Marine oxygen isotope stages 1 and 3 (MIS-1 and MIS-3) are shaded. All ages have 1 σ errors.

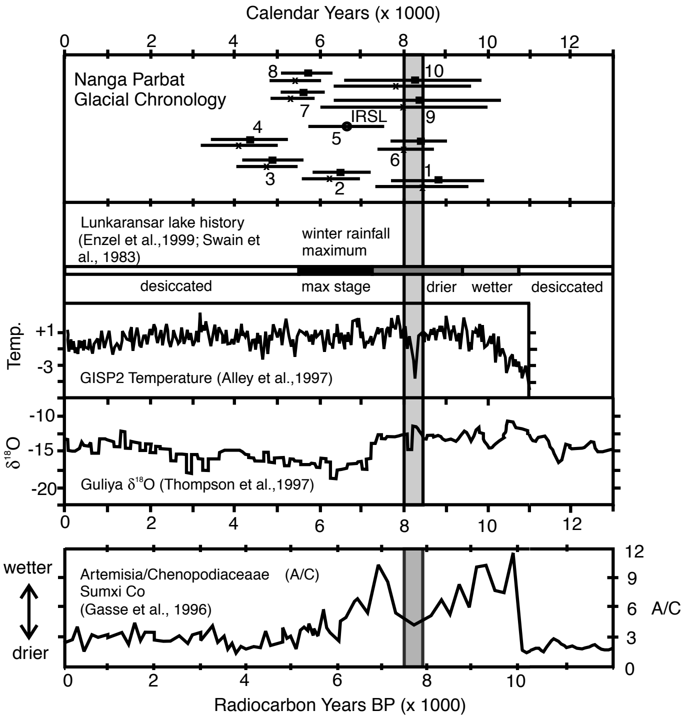

Figure 3. Comparison of Nanga Parbat glacial chronology with regional paleoclimate records. Cosmogenic ^{10}Be exposure ages computed with production rates of 6.01 atoms g^{-1} yr^{-1} (square symbol; Nishiizumi et al., 1989) and 5.75 atoms g^{-1} yr^{-1} (x symbol; Kubick et al., 1998). Differences between exposure ages for zero erosion and erosion rate of 1 mm/k.y. are contained within errors. Shaded stripe indicates response of southwest Asian monsoon and Nanga Parbat glaciers to worldwide cold event ca. 8–8.5 ka.

extended periods of high monsoon activity in MIS-3 and early in MIS-4, as do most of the few other previously dated glacial deposits from the region (Benn and Owen, 1998; Gillespie and Molnar, 1995; Richards et al., 2000). A general absence of glacial advances dating to MIS-2 correlates with regional aridity. New OSL ages of ca. 30–10 ka (Richards et al., 2000) from glacial deposits along the Indus River near Shatial and Jalipur, and near our sample 1, conflict with this interpretation (Fig. 2). These ages require confirmation, because they employ multiple aliquot OSL methods that cannot establish the extent to which sample grains were bleached by light prior to burial (Clarke et al., 1999).

Details of the Holocene south Asian climate record are reflected in the Nanga Parbat glacial chronology (Fig. 3). The early to middle Holocene of south Asia consisted of two wet periods separated by a drier, cooler episode (Gasse et al., 1996). The Nanga Parbat Holocene glacial maximum was reached at the end of the first wet period ca. 8 ka. Ice volumes then decreased until a glacial readvance or stillstand between ca. 7 and 5.5 ka during the second regional Holocene moist period. As the supply of moisture to the region waned, glaciers retreated and reached approximately present-day positions by ca. 5 ka.

CONTROLS ON GLACIAL ADVANCES

The correlation of ice volume with summer precipitation delivered by the southwest monsoon suggests that the Nanga Parbat glacial system was moisture limited during global glacial periods. Growth of glaciers during warm times of dominantly summer precipitation is possible because of high accumulation rates in frigid high-altitude catchments. For example, glaciers from Nepal (Ageta and Higuchi, 1984) and the Qinghai-Tibetan Plateau (Thompson et al., 1997; Liu et al., 1998) accumulate mass almost entirely during the summer. Because precession-forced changes in Northern Hemisphere insolation control first-order variation in monsoon intensity (Clemens et al., 1991), moisture-limited glaciation should be asynchronous with respect to global ice volumes. Local conditions at Nanga Parbat also promote glacial advances in response to summer precipitation increases. Hypsometry (area-altitude distribution) favors the preservation of increased snowfall as glacial ice because accumulation areas at Nanga Parbat quadruple with a 1000 m ELA depression (Brozovic et al., 1997). In addition, large avalanches, which are already common at Nanga Parbat under modern climate conditions (Gardner and Jones, 1993), increase in frequency and size with greater snowfall, and efficiently transfer ice to lower altitudes than would otherwise be possible.

On submillennial time scales, temperature and changing seasonality of precipitation were also important in forcing glacial advances. Calculated ELA depressions of 600–1100 m for the deposits we have dated as Holocene (Scott, 1992) are similar to those estimated for undated deposits assigned to the late Pleistocene last glacial maximum in surrounding Himalayan regions (Duncan et al., 1998). With constant temperature, ELA depressions of this magnitude require total accumulation rates to increase from 4 to 6 m/yr water equivalent at present (Gardner and Jones, 1993) to roughly 7 to 9 m/yr water equivalent during the early Holocene (Seltzer, 1994). Although this is a realistic increase given the large increases in precipitation that occurred in south Asia at this time (Gasse et al., 1996; Swain et al., 1983), advances may not have been sustainable without either a drop in temperature or an increase in winter precipitation.

The first advance at Nanga Parbat coincides with a sharp drop in temperature centered ca. 8–8.5 ka (Fig. 3). This temperature decrease was global in scale (Alley et al., 1997) and probably resulted from catastrophic drainage of Laurentide lakes into the North Atlantic at 8.47 ka (Barber et al., 1999). Although the cold period decreased summer precipitation in south Asia by interrupting monsoonal circulation (Alley et al., 1997), moisture levels indicated by pollen were still well above those of MIS-2 (Gasse et al., 1996; Fig. 3). This combination of relatively high summer accumulation and lower temperatures drove the largest advance at Nanga Parbat in more than 20 k.y. As temperatures rose after about 8.2 ka, monsoonal circulation strengthened. Glaciers at Nanga Parbat responded by withdrawing to the position of the second stillstand despite heightened summer accumulation, illustrating an overall sensitivity to temperature. We associate the second stillstand at Nanga Parbat with an increase in winter moisture that was much more effective in building ice volumes than summer precipitation. Lake histories and pollen from northwest India (Enzel et al., 1999; Swain et al., 1983; Fig. 3) show such an increase in winter moisture in the western Himalaya ca. 7–5.5 ka. A temperature decrease and/or increase in cold winter precipitation is also indicated by $\delta^{18}O$ ca. 7 ka in the Guliya ice core (Fig. 3).

CONCLUSIONS

The largest glacial advances in 20 k.y. occurred at Nanga Parbat during the early to middle Holocene summer monsoon precipitation maximum of south Asia. Earlier advances also occurred during times of high monsoon intensity in MIS-3 and MIS-4. In contrast to Richards et al. (2000), we found no evidence for expanded ice during MIS-2 at Nanga Parbat. These results suggest that a minimum amount of monsoon moisture must be supplied to the Himalayan glacial system to create ice expansions. During global glacial stages, a weak summer monsoon and dry westerlies provide too little moisture for large-scale advances despite regionally low temperatures. Once monsoon intensity increases during global interglacials, summer accumulation rates rise on high-altitude glaciers. In localities with suitable hypsometry and high avalanche rates, advances may occur despite a coeval rise in temperatures. However, expanded ice may not be generally possible without a drop in temperature and/or an increase in winter precipitation. For example, the abrupt global temperature decrease ca. 8.2 ka caused by changes in North Atlantic circulation apparently triggered the local Holocene glacial maximum at Nanga Parbat. Once temperatures rose, this advance could not be sustained despite increases in summer precipitation. Because Asian monsoon intensity responded to North Atlantic Heinrich events (Schultz et al., 1998), similar temperature-forced advances probably occurred during MIS-3 and MIS-4. Changes in the seasonality of precipitation are also important. At Nanga Parbat, increases in winter precipitation ca. 7–5.5 ka created positive mass balances. After about 5 ka, regional moisture became too low to sustain expanded ice, and glaciers withdrew to near present-day positions.

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