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A note on the extent of glaciation throughout the Himalaya during the global Last Glacial Maximum

Lewis A. Owen[a,*], Robert C. Finkel[a,b], Marc W. Caffee[b]

[a] Department of Earth Sciences, University of California, Riverside, CA 92521-0423, USA
[b] Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

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Abstract

Quantitative chronologies for the impressive glacial successions that occur throughout the Himalaya have, until recently, been almost totally lacking. Within the last decade two new techniques have promised to remedy this situation. These techniques, optically stimulated luminescence and cosmogenic nuclide surface exposure dating, enable the age of many glacial features to be determined and have allowed us to study the extent and timing of Himalayan glaciation in the late Quaternary. New data show that the local Last Glacial Maximum (LGM) occurred during the early part of the last glacial cycle, in most areas during marine isotope stage 3 (MIS-3). MIS-3 was a time of increased insolation, when the South Asian summer monsoon strengthened and penetrated further north into the Himalaya. The concomitant increased precipitation, occurring as snow at high altitudes, produced positive glacier mass balances, thereby allowing glaciers to advance. On the other hand, during the global LGM, ~18–24 ka, Himalayan glaciation was very restricted in extent, generally extending <10 km from contemporary ice margins. Lower insolation at this time produced a weaker monsoon cycle, which in turn resulted in lower snowfall and snow accumulation at high altitudes. The modest advances that nevertheless did occur at this time are the result of reduced temperatures.

1. Introduction

The high mountains of Central Asia constitute the most glaciated area outside of the Polar Regions (~126,200 km^2: Haeberli et al., 1989). The greatest glacial concentration occurs in the subtropical high mountains of the Greater Himalaya, Transhimalaya and southern Tibet. By mapping the abundant geomorphic evidence, Owen et al. (1998) have shown that in these regions, the extent of glaciation varied considerably throughout the Late Quaternary. Although most studies provide evidence for multiple glaciations, quantitative chronologies have been lacking. The scarcity of organic material in these sediments, generally deposited in high-energy high mountain environments, precludes the utilization of standard radiocarbon dating techniques. Recent advances in optically stimulated luminescence (OSL) and cosmogenic radionuclide (CRN) surface exposure age dating have enabled the age of many glacial features to be determined. In conjunction with careful and extensive field observations, these ages allow the timing and extent of glaciation in Central Asia to be studied throughout the Late Quaternary.

The timing of glaciation is an important parameter in climate studies. A detailed reconstruction of the chronology of glaciation is required to understand the relationships between glacial, climatic, hydrologic and biotic systems in extensively glaciated regions. This understanding of past climate change serves as a benchmark against which predictive models of future climate can be evaluated. Finally, a detailed reconstruction of glacial history is needed to determine ice volumes, which are an essential parameter for assessing the impact of Central Asian glaciation on surface albedo, oxygen isotopes and sea level.

As an integral component of a broad scientific effort to understand the climate system, considerable attention has been focused on examining and mapping the nature of the Earth's surface during the Last Glacial Maximum (LGM) at ~18 ka (CLIMAP Project Members, 1981). Since 1998, the EPILOG (Environmental Processes of the Ice age: Land, Ocean, Glaciers) program of the

*Corresponding author. Tel.: +1-909-787-3106; fax: +1-909-787-3106.
E-mail address: lewis.owen@ucr.edu (L.A. Owen).

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IGBP/PAGES program IMAGES (International Marine Studies of Global Change) has been producing a comprehensive reconstruction of the state of the Earth during, and in the transitions into and out of, a full glacial state. EPILOG has therefore been concentrating its efforts on examining the LGM, the period between 18 and 24 ka and essentially equivalent to marine isotope stage 2 (MIS-2). As a contribution to EPILOG, this paper reviews our current knowledge of the extent of glaciation during the global LGM for the Himalaya, including the Greater Himalaya and Transhimalaya, to the southern edge of the Tibetan Plateau.

Despite the vastness of the Himalayan range (~2000 km long and ~300 km wide), there are only seven regions where reliable numerical dating has been undertaken on unambiguous glacial chronologies that are relevant to reconstructing the extent of ice during the LGM. This paper will therefore focus on the evidence from these regions. The reader is also directed to Owen et al. (1998) and Barnard and Owen (2000) for a review of the glacial geology of other Himalayan regions and for a selective bibliography for Late Quaternary glaciation in Tibet and the bordering mountains.

2. Glacial geologic record

Controversy exists over the extent of former glaciations in many regions throughout the Himalaya. This controversy arises mainly from disagreements regarding the interpretation of landforms that may be of either glacial or mass movement origin. These conflicting interpretations occur because the effects of intense mass wasting make it easy to confuse glacial and mass movement landforms and sediments with each other. The sediments that comprise mass movement and glacial landforms are very similar and without careful analysis they can be easily misinterpreted (Gwen et al., 1998; Hewitt 1999). Owen (1993) provides detailed descriptions of the nature of glacial and non-glacial diamictons to aid in interpreting glacial landforms in the Himalaya. Guided by this work, we believe that the interpretation of the glacial and non-glacial landforms in the seven main study areas discussed in this paper is adequately constrained. In addition, the reader should bear in mind the uncertainties associated with each dating technique. We refer the reader to Richards (2000) and Owen et al. (2001) for full discussions on the problems associated with OSL and CRN surface exposure dating of moraines and their associated landforms. The location of each study area is shown in Fig. 1 and the glacial chronologies are described below.

2.1. Swat Himalaya

Porter (1970) recognized three Pleistocene glaciations (the Laikot (oldest), Gabral and Kalam) in the Swat Himalaya of Northern Pakistan, but was unable to date any of the moraine successions (Figs. 1 and 2). He showed that glaciation became progressively less extensive with time and that the Gabral and Kalam glacial deposits comprised two and three till units, respectively (Fig. 2). On the basis of thermoluminescence (TL) dating, Owen et al. (1992) obtained ages for the loessic silt that capped the youngest moraines of Gabral (Gabral II: ~22–18 ka) and the oldest moraines of the Kalam (Kalam I: ~3–7 ka). They assigned the moraines of the Gabral glaciation to the LGM and the Kalam glaciation to the mid-Holocene. On the other hand, using a combination of OSL dating techniques, Richards et al. (2000) dated glaciogenic sediment within tills of Gabral and Kalam age to ~77 and ~38 ka, respectively. They reassigned the Gabral age moraines to MIS-5/4 and the Kalam moraines to MIS-3. Richards et al. (2000) argued that the Owen et al. (1992) TL dates were substantially younger than the age of the glaciation because the loessic silts that overlie the moraines were deposited after the glaciation that produced the moraines.

Clearly, glaciation during the LGM in this region had to be much less extensive than the Kalam I moraines to allow their preservation. The moraine ridges of Kalam II and III have not been dated, but the similarity between the relative weathering characteristics of Kalam I moraines to Kalam II moraines makes it likely that there is not much of an age difference between them. The Kalam III moraines, however, are substantially displaced from those of Kalam I and II and they might correlate with the LGM. Whether or not the Kalam II or III are coincident with the LGM, it is clear that the extent of glaciation in the Swat Himalaya was very restricted during the LGM (Fig. 2) and that glaciation was more extensive during the earlier part of the last glacial cycle.

2.2. Middle Indus valley and Nanga Parbat Himalaya

Phillips et al. (2000) and Richards et al. (2000) provide a comprehensive set of OSL and CRN exposure dates for glaciation around Nanga Parbat Himalaya and in particular in the middle Indus valley. Both studies argue that the maximum extent of glacier ice during the last glacial cycle occurred during MIS-3. Using OSL methods on glaciofluvial sediments, Richards et al. (2000) assigned a tillite (Jalipur Tillite) in the main Indus valley to the LGM. Phillips et al. (2000), however, found no evidence of and had no CRN exposure dates to indicate the presence of glaciers in the Indus valley during the LGM. They believe that the Indus valley became reoccupied during the early Holocene. However, Richards et al. (2001a) argue that absence of evidence is not necessarily evidence of absence. Despite this disagreement, the extent of ice around Nanga Parbat was relatively restricted during the LGM.

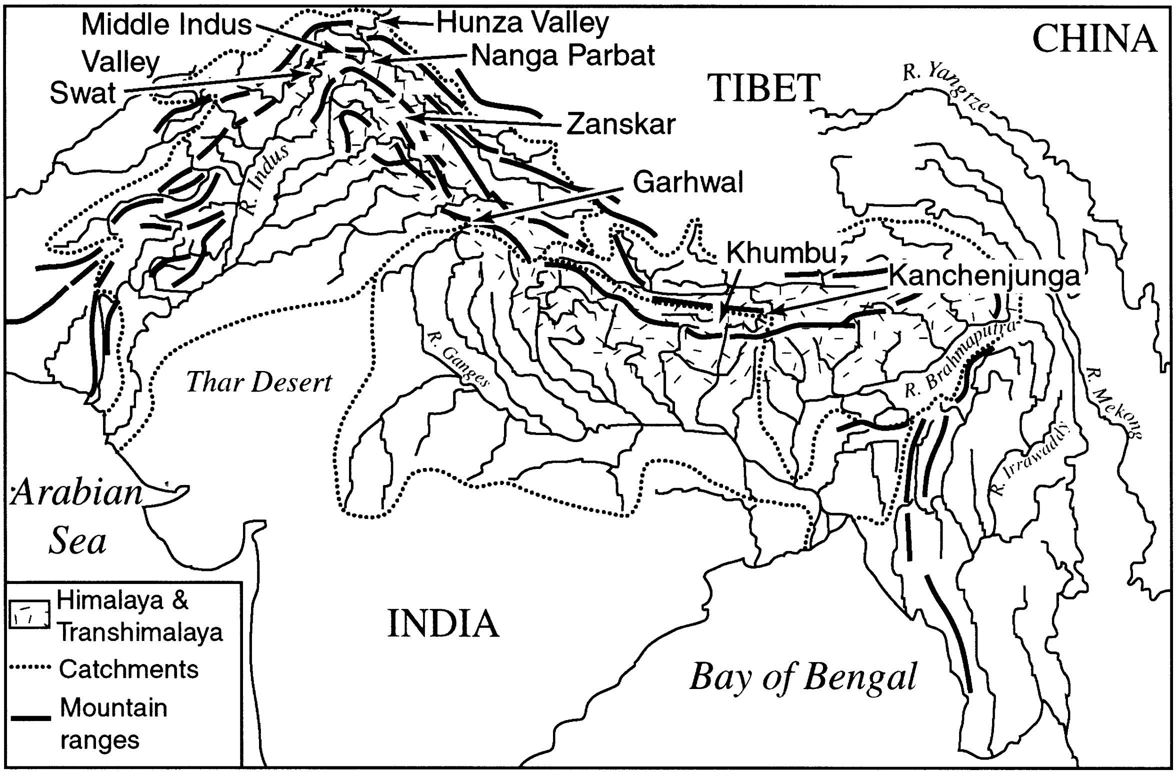

Fig. 1. The location of the study areas discussed in this paper.

2.3. Hunza valley

Derbyshire et al. (1984) described evidence for at least eight glacial advances in the upper Hunza valley of the Transhimalaya (Fig. 1). They refer to these as the Shanoz (oldest), Yunz, Borit Jheel, Ghulkin I and II, Batura and Pasu I and II glacial stages. They provided TL dates of ~139, ~50–65 and ~47 ka for the Yunz, Borit Jheel and Ghulkin I Glacial Stages, respectively. Owen et al. (2002) reexamined the glacial landforms and sediments in the upper Hunza valley and using CRN exposure age dating they defined the ages of the Borit Jheel (~42–52 ka), Ghulkin I (~21–25 ka), Ghulkin II (~15–18 ka) and the Batura (~9–11 ka) glacial stages. The Ghulkin I Glacial Stage is coincident with the LGM during which, as shown in Fig. 3, glaciers only advanced a few kilometers from the present ice fronts.

2.4. Zanskar

Taylor and Mitchell (2000) recognized three glacial advances in the Zanskar Range of the Transhimalaya of Northern India. They tentatively correlated these to the glacial stages (Chandra (oldest), Batal and Kulti) of Owen et al. (1996, 1997) to the south in the Lahul Himalaya. Using OSL methods, they dated the Batal Stage to between ~40 and ~78 ka and argued that this was probably the maximum extent of glaciation during the last glacial cycle and hence it probably spanned much of MIS-3 and MIS-4. They also were able to date the Kulti Glacial Stage at between ~10 and ~16 ka, but suggested that this glaciation might be older and possibly coincident with the LGM. The Kulti glaciation was restricted to glacial advances of little more than 10 km beyond present ice margins (Fig. 4). If the Kulti glaciation was coincident with the LGM then the extent of LGM glaciation was small. Alternatively, if the Kulti glaciation was restricted to ~10–16 ka, then the extent of glaciation had to be negligible during the LGM in this region.

2.5. Garhwal Himalaya

Using geomorphic and sedimentological evidence, Sharma and Owen (1996) recognized a major glacial advance along the Bhagirathi valley in the NW Garhwal Himalaya that they assigned to the Bhagirathi Glacial Stage. They produced an OSL date of ~63 ka (MIS-4) on glaciofluvial sediments within the end moraine for the extensive trunk valley glacier that existed along the Bhagirathi valley (Fig. 5). Furthermore, they suggested, on the basis of OSL dates on glaciofluvial and glaciolacustrine sediments within lateral moraines along the Bhagirathi valley, that this valley glacier existed until ~5 ka, after which there were two minor advances, the Shivling Glacial Advance (~5 ka) and the Bhujbas

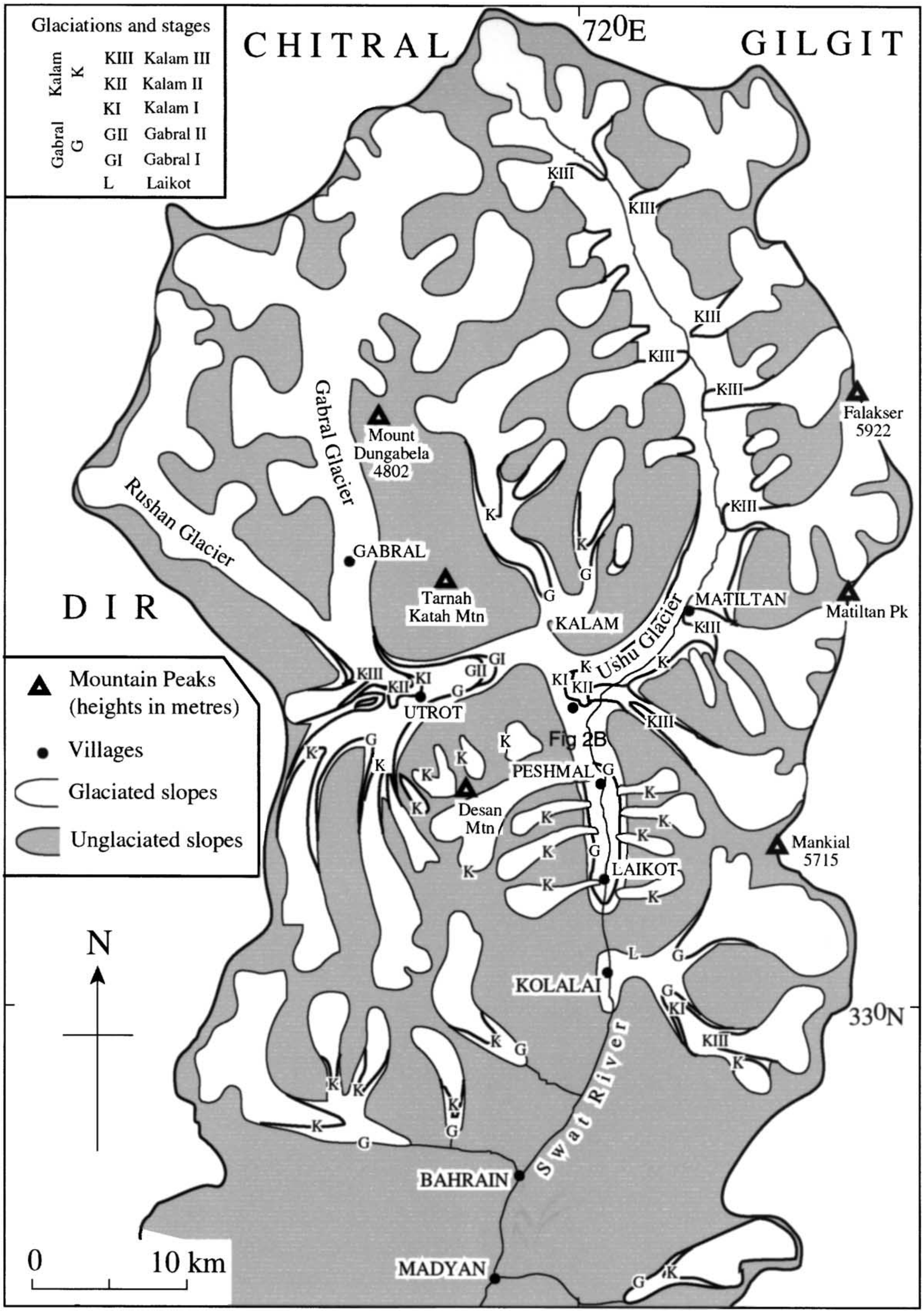

Fig. 2. Reconstructions of the extent of glaciers during past glaciation for the Swat Himalaya (adapted from Porter, 1970).

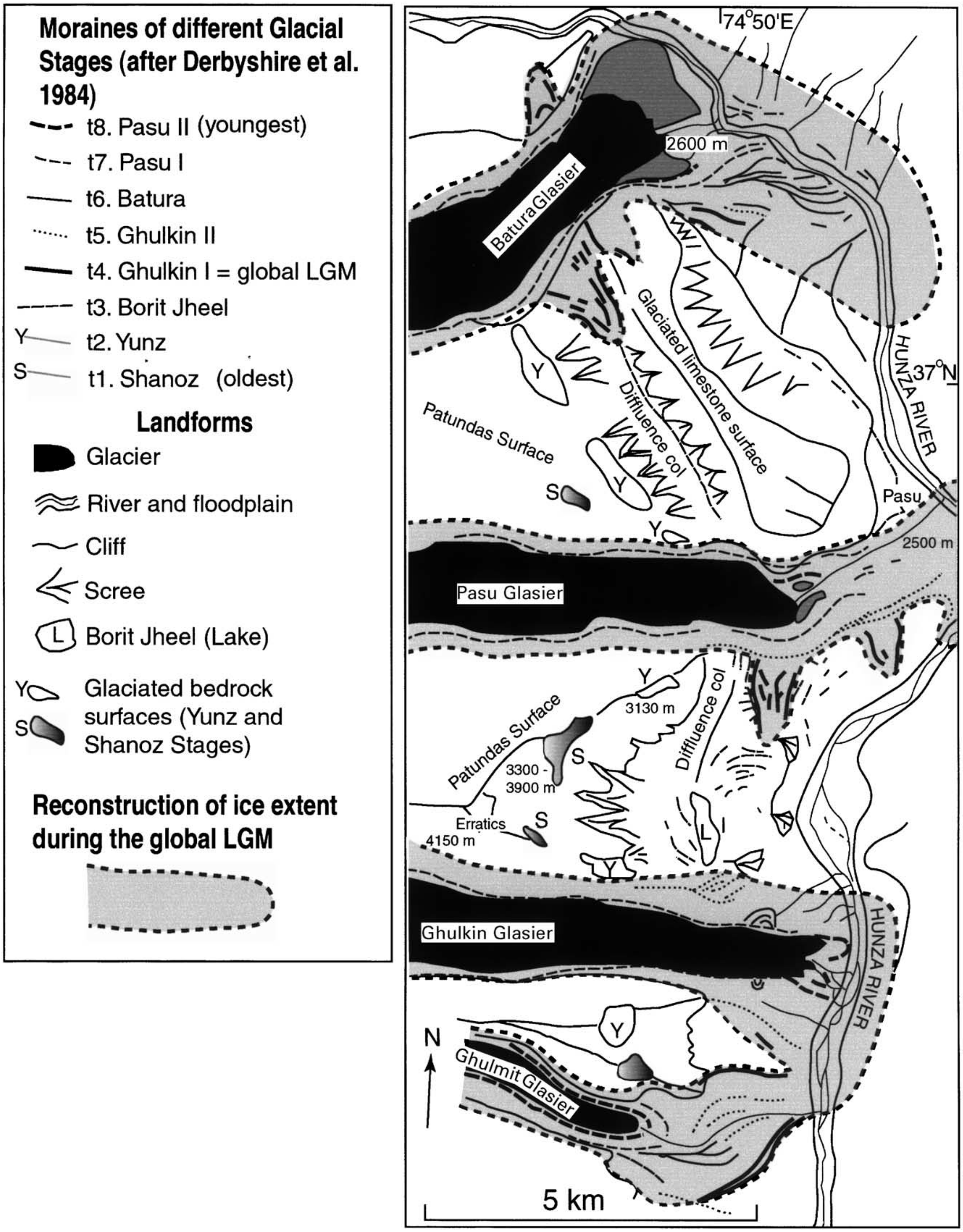

Fig. 3. Distribution of glacial landforms and contemporary glaciers in the Upper Hunza valley highlighting the extent of glaciation during the LGM (adapted from Derbyshire et al., 1984 and Owen et al., 2002).

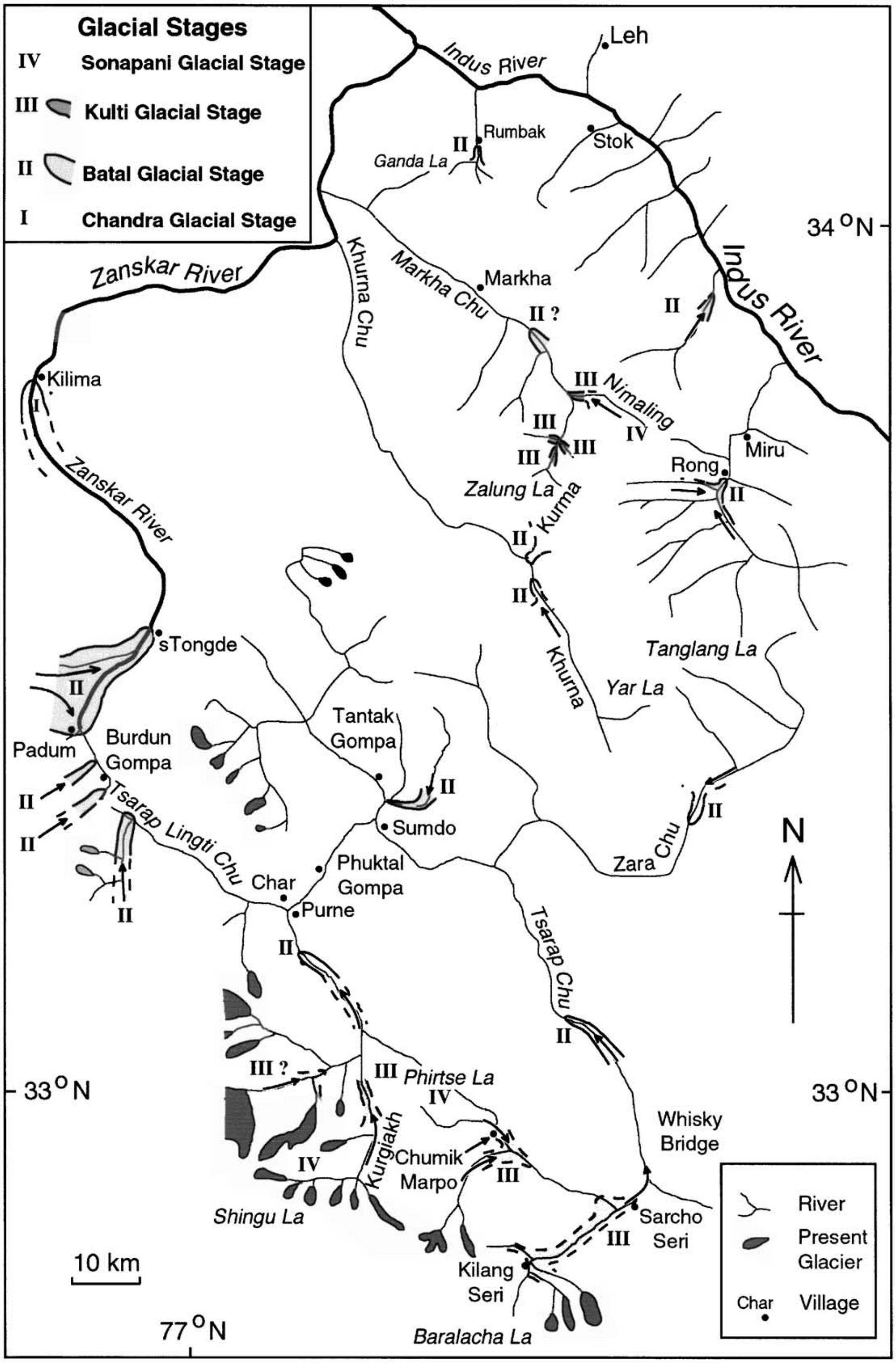

Fig. 4. Extent of glaciation in the Zanskar Range (adapted from Mitchell and Taylor, 1999 and Taylor and Mitchell, 2000).

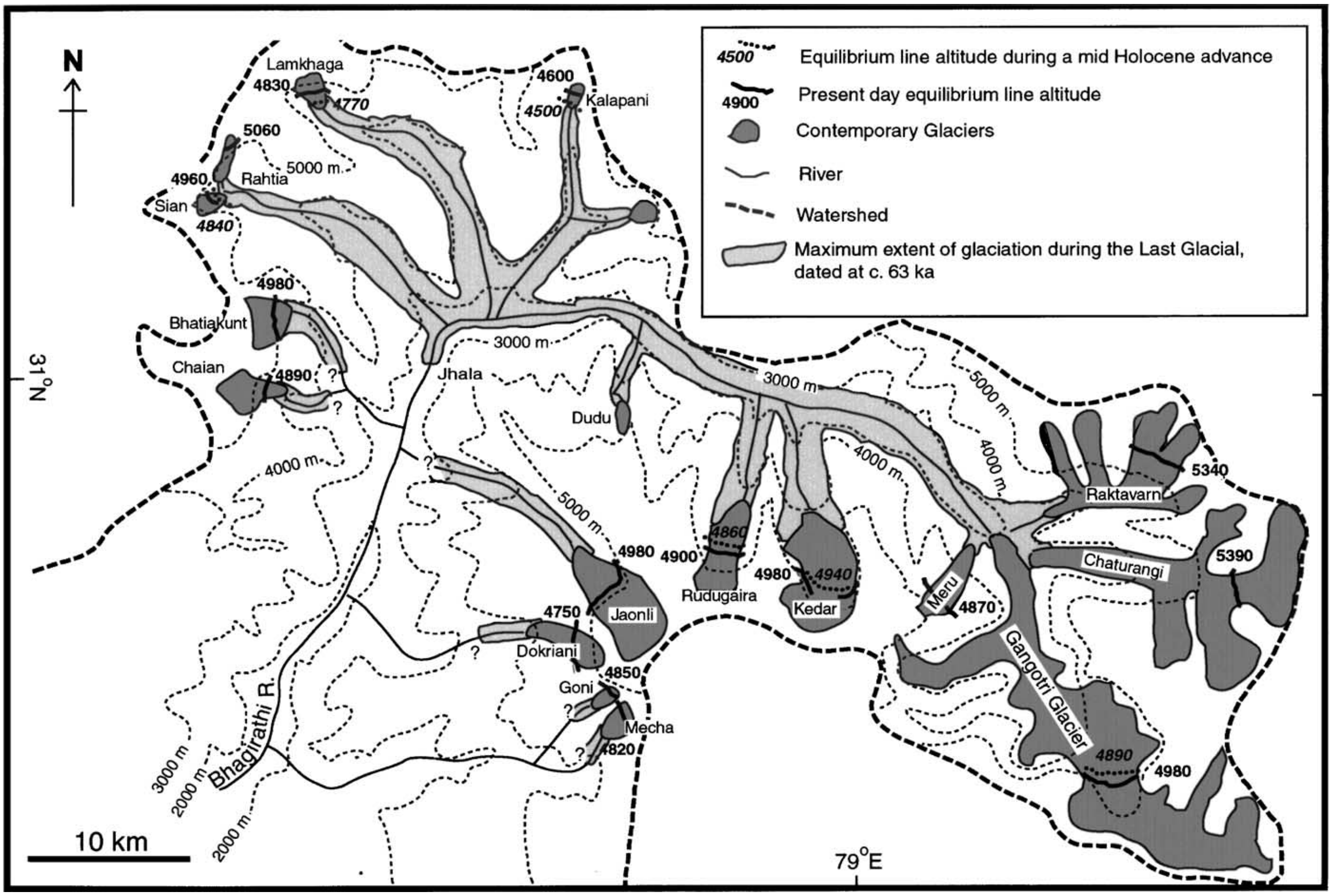

Fig. 5. Reconstruction of the maximum extent of glaciation during the last glacial cycle in NW Garhwal (adapted from Sharma and Owen, 1996).

Glacial Advance (~200–300 yr BP). The ~63 ka end moraine is located at Jhala, ~40 km from the contemporary glaciers, and is a single relatively small (<50 m high) ridge. The relatively small end moraine complex suggests that it is unlikely that the terminus of the Bhagirathi glacier occupied the valley fully to the Jhala end moraine throughout the whole of the Bhagirathi Glacial Stage. It is likely, however, that during the LGM, glaciers in the Garhwal Himalaya advanced much less than 40 km beyond their present ice fronts.

2.6. Khumbu Himal

In the Khumbu Himal, Iwata (1976) recognized evidence for four glaciations, the Thyangboche (oldest), the Periche, the Thuklha and the Lobuche I–III. However, he was unable to numerically date the landforms and sediments associated with these glaciations. Using OSL methods, Richards et al. (2001a) dated glaciofluvial and galciolacustrine sediments within moraines of Periche and Lobuche age to the LGM (~18–25 ka) and Late Holocene (~1–2 ka), respectively. Furthermore, they found evidence for a glacial advance at ~10 ka that they assigned to a new glacial stage, the Chhukung Glacial Stage. Mapping the extent of the Periche glaciers shows that the glacial advance during the LGM was within 10 km of the present ice margins (Fig. 6).

2.7. Kanchenjunga Himal

Kuhle (1990), Meiners (1999) and Asahi and Watanabe (2001) mapped glacial landforms in the Kanchenjunga Himal, but disagreed on the maximum extent of glaciation in this region. None of these workers provided numerical dates on the glacial landforms and sediments. However, recent OSL dates on tills show that glaciers advanced in this region at ~6, ~9 and ~22–23 ka (Katsuhiko Asahi, pers. comm.; Asahi et al., 2000). The LGM (~22–23 ka) ice limit within this region was within ~10–15 km of the present ice margins.

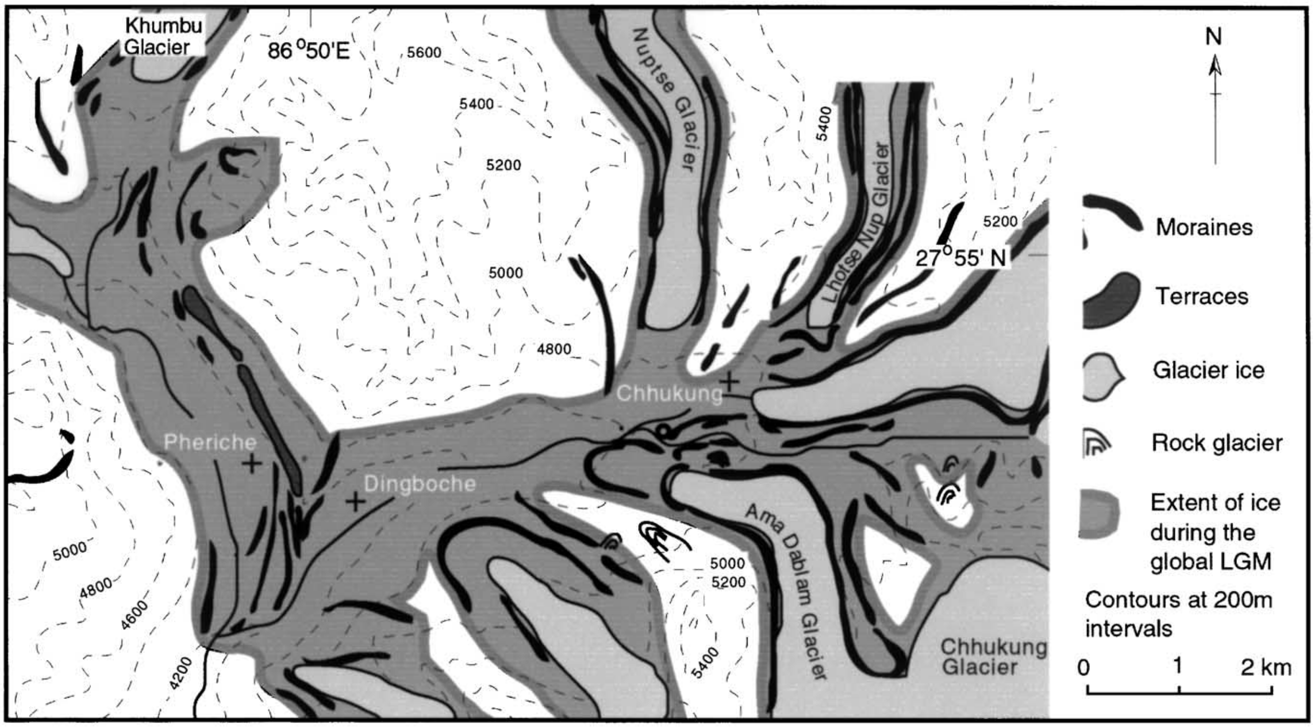

Fig. 6. The extent of glaciation in the Khumbu Himalaya, south of Everest, during the LGM (adapted from Richards et al., 2001b).

3. Discussion

During the last few years, new geomorphic studies of glacial features coupled with OSL and CRN surface exposure dating have enabled moraines and landforms that formed during the LGM to be identified in the seven areas described above (Fig. 7). In addition, the extent of glaciation during the LGM has been adequately reconstructed. Prior to these studies, researchers were only able to hypothesize about the extent of glaciation during the LGM. Without geochronological information about the age of landforms and sediments, researchers have, in some instances, overestimated the extent of ice cover throughout the Himalaya and Tibet during the LGM (e.g. Kuhle, 1985). Furthermore, many spurious reconstructions of former glacial extent followed on the misidentification of glacial and non-glacial landforms and diamicts (see Owen et al., 1998 and Hewitt, 1999 for further discussion). Detailed modern sedimentological and geomorphic analysis, however, has largely resolved this problem (e.g. Owen et al., 2000; Taylor and Mitchell, 2000).

The studies described above show that most glaciers advanced within ~10 km from the present ice margins during the LGM (Figs. 2–5 and summarized in Fig. 7). Since similar patterns of glaciation exist in each of the study areas spaced along the length of the Himalaya, it is likely that restricted glacier advance during the LGM is characteristic of the entire Himalaya. Furthermore, in each study area, the local LGM occurred early in the last glacial cycle. This supports the hypotheses of Gillespie and Molnar (1995) and Benn and Owen (1998) that the maximum extent of glaciation in the Himalaya occurred earlier than the LGM.

The South Asian summer monsoon is the dominant climatic system controlling the nature of glaciation throughout the Himalaya, although the mid-latitude westerlies may have an important influence at the westernmost end of the mountain belt (Benn and Owen, 1998). Prell and Kutzbach (1987) discussed the nature of variability in the South Asia summer monsoon over the past 150,000 yr. They showed that monsoon precipitation in South Asia was reduced during the LGM relative to the MIS-3 as a consequence of lower insolation during the LGM. Furthermore, they showed that monsoon precipitation increased during the Early Holocene insolation maximum. Occurrence of the local LGM early in the last glacial cycle, is consistent with the view that abundant precipitation is required to allow glaciers to grow in the Himalaya. The relative reduction in precipitation during the LGM helps explain why glaciation was more restricted at this time than during the MIS-3.

Reconstructions of equilibrium-line altitudes (ELAs) during past glaciations have allowed assessment of the magnitude and regional variation of past climate change for numerous mountain regions throughout the world (e.g. Miller et al., 1975; Sissons and Sutherland, 1976;

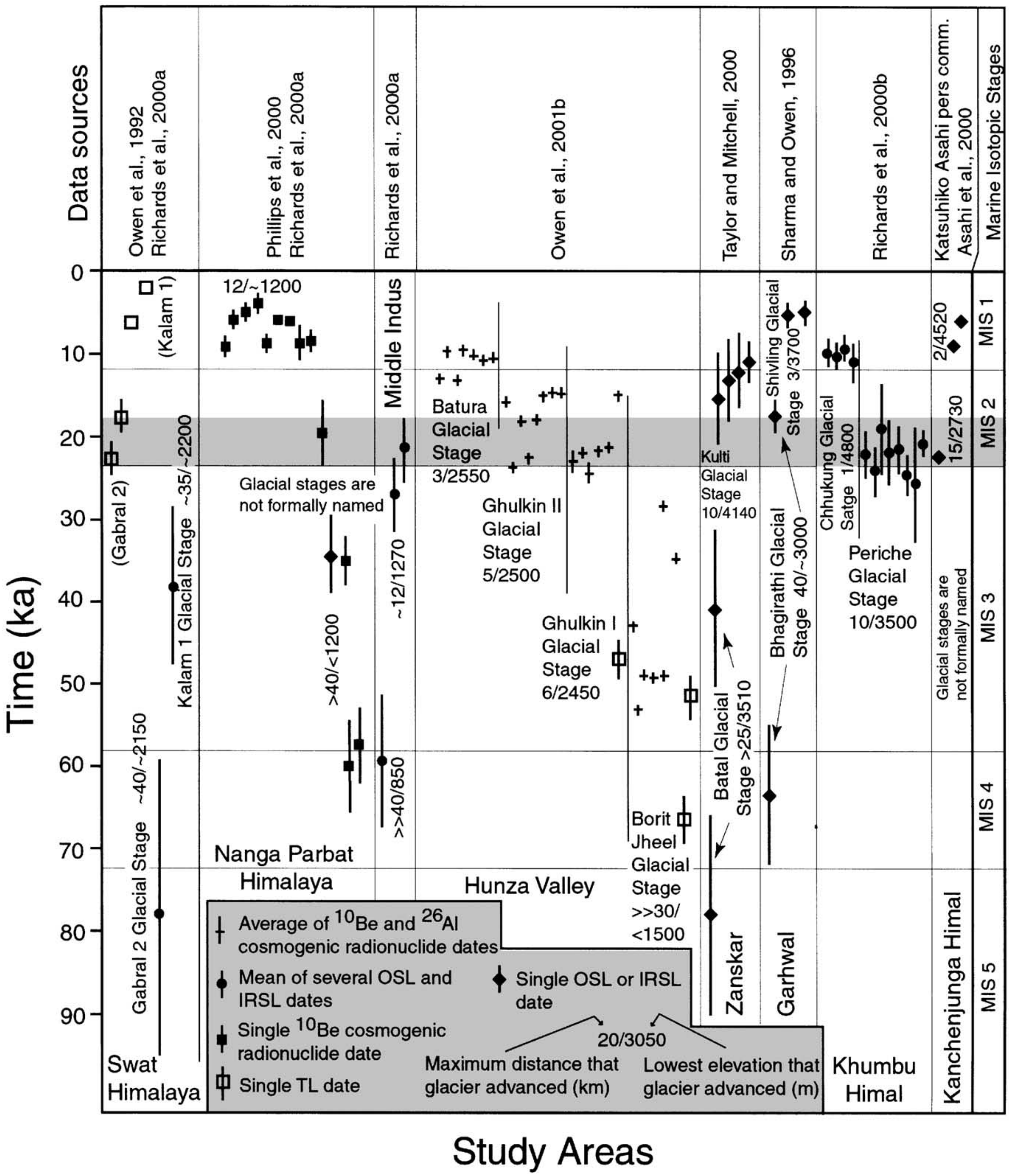

Fig. 7. Summary of the glacial chronologies discussed in this paper. Only glacial stages that have been numerically dated are included for each region. The light gray horizontal band highlights the LGM. The dates on glacial stages in the Swat Himalaya that are highlighted in parentheses are underestimates derived from ages on loess deposits that actually overlie the glacial deposits.

Clark et al., 1994). Similar attempts have been made for many regions of the Himalaya (see the summary in Table 6 of Sharma and Owen, 1996). The new availability of numerical dates potentially allows regional comparisons of the ELA depressions at different times throughout the last glacial cycle to be made. Benn and Lehmkuhl (2000), however, have warned of the difficulties of determining ELAs on the steep debris-covered glaciers in the high-altitude Himalaya because the relationship between glacier mass-balance characteristics and climatic variables such as precipitation and air temperature is very complex in these situations. Furthermore, the ELAs can vary considerably even within a small region of the Himalaya due to aspect, topographic constrains and valley direction (Sharma and Owen, 1996). Such variations are illustrated extremely well in the Garhwal Himalaya (Fig. 5). At this time, therefore, it seems premature to compare the regional variations for ELAs across the Himalaya.

Further regional mapping and numerical dating is required to reconstruct and refine the pattern of glaciation throughout the high mountains of Central Asia. Richards et al. (2001b) highlighted the need for the use of multiple techniques and multiple dating analyses to test method reliability. Only after such systematic studies have been completed throughout many more regions of the Himalaya will it be possible to produce a comprehensive map of the extent of glaciation for the Himalaya during the LGM and for other times, such as MIS-3, which is likely to be the local LGM in this region.

The glaciated area in the Himalaya constitutes $<8\%$ of the total glaciated surface of the Earth. The thickness of glaciers in the Himalaya is not very well known, but few glaciers exceed several hundred meters. Since the Antarctic and Greenland Ice Sheets constitute $>90\%$ of the glaciated surface and have depths of several kilometers, the percentage volume of ice stored in the Himalayan glaciers is negligible in comparison to the northern and southern hemisphere ice sheets. Given that the extent of glaciation during the LGM throughout the Himalaya was so restricted, Himalayan glaciation did not significantly contribute to processes such as sea level change or to changes in oxygen isotopes during the LGM and later. Nevertheless, Himalayan glaciation is important when considering the nature of environmental change and landscape evolution in the mountains of Central Asia. Important lessons may be learned from understanding the link between climate change and glaciation in the Himalaya. In particular, with the likelihood of global warming over the coming years, glaciers in the Himalaya may advance rather than retreat in response to warming as precipitation is increased due to strengthened South Asian summer monsoon.

4. Conclusion

The OSL and CRN exposure dating in conjunction with new geomorphic and sedimentological analysis for selected regions of the Himalaya has enabled the determination of the extent of glaciation during the LGM (Fig. 7). These studies show that most glaciers advanced within ~ 10 km of their present ice fronts. This is in sharp contrast to the extensive glacier advances during the early part of the last glacial cycle, most commonly during the MIS-3. This pattern suggests that the variation in the supply of monsoon precipitation, as snow, in high-altitude glacial environments, ultimately controlled by insolation changes, has strongly influenced the nature of glaciation throughout the Himalaya. It is the greater monsoon precipitation during MIS-3 compared to the LGM that caused glaciers to be more extensive during this time. Nevertheless, the substantially colder climate during the LGM did allow glaciers to advance several kilometers beyond their present positions. With the development of new dating techniques, we are now beginning, for the first time, to be able to attribute past glacier fluctuations in the mountains of Central Asia to the causative climatic forcing factors. However, given the vastness of the region, the geologic data is still very sparse and much work is needed to complete a comprehensive database that will allow an exhaustive examination of the links between climate and glaciation in the Himalaya. We would therefore like to encourage researchers to test our view that glaciation throughout the Himalaya was restricted during the global LGM and that the local LGM occurred earlier in the last glacial cycle, probably during the MIS-3.

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