Geomorphic evidence of glaciations around Mount Kailash (Inner Kora): implication to past climate

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Geomorphological observations of palaeoglaciation around the southern flank of Mount Kailash (Serlung Chu valley) are presented. Three distinct events of glaciation with decreasing magnitude (Kailash stage (KS)-I to KS-III) are well represented by the trails of lateral moraine. Inferred chronology of the glaciations suggests that the KS-I event pre-dates the Last Glacial Maximum (LGM), KS-II is attributed to the LGM, whereas KS-III corresponds to the early/mid-Holocene. The push moraine and the exposed glaciated bedrock proximal to the Mount Kailash are assigned to the Little Ice Age (LIA). A decrease in glacier ice volume after KS-III glaciation is attributed to the decrease in monsoon and an increase in the summer temperature after LIA.

Keywords: Geomorphic evidence, glaciations, lateral moraine, monsoon, past climate.

GLACIERS are not only important geomorphic agents in shaping the landscape, but are excellent recorders of past climate. They retreat and advance in response to climatically controlled changes in accumulation and ablation[1]. One of the direct manifestations of glacier advancement is the deposition of moraines (terminal and lateral); their distribution in the valley determines the past glacial extent and can be interpreted in terms of past precipitation and temperature changes[2]. Outside the polar region, maximum concentration of glaciers is found in the Himalaya and Tibetan plateau. Studies have shown that the elevated landmass of Tibetan plateau (2.5×10^6 km^2 with an average elevation of ~ 4.5 km) dramatically changes the albedo of Eurasia, thereby modifying the temperature and air pressure gradients between continent and ocean, which in turn drive the summer monsoon[3]. This advection of oceanic moisture in summer is a critical factor in glacier formation[4], which moves northward from the foothill of the Himalaya to the Tibetan plateau declines sharply from south to north across the Himalaya and is low over western Tibet[5]. Variation in snow and ice across the Himalaya and Tibetan plateau is caused due to changing rainfall gradient. This is well represented by the low equilibrium line altitude (ELA) in southeastern Tibet which is ~ 4300 m and in western Tibet it is over 6000 m (ref. 6). ELA defines the boundary between the zone of accumulation and that of ablation. In general, southwestern Tibet which lies to the north of the Trans Himalaya is influenced by moderate summer monsoon[7,8]. Evidence from western Himalaya suggests that on millennial scales, glacial oscillations reflect that periods of positive mass balance coincide with phases of high insolation/strengthened southwest monsoon[9,10]. Therefore, palaeoglaciation study can also be used to ascertain the past climate (monsoon) variability in this ecologically sensitive terrain.

The well-preserved moraines and valley fills that are present throughout Tibet and the bordering mountain suggest the former extent of valley glaciers in this region. Considering the sensitivity of the mountain glaciers to climate change, a systematic study of glaciogenic sediments and landforms can enable the reconstruction of the past climatic history[11]. Such studies are important because they can serve as a benchmark against which predictive models of future climate can be evaluated[10]. The purpose of the present study has been to document the glacial geomorphology and provide a broad framework of glacial history around Mount Kailash. In order to achieve the above objectives, detailed field mapping of the glaciogenic landforms was carried out using topographic maps (1 : 50,0000 scale) and satellite remote sensing data (IRS P6 LISS-IV September 2004 and IKONOS June 2009). In order to reconstruct the palaeo ELA, highest elevation of lateral moraines (emerging point) has been used[12], which was obtained using a handheld Ground Positioning System (GPS).

The study area lies in the Kailash range dominated by Kailash conglomerate (Molasses) which was deposited over the Kailash Granite[13]. It is suggested that sediments of the Kailash range (including the Kailash Mountain) were deposited during the upliftment of the Himalaya and can be considered to be the northern limit of the latter[13]. The Indus–Tsangpo Suture Zone (ITSZ) marks the collision boundary between the Indian and Tibetan plate that passes north of the Barkha plain (BP, Figure 1). The ITSZ demarcates two contrasting topographies: (i) a low-lying BP in the south and (ii) an elevated topography that includes Mount Kailash in the north. In addition, sharp change in elevation along ITSZ is expressed by the presence of southward-trending coalescing alluvial fans east of Darchin (AF, Figure 1). Dzong Chu and Lha Chu (Chu = river) are two major rivers that circumvent the outer periphery of the Kailash mountain (Figures 1 and 2). The present study was carried out in the Serlung Chu valley (30°58′–31°05′N and 81°15′–81°20′E). The trek route for inner circumambulation (Inner Kora) follows the Serlung Chu, which is fed by two tributary streams that originate from the southeastern and southwestern hanging glaciers from Mount Kailash (Figures 1 and 2). Serlung Chu valley rises from 4700 m (north of Darchin)

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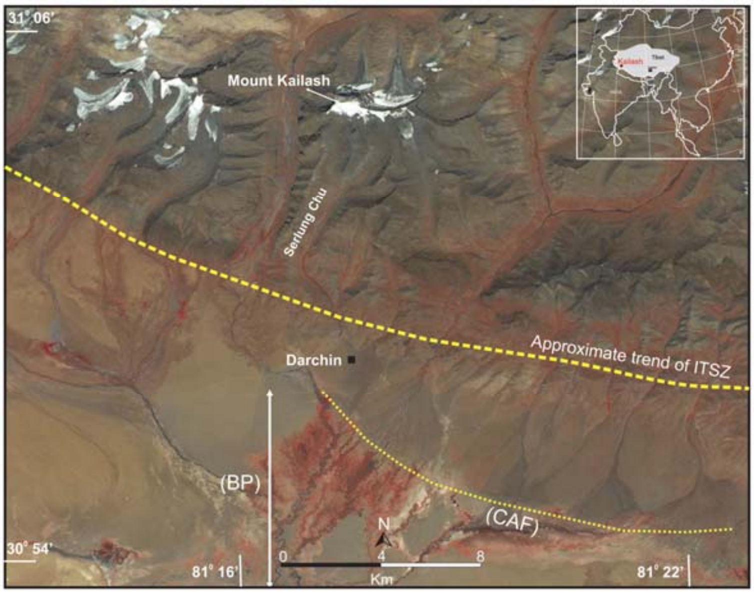

Figure 1. September 2004 IRS P6 LISS-IV data showing various geomorphic features around the study area. The approximate trend of the Indo-Tsangpo Suture Zone (ITSZ), is also marked. BP, Barkha plain; CAF, Coalescing alluvial fans.

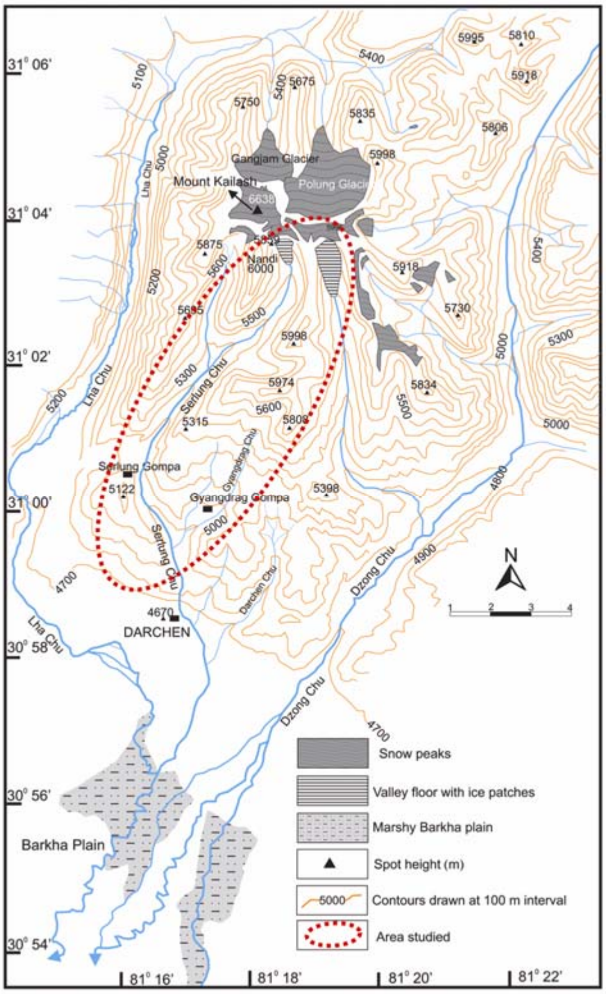

Figure 2. Geomorphological map of the area around Mount Kailash. The study was conducted along the Serlung Chu valley (Inner Kora) marked red with a dotted ellipsoid.

to > 6000 m around Kailash Mountain (Figure 2). The annual rainfall in the region is < 200 mm, which occurs during June–September, and is caused due to the summer monsoon cloud originating from the Bay of Bengal and Arabian Sea[14].

Glaciers are important geomorphic agents in shaping the landscape and are responsible for carving out some of the most spectacular geomorphic features, particularly in the Himalaya and Tibetan plateau. As the glacier ice moves it not only erodes the valley bottom, but also plucks the rocks from valley flanks. As a consequence, wide *U*-shaped valleys are the common geomorphic expression of former grandeur of valley glaciers. Such features are quite spectacular all around the Kailash Mountain (Figure 3 *a*). One can observe at least four such valleys radiating outwards from the Kailash peak, suggesting existence of large valley glaciers in the past. One such relict glaciated valley oriented southeast is shown in Figure 3 *b*.

Evidence of the existence of extensive glaciers around Mount Kailash comes from the preservation of glacial striations observed ~ 5700 m (~ 200 m above the valley floor) and the presence of ~ 500 m long valley wide glacially polished exposed bedrock at 5500 m (Figure 3 *c*). These features suggest former extent of ice cover in the southern part of Mount Kailash. Glacial striations are formed by the moving ice on the rocky substratum. These are scratches and grooves formed parallel to the direction of glacier movement. Similarly, the glacially polished bedrock exposure represents former glacial substratum which is now vacated by the glacier.

A relict cirque is another characteristic erosional feature found in the ancient glaciated valleys. An active cirque can be considered as a feeder glacier to the main

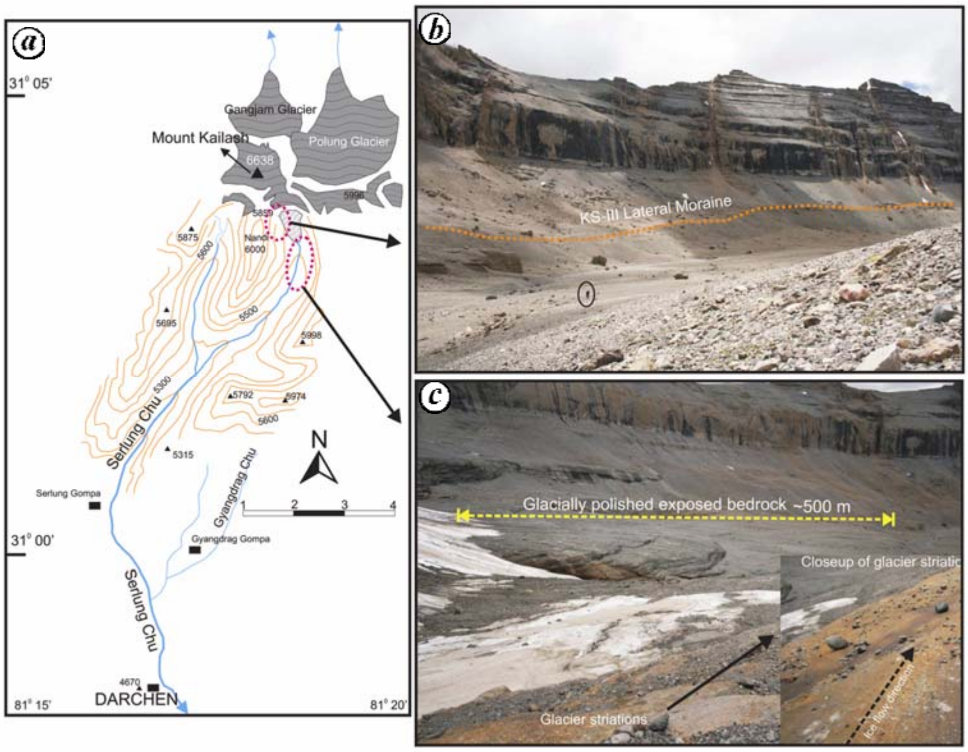

Figure 3. ***a***, Map of the study area showing the location of (***b***) left flank of the U-shaped valley carved by former glaciers, a man (circled) in the middle for scale and (***c***) exposed glaciated bedrock (~ 500 m long); terminus of the existing glacier is seen to the left as well as glacier striations proximal to the ledge connecting Mount Kailash and Nandi peak.

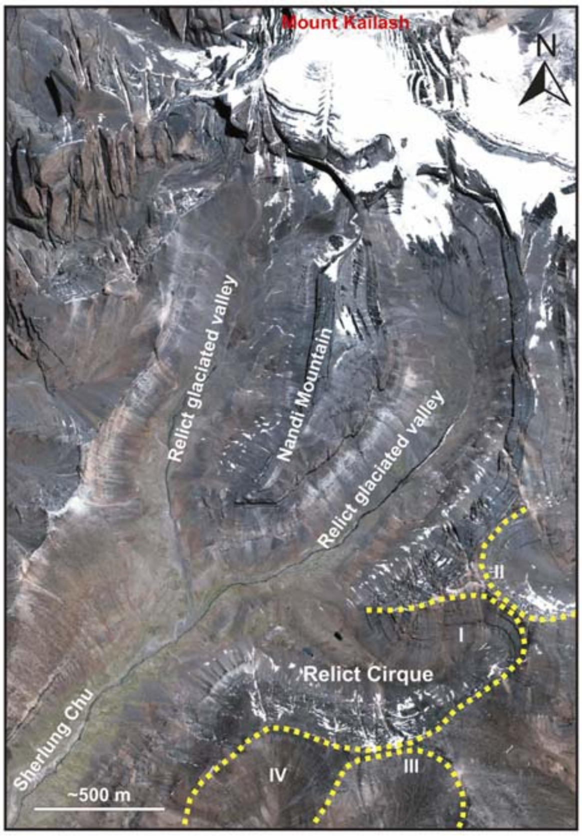

Figure 4. IKONOS data showing the relict glaciated valleys and cirques (I–IV) which indicate the grandeur of glaciers around Kailash in the past.

valley glacier. After the glacier recedes, a relict cirque resembles an amphitheater (Figure 4). The relationship between the modern regional snowline and the altitude of the floors of small, independent cirques in glaciated mountain ranges has long been used to provide the first-order approximation of the snowline altitude[15]. In the study area four relict cirques can be seen in the satellite data, marked as I–IV in Figure 4. The cirque floor altitude of a west-oriented relict cirque (cirque I, Figure 4) was located ~ 5500 m, which broadly coincides with the highest elevation of the youngest lateral moraine (discussed later), implying that the cirque was active during the youngest glacial advance.

Geomorphic expression of glacial erosion around Kailash region is manifested by the pyramidal shape Mount Kailash. Such morphology develops in areas where headward erosion of a ring of cirque glaciers around a single high mountain deepens the valley from more than three sides. The features looks like a spire of rock and are called as 'horn'. When the cirque glaciers finally disappear, they leave a steep, pyramidal mountain outlined by headwalls of the cirques[16]. This suggests that in the past glaciers around Kailash Mountain operated in a much larger scale, which led to the sculpturing of peaks and incision of deep and wide valleys.

Reconstruction based on moraine stratigraphy in areas dominated by monsoon suffers from the difficulty in differentiating the moraines from those of the frequent mass wasting[17,18]. In addition, reconstruction of the former extent of glaciers requires detailed geomorphic mapping and analyses of landforms and sediments. The most accurate methods also require that there is sufficient geomorphic evidence, usually lateral–terminal moraines and trimlines, to allow the shape of the former glacier to be reconstructed[18]. In the study area low monsoon precipitation, wide valley and absence of active cirque glaciers facilitated the preservation of lateral moraines. Based on the field morpho-stratigraphic position and morphology of the lateral moraine ridges, three distinct glacial advances with progressive decrease in the magnitude have been identified in the Serlung Chu valley (Figures 5 and 6).

The degraded longest and oldest lateral moraine can be traced based on the hummocky morphology along the western flank of Serlung Chu valley. The lateral traces of this moraine ridge, at places are overlain by the debris flows and were dissected by seasonal streams (Figure 5) and named as Kailash stage-I (KS-I). The highest elevation of KS-I was located at 5200 m, whereas its terminus appeared to be around 4800 m in the vicinity of ITSZ (Figure 6). The lateral moraine associated with the second glacial advance was fluvially modified by Serlung Chu. Named as KS-II advancement, it emanates from a height of 5300 m and terminates at around 5100 m near Serlung Gompa (Figures 5 and 6). KS-II is separated from KS-I by a vertical offset of ~30 m (Figure 5). The youngest lateral moraine termed as KS-III originates from 5500 m at the base of the Kailash peak and terminates as a curvilinear ridge at 5200 m below the confluence of the tributary streams (Figure 6). In addition, the conical heap of moraines (relict push moraines) between 5500 and 5700 m (Figure 6) suggest that the glacier has receded during the post-KS-III as well.

Glacier responds sensitively to the ambient temperature and precipitation, which in turn shift ELA. In the field, ELA is associated with the emergence of the lateral moraines[12]. Thus the magnitude of past climatic changes can be ascertained by estimating the altitudinal difference between the past and present ELAs[19]. This technique was successfully employed in the Goriganga basin (Trans Himalaya)[20], located south of Mount Kailash, to estimate past temperatures and ice volume. Although glaciers to the south of Mount Kailash have receded significantly, on the southeastern flank, a thick pile of permanent ice occupies the eastern saddle of the mountain at around 5800 m. This ice cap can be assumed to be the modern ELA and compares well with the observation made by earlier workers in southwestern Tibet[6]. The saddle ice feeds the glacier below, which merely descends a few hundred meters mixed with debris (Figure 7). In order to estimate the past temperatures associated with the individual glacial advances, ELA depression is multiplied by

Figure 5. Field photograph of lateral moraines deposited during there major glaciations in the Serlung Chu valley (southern Kailash). These glaciations from older to younger are named as Kailash stage-I (KS-I), KS-II and KS-III.

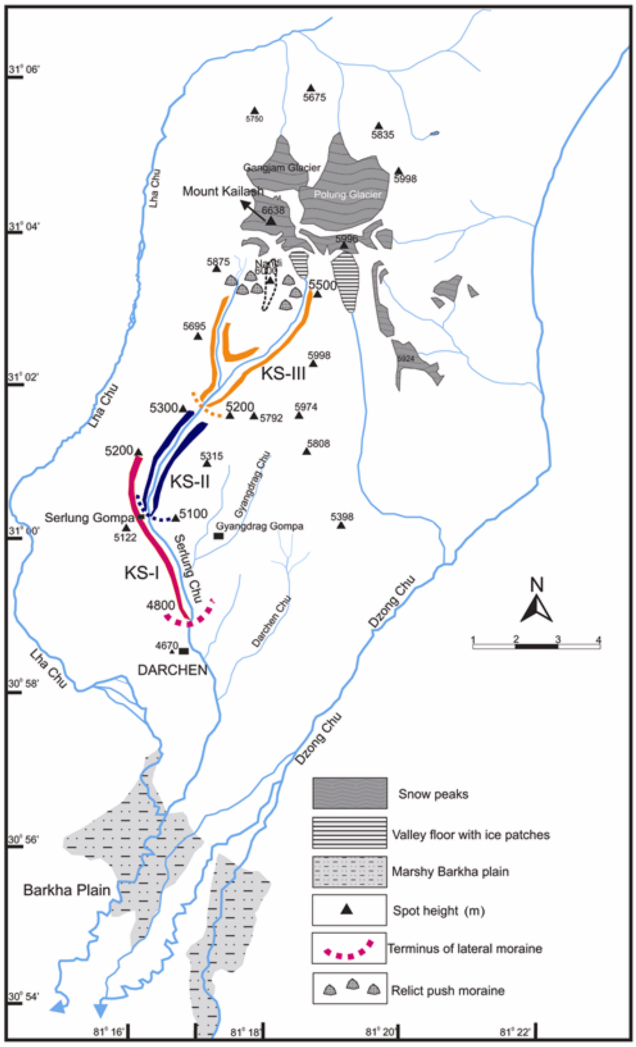

Figure 6. Geomorphological position of lateral moraines observed in the field. The emerging point of KS-I was ~5200 m and termination ~4700 m, KS-II appeared at ~5300 m and terminated at ~5100 m, whereas KS-III emerged at ~5500 m and terminated at ~5200 m. Exposed glaciated bedrock and push moraines are also shown proximal to Mount Kailash between 5500 and 5600 m.

the adiabatic lapse rate. Lapse rate is the change in temperature as function of elevation. In southern Tibet, adiabatic lapse rate of 0.62°C/100 m has been used[21]. In the absence of any direct measurement from the study area, the above lapse rate has been used for temperature estimation. Table 1 gives the results of our preliminary temperature estimates in the valley during advancement of KS-I to KS-III glaciations.

The erosional and depositional landforms discussed above suggest that compared to the present, glaciers were more extensive in the past. This accords well with the suggestion that throughout Tibet and the bordering mountains, glaciers oscillated many times during the late Quaternary. It has been observed that in regions influenced by the monsoon, glaciation appears to be controlled by monsoonal precipitation which influences the glacier mass balance. This relationship allowed glaciers in high-altitude regions to advance during times of increased precipitation[22]. There appears to be a correlation between the increased precipitation and glacier advances in areas influenced by the monsoon[10,22]. The above correlation is summarized in Figure 8. Reconstruction of former extent of glaciers provides a qualitative picture of the ambient climatic condition. Such reconstruction, however, requires accurate dating of glaciogenic features and sediments for regional and global climatic correlation[18]. The present study lacks absolute ages due to paucity of organic carbon (for radiocarbon dating) and laminated sediments (for optical dating). However, it provides a broad framework of palaeoglaciation around one of the most spectacular landscapes in southwestern Tibet. In order to ascertain the tentative chronology of different advances, we resort to circumstantial evidences, particularly the limited chronologically constrained moraines and climatic events from the region[10,23–25].

Studies in many parts of Tibet and the Himalayan regions show that glaciation was more extensive during the earlier part of the last glacial cycle and was limited in extent during the Last Glacial Maximum (LGM; Figure 8). Similarly, Holocene glacial advances were also limited in extent, with glaciers advancing just a few kilometres from their present ice margins[22]. The above inferences are based on the regional studies, viz. Ladakh to Nepal and eastern Tibetan plateau[20,23–25]. Also, if we compare the most proximal terrain, the Trans Himalayan region of Uttarakhand, chronology of relict lake sequence and moraines suggests that compared to the LGM glacier were more extensive during pre-LGM period probably correspond to the Marine Isotopic Stage-4 (MIS-4) (refs 20 and 26) or early part of MIS-3 (ref. 27). In addition, the youngest glacial advance north of Badrinath in the Alaknanda valley was dated to 4.5 ka, whereas the conical heap of moraines proximal to the present-day snout was attributed to the Little Ice Age (LIA)[28].

Glacial expansion is generally a response to lower temperatures, but at high altitudes it may be more sensitive to changes in moisture transport[29]. Depending upon the geographical position of glaciers in the Himalaya, both precipitation and temperature modulate the ELA position. For example, in the southern monsoon-dominated Himalaya, lowering of ELA is associated with decrease in

Table 1. Estimation of equilibrium line altitude (ELA) depression and associated temperature change during KS-I to KS-III glaciation

Glacial stage	ELA (m)	ELA decline (m)	Temperature decline (°C)
Modern glacier	5800	–	–
KS-III	5600	200	~ 1
KS-II	5300	500	~ 3
KS-I	5200	600	~ 4

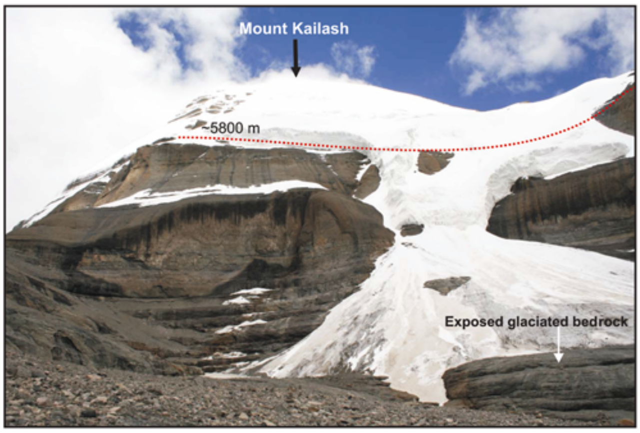

Figure 7. Field photograph showing the southeastern face of Kailash. Note the exposed bedrock and protruding ice from the saddle. The saddle ice roughly coincides with the equilibrium line altitude (~ 5800 m).

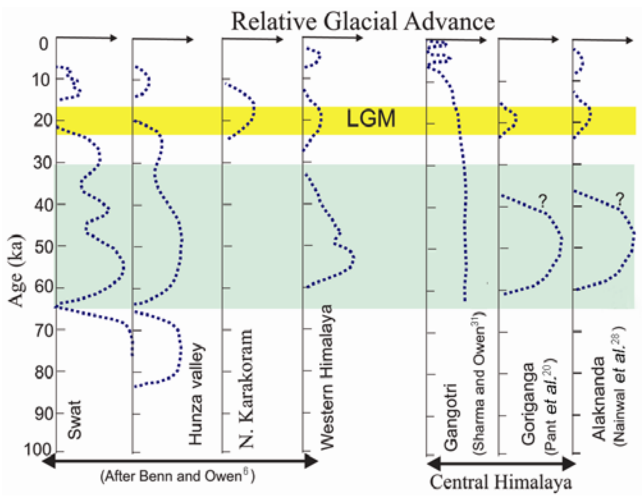

Figure 8. Chronology of Late Quaternary glaciation in the Himalaya suggests maximum valley glaciation (schematic) occurred between 60 and 30 ka (highlighted by light blue box) during the late MIS-4 and MIS-3. These periods coincide with relatively enhanced monsoon compared to the Last Glacial Maximum (LGM).

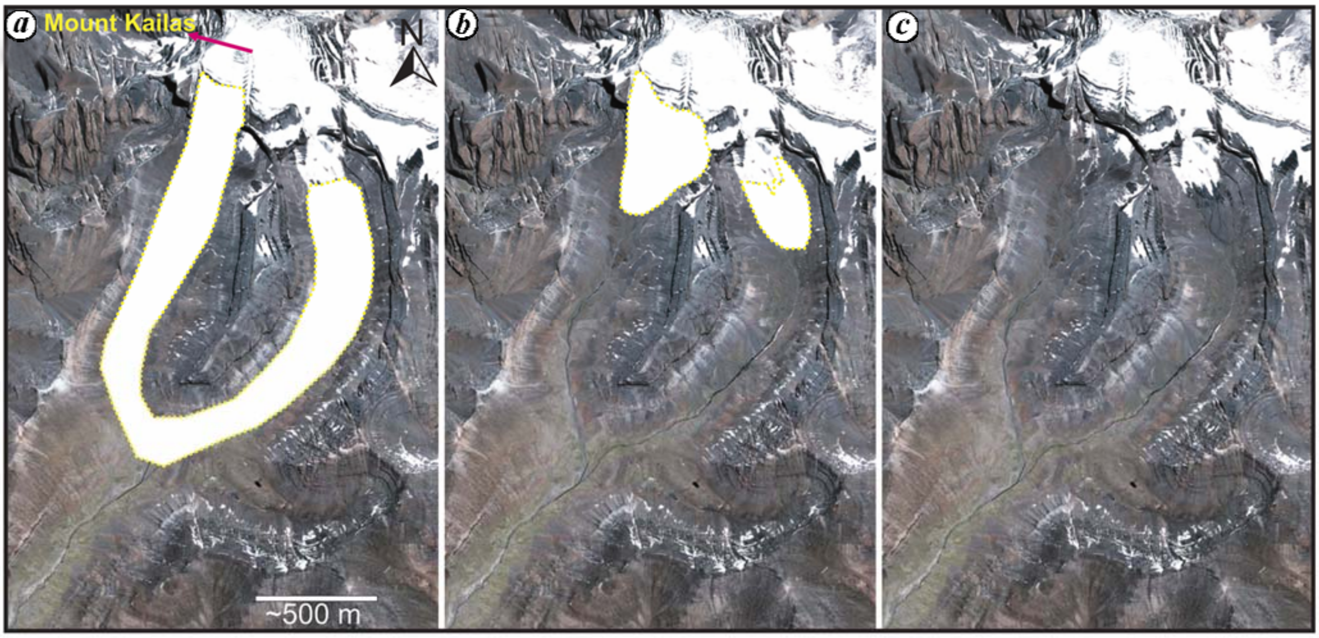

Figure 9. Glacier reconstruction based on the lateral moraine associated with KS-III glaciation, push moraine and exposed glaciated bedrock. The observations are superimposed on June 2009 IKONOS data. The reconstructed glacier extents are bordered with yellow dots. Glacier extent during (***a***) KS-III, (***b***) deposition of push moraine and glaciated bedrock development and (***c***) present position.

summer temperature and increase in monsoonal precipitation. Compared to this in the drier, western and northern Central Asia, it is temperature that governs the position of ELA (ref. 1). In a broadly comparable terrain in southern Tibet (Nyalam), it was observed that during LGM (MIS-2) snowline depressed by ~ 450 m, which translates into a temperature decline of around 3°C. Compared to this, during post-LGM (Late Glacial), snowline depression and the corresponding temperate decline were estimated to be ~ 250 m and ~ 2°C respectively. It has been observed that glaciers in Tibet expanded when the melting during the ablation season was reduced by cooler summer temperature and not during periods of the increased moisture supply associated with a strengthened monsoon[21].

Since our study is limited by chronology, we ascertained the timing of individual glacial stages by comparing the ELA depression estimated from the present study with that of the climatically identical and geographically proximal Nyalam valley[21]. The timing of KS-I glaciation is uncertain. However, looking at the ELA depression of ~ 600 m and associated temperature decline of ~ 4°C, this event is likely to pre-date LGM. A comparable ELA depression (~ 500 m) and the associated temperature decline (~ 3°C) during KS-II advance compare well with the glacial expansion observed during LGM in Nyalam valley[21]. Whereas KS-III would correspond to the post-glacial (Holocene?) advance (ELA depression ~ 200 m and temperature decrease ~ 1°C). In addition, exposed glaciated bedrock and conical heap of moraines (Figures 3 and 6) probably correspond to recent or sub-recent increase in temperature after LIA (~ 19th century AD). Figure 9 is a pictorial depiction of the changes in ice cover since the KS-III glaciation to the Present. This depiction is based on the mapping of lateral moraines associated with KS-III glaciation and the glaciogenic features discussed earlier.

Our inferences although speculative, provide a broad framework of Late Quaternary glacier history from one of the most ecologically fragile terrains in the Himalaya. The observations presented here indicate that glaciers in southern Kailash region are on a receding trend. At this stage, it is difficult to ascertain if the recession was due to the change in precipitation or temperature. Existing climatic data suggest that compared to the early Holocene, a gradual decline in monsoon was observed in Tibet, particularly after 3 ka. However, the decrease in moisture was not all that low compared to LGM[30]. Therefore, it can be inferred that after the KS-III glaciation, there would have been a decrease in rainfall around Mount Kailash. However, considering the present-day rainfall of ~ 200 mm, it is not all that low to cause alarming recession of the glaciers. We hypothesize that after the KS-III glaciation, a steady increase in the summer temperature with a brief reversal during the LIA, when the marginal increase in glacier covering the exposed glacially polished bedrock and deposition of push moraines occurred. Climatic scenarios and circumstantial evidences suggest that the current recession would have occurred after LIA around the beginning of the 19th century. In the near future once the stratigraphic and geomorphic evidences presented in the present study are chronologically constrained, we would be in a better position to ascertain the climatic pattern that prevailed during the Kailash glaciation. In addition, chronology of past glaciation would possibly help in understanding the potential evolution of the glaciers around Mount Kailash in response to the anticipated global warming scenario.

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ACKNOWLEDGEMENTS. N.J. and P.S.T. thank Astapad Research Foundation, LD Institute of Indology, Ahmedabad, for support and Dr Rajnikant Bhai Shah for IKONS data. P.S.T. also thanks Dr R. R. Navalgund, Director, SAC, Ahmedabad and Dr Ajay, then Group Director, FLPG/RESIPA/SAC for encouragement and Sashikant Sharma for processing the IKONOS data. We thank two anonymous reviewers for critical comments and suggestions.

Received 10 May 2010; revised accepted 18 November 2010