Beryllium-10 dating of Mount Everest moraines indicates a strong monsoon influence and glacial synchroneity throughout the Himalaya

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ABSTRACT

Moraine successions in glaciated valleys south of Mount Everest provide evidence for at least eight glacial advances during the late Quaternary. Cosmogenic radionuclide (CRN) surface exposure dating of moraine boulders defines the timing of each glacial advance and refines the previous glacial chronologies. The CRN data show that glaciation was most extensive during the early part of the last glacial (marine oxygen isotope stage [MIS] 3 and earlier), but limited during MIS 2 (the global Last Glacial Maximum) and the Holocene. A previously assumed Neoglacial advance is dated to 3.6 ± 0.3 ka and the CRN dates confirm a glacial advance ca. 1 ka. These results show that glaciations on the south side of Everest were not synchronous with the advance of Northern Hemisphere ice sheets, yet glaciations within the Himalaya, the world's highest mountain belt, were synchronous during the late Quaternary. The existence of glacial advances during times of increased insolation suggests that enhanced moisture delivered by an active south Asian summer monsoon is largely responsible for glacial advances in this part of the Himalaya. These data allow us to quantify the importance of global climate change and monsoon influence on glaciation in the Himalaya.

Keywords: cosmogenic radionuclides, Himalaya, glacial geology, geochronology, monsoon, Everest.

INTRODUCTION

The Himalaya and Transhimalaya are the most glaciated mountain regions on Earth and are at the boundary between the climatic influence of the south Asian summer monsoon and the Eurasian westerlies. Glaciation in this region responds sensitively to changes in global climate and provides a proxy for quantifying regional and global climate change. Furthermore, glacial fluctuations in the Himalaya significantly affect the hydrological balance of a region that is home to 66% of the global population. Despite the importance of Himalayan glaciation, the dynamics and controls on glaciation in this region are only vaguely understood.

Quantifying the timing and extent of glaciation south of Mount Everest in the Khumbu Himal, and in the broader Himalaya, is a prerequisite for connecting Himalayan climate fluctuations to changes in global climate. While the region south of Mount Everest is one of the most studied areas of the Himalaya, an understanding of the Quaternary history rests on seven studies (Benedict, 1976; Iwata, 1976; Fushimi, 1978; Müller, 1980; Aoki and Imamura, 1999; Richards et al., 2000a; Table 1; Fig. 1). The major emphasis of our work is to ascertain, using cosmogenic radionuclide (CRN) ^{10}Be surface exposure dates, a chronology for the glacial successions in the Khumbu Himal to help elucidate the nature of glaciation in relationship to regional and global climate change. This study is also the first comprehensive assessment of the concordance between CRN and optically stimulated luminescence (OSL) dating.

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METHODS

Sampling sites were initially selected using aerial photographs; additional sites were selected in the field as morphostratigraphic relationships were examined. Sites were judged based on their amenability to CRN dating[1] and on their relationship to sites dated by Iwata (1976) and Richards et al. (2000a) (Fig. 1). Several boulders were dated from each moraine ridge to provide a check on the reproducibility of the dating and to assess the possibility of CRN inheritance. Details of the sample preparation and calculation were given in Owen et al. (2001, 2002a) (see footnote 1).

[1]GSA Data Repository item 2003079, cosmogenic radionuclide dating methods and Table DR1, cosmogenic radionuclide surface exposure ages, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

RESULTS AND DISCUSSION

The CRN dates for each boulder are listed in Table DR1 (see footnote 1) and are plotted in Figure 2 by moraine and glacial stage. With the exception of the oldest moraines, the similarity of the ages of boulders on individual moraine ridges provides a good degree of confidence in the dating. Confidence in our dating is further supported by the fact that morphostratigraphically younger moraines have CRN dates that provide progressively younger ages (Figs. 1 and 2). The tight clustering of ages on individual moraines, with the exception of the Thyangboche I glacial stage moraines, suggests that CRN inventories are not significantly altered by erosion. To the extent that it is a stochastic process, weathering produces scatter in the CRN concentrations. Uniform loss of material from all samples cannot be ruled out as a possibility using our data alone. For erosion rates of 1–5 m/m.y., an exposure age of 10 ka calculated assuming zero erosion would underestimate the true age by 1%–4%; an age of 20 ka by 2%–9%; and an age of 40 ka by 4%–20%.

The Thyangboche glacial stage is the oldest recognized in this region. We have subdivided this (Thyangboche I and II) on the basis of morphostratigraphy and the CRN dating. The age of the younger advance, Thyangboche II, is 35 ± 3 ka (n = 3); the stated error is the standard deviation. This occurred during the latter part of marine oxygen isotope stage. The age of older glacial stage, Thyangboche I, is poorly defined (59 ± 29 ka, n = 6), and the data cluster into two groups, 86 ± 6 ka (n = 3) and 33 ± 7 ka (n = 3). We can only speculate on the true age of this moraine, except to state that it is morphostratigraphically older than Thyangboche I and therefore must have formed prior to 35 ± 3 ka. The older CRN ages for this stage might be the result of inherited CRNs from preexposure boulders, while the younger ages may be the result of weathering, toppling of boulders, and/or ex-

TABLE 1. TENTATIVE CORRELATIONS, RELATIVE CHRONOLOGIES, AND NUMERICAL DATES FOR THE GLACIAL SUCCESSIONS IN THE KHUMBU HIMALAYA SOUTH OF MOUNT EVEREST

Iwata (1976)	Fushimi (1977)	Williams (1983)	Müller (1980), Benedict (1976), Fushimi (1978)	Richards et al. (2000a)	This study
			Outer moraine (Pumore) (ca. 410–550 ^{14}C yr B.P.)		Historical (<500 yr B.P.)
Lobuche I–III (late Holocene*)	Thuklha 3–4 (late Holocene*)	Yykugikcga I–III (late Holocene*)	Outer moraine (Tsola) (ca. 1150–1200 ^{14}C yr B.P.)	Lobuche (ca. 1–2 ka: OSL)	Lobuche (ca. 1 ka)
Thuklha (<5 ka*)	Thuklha 1 (<5 ka*)	Tamba (<5 ka*)	Dhugla I and II		Thuklha (3.6 ± 0.3 ka)
				Chhukung (ca. 10 ka: OSL)	Chhukung (9.2 ± 0.2)
Periche (ca. 20 ka*)	Periche (ca. 20 ka*)	Lhaog (ca. 20 ka*)		Periche (18–25 ka: OSL)	Periche II (16 ± 2 ka) Periche I (23 ± 3 ka)
Thyangboche (ca. 40–50*)					Thyangboche II (35 ± 3 ka) Thyangboche I (86 ± 6 ka)
Platform (>150*)	U1 U2–3				

*The ages given are estimations of the age of the moraines based on relative-weathering criteria and tentative correlation with glacial successions elsewhere in the world. OSL is optically stimulated luminescence.

humation. If all the boulders have been exhumed, weathered, and/or toppled, they could be older than 90 ka. In a similar setting, in the Hunza Valley of northern Pakistan, Owen et al. (2002a) showed that analyses of boulders having ages older than 60 ka frequently produce young ages because they are commonly deeply weathered and may rapidly break down after ~60 k.y. We therefore believe that a similar effect exists here and that this moraine is much older than 35 ka.

Glacial deposits from the Thyangboche glacial stages are confined to widely separated, eroded shoulders and ridges at altitudes of above 4500 m above sea level, but the extent of this glaciation can not be traced far down the Tsola Glacier because intense erosion and slope instability have destroyed much of the glacial evidence. Nevertheless, these must have been broad valley glaciations and they were the most extensive glaciation recognized in the Khumbu Himal. Similar style glaciations, have been dated to marine oxygen isotype stage (MIS) 3 in the Garhwal Himalaya of northern India (Sharma and Owen, 1996) and in the middle Indus Valley, Nanga Parbat (Richards et al., 2000b; Phillips et al., 2000), Chitral (Owen et al., 2002c), and the Hunza Valley, Karakoram Mountains (Owen et al., 2002a) of northern Pakistan (Fig. 3).

An extensive glaciation during MIS 3 (Thyangboche II) suggests that increased levels of precipitation fell as snowfall at high altitudes. This glaciation occurred during times of increased insolation when the south Asian summer monsoon's influence was greater in the Himalaya. The resulting positive glacial mass balance allowed glaciers to advance under the monsoon influence. This interpretation is supported by the work of Prell and Kutzbach (1987) and Thompson et al. (1989, 1997), who demonstrated the existence of high insolation, enhanced monsoons, and glacial growth during these times, coincident with the double insolation maxima that occurred during MIS 3 and MIS 5 (Fig. 2).

CRN dates on the Periche glacial stage moraines above Periche village are consistent with the two ^{10}Be dates on the Periche moraines determined by Aoki and Imamura (1999) and support the OSL dating of Richards et al. (2000a). The morphostratigraphy and our CRN dates, however, show that the Periche glacial stage can be subdivided into two distinct sets of moraines. The older set represents a slightly more extensive glaciation that spans the global Last Glacial Maximum (23 ± 3 ka, n = 8, E41 and E59 rejected), whereas the younger set occurred later, ca. 15 ka (16 ± 2 ka, n = 4, E71 rejected). While these dates are distinguishable at the 1σ level, they are less so at the 2σ level. However, field observations indicate two advances, and we interpret our CRN ages accordingly. We assign these moraines to the Periche I and Periche II glacial stages, respectively. The OSL dates of Richards et al. (2000a) were determined on glaciogenic sediments from near the base of the moraine and they represent the early part of the Periche glacial stage (now assigned the Periche I glacial stage), and hence they do not help define the Periche II glacial stage. The extent of glaciation during the Periche glacial stages was restricted to ~5 km beyond the contemporary ice margins. Similar advances at this time are recognized in the Hunza and Middle Indus valleys of northern Pakistan (Richards et al., 2000b; Phillips et al., 2000; Owen et al., 2002a) and in the Kan-

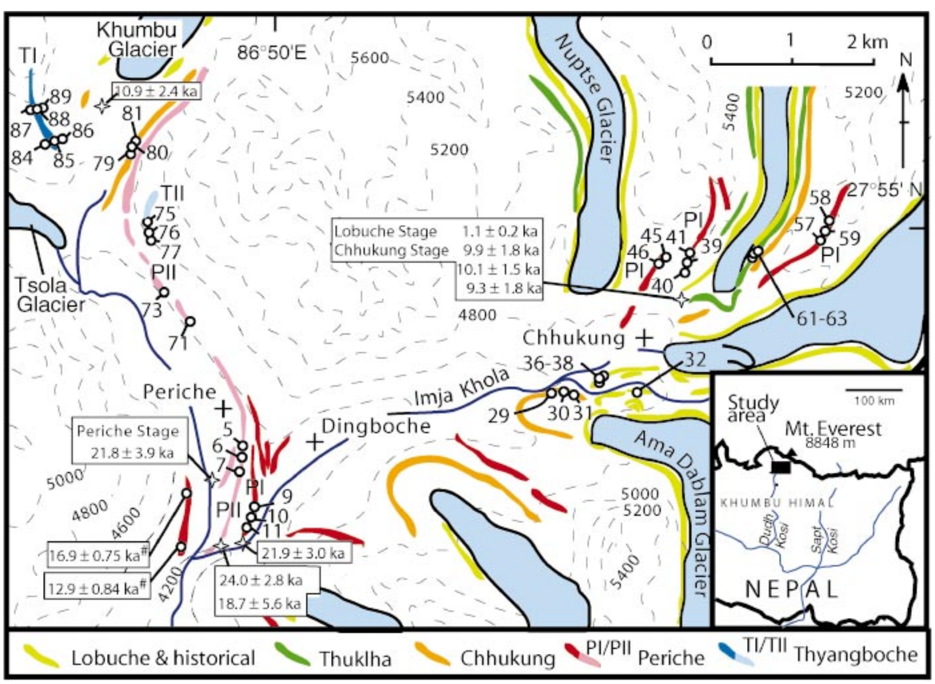

Figure 1. Glacial landforms and sampling locations in Khumbu Himal south of Mount Everest. Optically stimulated luminescence dates of Richards et al. (2000a) are located by stars and cosmogenic radionuclide dates of Aoki and Imamura (1999) are shown and indicated with pound sign. Sampling locations dated in this paper are indicated by open circles.

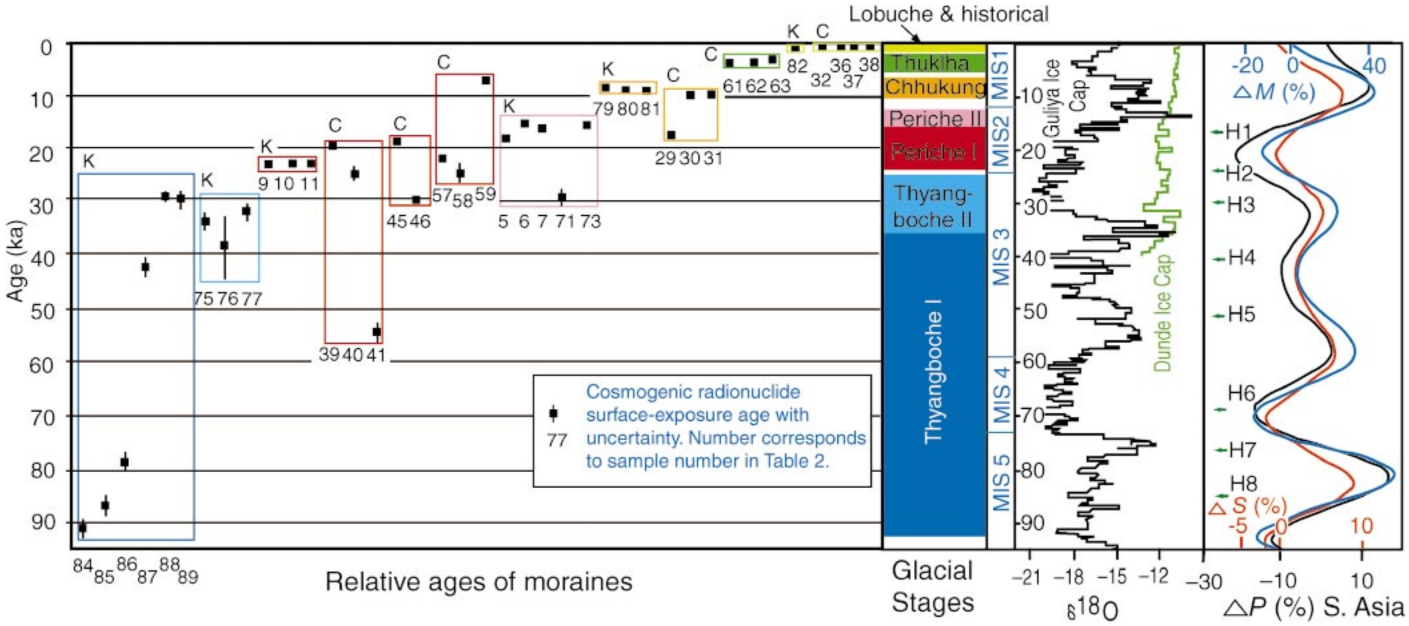

Figure 2. Cosmogenic radionuclide (CRN) ages for moraines in Khumbu Himal south of Everest compared with other climate indicators. Oxygen isotope $\delta^{18}O$ (‰) data from Dunde ice cap and Guliya ice cap cores in Tibet show more negative values during cold periods (Thompson et al., 1989, 1997). Simulated monsoon pressure index (ΔM percentage, solid blue line) for Indian Ocean and simulated changes in precipitation (ΔP percentage, black line) in southern Asia (Prell and Kutzbach, 1987) show higher values when south Asian monsoon is more active, bringing moisture to Khumbu region. Variations in Northern Hemisphere solar radiation (ΔS percentage, solid red line; Prell and Kutzbach, 1987) are correlated with monsoon indices. H1 to H7 show timing of Heinrich events during past 70 k.y. (Bond et al., 1992). CRN ages are plotted along x-axis according to their relative ages. Each box encloses samples from same moraine. MIS—marine oxygen isotope stage.

chenjunga Himal (Tsukamoto et al., 2002). These data also support the view that glaciation during the global Last Glacial Maximum was very restricted in the Himalaya as a consequence of reduced precipitation resulting from the weakening of the south Asian summer monsoon. Nevertheless, cooling was substantial enough to support positive glacial mass balances and to allow the glaciers to advance several kilometers (Owen et al., 2002c).

The early Holocene dates on the Chhukung glacial stage (9.2 ± 0.2 ka, n = 5, E29 rejected) support the OSL dating of Richards et al. (2000a). A glacial advance at this time provides further support to the view that glaciation in this part of the Himalaya is strongly influenced by increased monsoon precipitation at high altitudes during times of insolation maxima. This glacial advance, however, was restricted to within ~1 km of the contemporary glaciers. A similar advance is documented in the Lahul Himalaya, Hunza valley, Nanga Parbat, and Kanchenjunga (Owen et al., 2001, 2002a; Phillips et al, 2000; Tsukamoto et al., 2002) (Fig. 3).

The previously undated Thuklha glacial stage yields ages of ca. 3–4 ka (3.6 ± 0.3 ka, n = 3). This advance occurred slightly later than the onset of Neoglaciation that Grove (1988) showed to have occurred in most mountain regions after ca. 5 ka. Similar glacial advances are recognized in Chitral, Garhwal, Langtang, and Kanchenjunga (Owen et al., 2002b; Sharma and Owen, 1996; Tsukamoto et al., 2002; Shiraiwa and Watanabe, 1991; Shiraiwa, 1993; Barnard et al., 2003) (Fig. 3). Late Holocene lateral-frontal moraines are present around the contemporary glaciers.

CRN dating provides ages younger than 1 ka (E32 and E38) that are assigned to the Lobuche glacial stage. Samples E36 and E37 have extremely young ages, suggesting that their surfaces may have been recently exposed, possibly as the result of toppling. Nevertheless, these dates help substantiate the OSL dat-

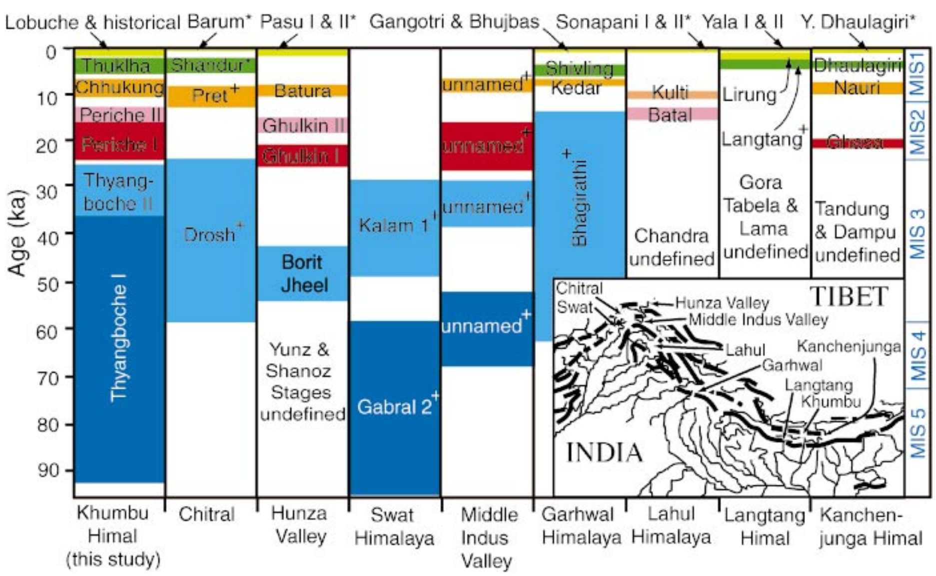

Figure 3. Himalayan glacial chronologies that have been numerically dated (data from Shiraiwa, 1993; Sharma and Owen, 1996; Richards et al., 2000a, 2000b; Phillips et al., 2000; Owen et al., 2001, 2002a, 2002c; Tsukamoto et al., 2002; Barnard et al., 2003). Heavy black lines indicate mountain ranges. Color bar represents likely duration of each glacial advance; name of each glacial stage is in box. Asterisk and cross after each name indicate that no numerical dating has been undertaken to confirm age, and duration of glacial is poorly defined, respectively. Tentative correlation is suggested by applying similar colors to bars. MIS—marine oxygen isotope stage.

ing of Richards et al. (2000a), and are in broad agreement with the radiocarbon dating of Müller (1980), Benedict (1976), and Fushimi (1978), who showed that these moraines formed ca. 1 ka and may be tentatively correlated with the little climatic optimum. An advance during the optimum further supports the view that positive glacial mass balances are achieved during times of increased warmth, when the monsoon may have progressed farther into the mountains to deposit abundant snow at high altitudes.

Müller (1980), Benedict (1976), and Fushimi (1978) showed that glaciers advanced a few hundred meters from their present position ca. 400–500 ^{14}C yr B.P. Due to the inherent inaccuracies of very young CRN ages, we did not collect samples from these moraines. Radiocarbon dating, however, shows that this advance occurred shortly before or broadly coincident with what is generally considered the onset of the Little Ice Age in other parts of the world (Grove, 1988). We therefore refrain from calling these Little Ice Age moraines and refer to them simply as historical advances, although no historical data have been discovered that document their former positions.

The CRN dates, together with the previously published OSL and radiocarbon dates on the glacial successions around the Khumbu Glacier and Chhukung, provide the most comprehensive set of numerical dates for any area of the Himalaya. This region therefore may be used to help test and establish chronologies in adjacent regions, and to test whether glaciation is synchronous throughout the Himalaya. Initial comparisons with regions such as the Hunza valley, Nanga Parbat, Garhwal, Langtang, and the Lahul Himalaya suggest that glaciation is broadly synchronous along the length of the Himalaya (Fig. 3). Of particular note is the realization that glaciers advance readily during times of increased insolation and global warmth. This finding strongly supports the idea that the northward penetration of the monsoon is a major force in driving glaciation throughout the Himalaya by increasing snowfall at high altitudes. During times of lower insolation, such as MIS 2, however, glaciers were able to make small advances in response to lower temperatures. These advances were substantially less extensive than their counterparts in middle and high-latitude Northern Hemisphere mountain regions (Clark and Mix, 2002).

CONCLUSIONS

In the Khumbu Himal, CRN dating helps define the timing of eight glacial advances: Thyangboche I (older than 30 ka), Thyangboche II (MIS 3, 35 ± 3 ka), Periche I (global Last Glacial Maximun, 23 ± 3 ka), Periche II (ca. 16 ± 2 ka), Chhukung (early Holocene, 9.2 ± 0.2 ka), Thuklha (Neoglacial, 3.6 ± 0.3 ka), Lobuche (little climatic optimum), and historical (~500 yr B.P. to present). The CRN dating substantiates the OSL dating of Richards et al. (2000a) on the three glacial advances and the radiocarbon dates of Müller (1980), Benedict (1976), and Fushimi (1978) for one glacial advance. Furthermore, we provide the first numerical dates for the Thyangboche and Thuklha glacial stages. These dates of the Thyangboche II, Chhukung, Thuklha, Lobuche, and historical advances support the view that glaciation in the Himalaya is largely influenced by the south Asian summer monsoon (Benn and Owen, 1998); i.e., during insolation maxima, the south Asian summer monsoon provides more precipitation as snow at high altitudes to cause a positive mass balance that causes glaciers to advance. Furthermore, these dates support the view of Gillespie and Molnar (1995) and Benn and Owen (1998) that glaciation (i.e., major advances) throughout the Himalaya was not synchronous with the Northern Hemisphere ice sheets, and stress the importance of monsoon control on glaciation. Nevertheless, there is a global climatic connection, exemplified by a glacial advance, albeit to a very restricted extent (Periche glacial stage), during the global Last Glacial Maximum, despite reduced precipitation. This pattern and the timing of glaciation are similar to the glacial histories for other parts of the Himalaya and suggest that glaciation is synchronous throughout the monsoon-influenced areas of the Himalaya (Fig. 3).

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