# Correspondence

## *Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalaya*

The Nepal Himalaya contain many debris-covered glaciers, some of which have large glacial lakes at the terminus. These lakes have been growing since the 1950s and 1960s (Yamada, 1998), giving rise to the potential hazard of glacial-lake outburst floods (Richardson and Reynolds, 2000).

Reynolds (2000) reported that in the Bhutan Himalaya, glacial lakes form in those parts of a glacier where the inclination of the glacier surface is <2°. Quincey and others (2007) reported that glacial lakes develop on debris-covered glaciers with low slopes and a surface speed $<10\,\mathrm{m\,a^{-1}}$. Suzuki and others (2007) calculated the thermal resistance of debris-covered glaciers and found that those with relatively thin debris layers tend to develop glacial lakes at their terminus. This finding suggests that glaciers with high rates of ablation tend to develop glacial lakes. In summary, the available evidence indicates that glaciers that record a relatively large lowering of their surface are likely to develop glacial lakes at their terminus. Indeed, Kirkbride (1993) reported that lowering of the glacier surface resulted in the formation of supraglacial ponds and the commencement of calving at the glacial lake.

Here we identify the formation conditions of glacial lakes by analysing two easily measurable topographic parameters: inclination of the glacier surface and the difference in height between the glacier surface and lateral moraine ridges (herein, this difference is referred to as the DGM, an indicator of glacier surface lowering on debris-covered glaciers). Using these data, it is possible to predict the likelihood of glacial lake formation at debris-covered glaciers in the Himalaya.

## METHOD

We examine debris-covered glaciers in the Nepal and Bhutan Himalaya (Fig. 1a). The data sources, methods, dates and locations for analysed glaciers are summarized in Table 1. Glacier surfaces during the Little Ice Age (LIA) maximum reached at least the height of present-day lateral moraine ridges. The DGM therefore indicates the degree to which the glacier surface has lowered since the LIA glacial maximum.

The height of moraine ridges must be determined with relatively high accuracy to enable analysis of glacier surface lowering. Lateral moraines form sharp, steep features within the terrain; however, the average height of moraine crests observed in an Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) satellite digital elevation model (DEM) is >10 m lower than that measured in the field, even at a spatial resolution of 15 m (Fujita and others, 2008). The errors involved in reading measurements from a map contour are ±6 m in the horizontal and ±2.3 m in the vertical (for surface inclinations of 10°, the maximum in our analysed glaciers), due to the thickness of the drawn contours. We are thus unable to use a DEM based on ASTER satellite images.

We digitized the topographic maps of selected debris-covered glaciers, restricting our analysis to clear moraine ridges. We then constructed longitudinal profiles of the present-day glacier surface and lateral moraine, and calculated the DGM. The average DGM is the value derived from the total area of the side face of a lateral moraine divided by the total analysed distance from the terminus along the flowline. Average slope inclination was calculated based on the total analysed horizontal distance along the flowline and the difference in height between the terminus and the highest analysed zone.

In 2004, we carried out a field survey at Lugge and Thorthormi Glaciers in the Lunana region of the Bhutan Himalaya (Fig. 1d) using a carrier-phase differential GPS (Fujita and others, 2008). At Thorthormi Glacier, sites TGa, TGb and TGc (Fig. 1d) were located on the glacier surface, and sites TMa and TMb were located on the moraine ridge. At Lugge Glacier, sites LGa, LGb and LGc were located on the glacier surface, and sites LMa and LMb were located on the moraine ridge. The inclination of the glacier surface at Thorthormi and Lugge Glaciers was calculated from the difference in height and distance between TGc and TGa, and between LGa and LGc respectively. To calculate DGM at Thorthormi Glacier, we used the average height difference between TMa and TGa and between TMb and TGb. At Lugge Glacier, we calculated DGM based on the height difference between LMa and LGa, and between LMb and LGb. Because access to the glaciers was limited, we were unable to obtain field data for the entire glacier in each case.

## RESULTS AND DISCUSSION

Figure 2 shows values of DGM plotted against the inclination of the glacier surface. We identified three types of glaciers according to development of the glacial lake at the time the photograph was taken or when a survey was carried out to verify the topographic maps. The first glacier type, 'with glacial lake', describes glaciers with a glacial lake that coalesces into a single, continuous glacial lake. The second type, 'with separate glacial lake', refers to glaciers with a growing glacial lake at the terminus and with a water surface >1 km in length, although the water surface is discontinuous due to interruptions by glacier ice. The third type, 'no glacial lake', refers to glaciers with glacial lakes <1 km in length. According to this scheme, there are five glaciers in the Himalaya classified as 'with glacial lake': Lugge, Lhotse Shar (Imja Glacial Lake), Trambau (Tsho Rolpa), Thorthormi and Lower Barun glaciers. Thorthormi Glacier is of the second type ('with separate glacial lake').

We also analysed DGMs and inclinations at Tasman Glacier, New Zealand, based on longitudinal profiles of the glacier surface and lateral moraine as compiled in 1965 and 1986 (Kirkbride and Warren, 1999, fig. 5), and longitudinal profiles of the glacier surface in 2007 (Quincey and Glasser, 2009). We assumed the height of the lateral moraine in 2007 was equal to that reported by Kirkbride and Warren (1999). The lower part of Tasman Glacier is also covered by debris. In 1965, several small supraglacial ponds (<500 m along the major axis) were located near the terminus, corresponding to the type 'with no glacial lake'. By 1986, the ponds had grown to large lakes (>1 km along the major axis), although the large supraglacial ponds on the right and left sides of the glacier terminus remained separate. By 2007, however, the

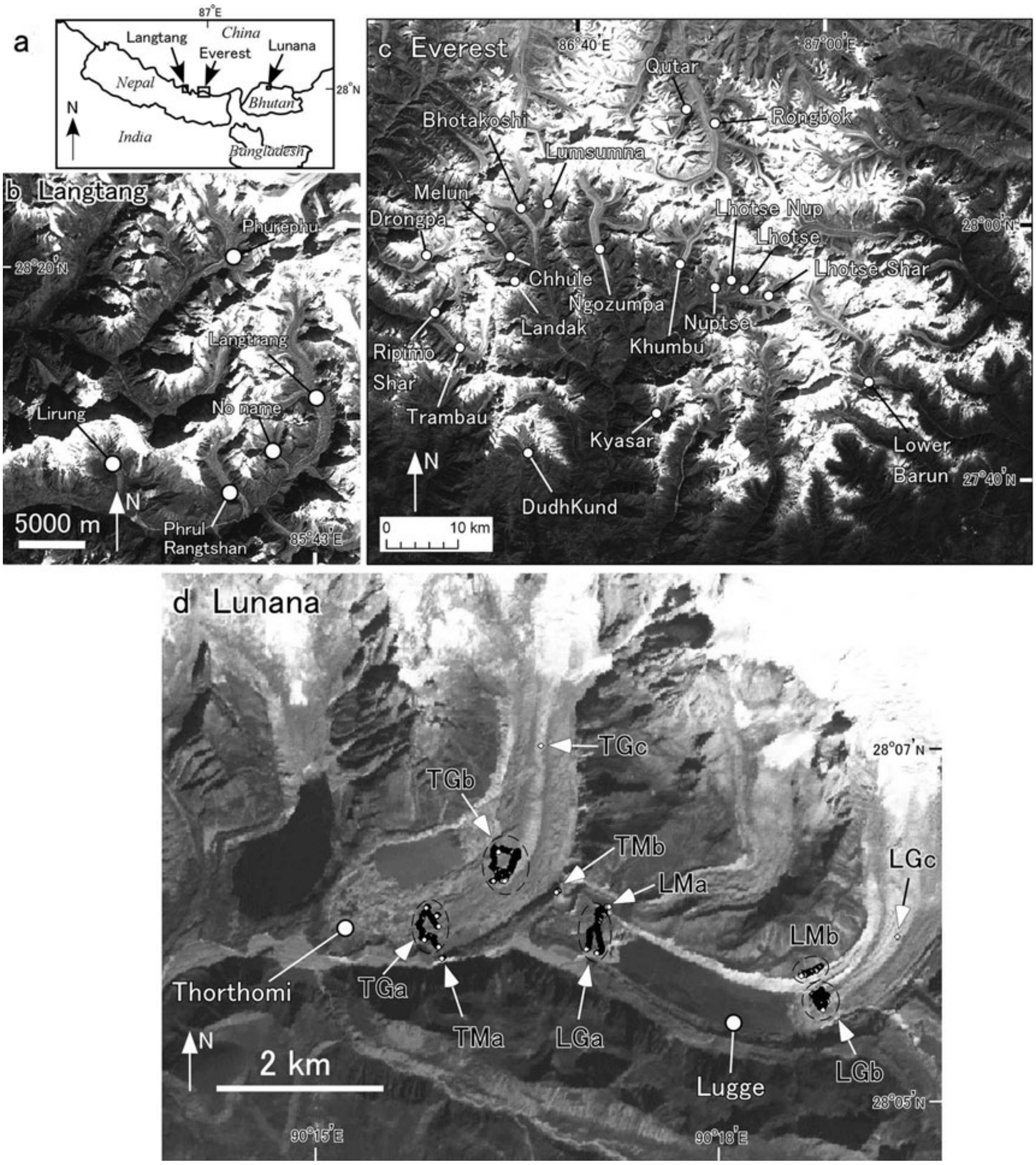


**Fig. 1.** Locations of debris-covered glaciers. (a) Locations of study sites. (b–d) Specific locations of analysed glaciers at (b) Lantang Himal, Nepal, (c) the Everest region and (d) the Lunana region, Bhutan. Also shown in (d) are the locations of survey points on Thorthormi and Lugge Glaciers.

lakes had coalesced to form a single water body with a surface area of ~6 km$^2$ (Quincey and Glasser, 2009).

In Figure 2, the distribution of Himalayan glaciers with a supraglacial lake is different from that for glaciers with no such lake. Glacier lakes are not present upon glaciers with a small DGM value or with steep surfaces. For all glaciers with large supraglacial lakes, values of DGM exceed 60 m and the average inclination of the glacier surface is <2.0°.

During the field survey conducted in 1998, several large supraglacial ponds were observed at the terminus of Thorthormi Glacier. N. Naito and others (unpublished information) reported that for the lower part of the glacier, the rate of lowering of the surface was about 2.5 m a$^{-1}$, about half the rate at Lugge Glacier, which possesses a glacial lake. An ASTER satellite image captured on 1 January 2008 shows that the supraglacial ponds at Thorthormi Glacier have yet to amalgamate.

A satellite image captured in 2003 shows a single large glacial lake at the terminus of Drongpa Glacier (Quincey and others, 2007), whereas two small supraglacial ponds were observed at the terminus in the 1960s (Schneider, 1992). This glacier has a large DGM value (based on the findings of Schneider (1992), who carried out fieldwork in the 1960s) compared with other glaciers, although the water surface has not increased in size, as the surface inclination is >2°. Reynolds (2000) reported that glacial lakes expand if the inclination of the glacier surface is <2°. The high DGM indicates the future formation of a glacial lake.

Although the inclination of the glacier surface at Khumbu and Ngozumpa Glaciers in 1992 was <2°, they currently have no glacial lakes. However, it is possible that glacial lakes will develop at the terminus given a sufficient lowering of the surface. Although Bhotekosi, Rongbok, Lumsumna and Qutar glaciers currently lack glacial lakes, they may

**Table 1.** Locations of analysed glacial lakes and data sources. 'Tas65', 'Tas86' and 'Tas07' indicate data obtained for Tasman Glacier in 1965, 1986 and 2007, respectively. Names in parentheses are those used in Schneider (1992)

| Lake name (Fig. 2) | Glacier | Glacial lake | Location | Data source | Survey or shooting year of data source |
|---|---|---|---|---|---|
| Bho | Bhotekoshi (Lunag) | | 27°59′6.47″ N, 86°36′27.46″ E | Nepal: Survey Department (1997c,d) | Photography 1992, field verification 1996 |
| Chh | Chhule (Dingjung) | | 27°57′9.18″ N, 86°34′5.49″ E | Nepal: Survey Department (1997c) | Photography 1992, field verification 1996 |
| Dro | Droungpa | Droungpa | 27°56′57.15″ N, 86°27′2.07″ E | Schneider (1992) | Fieldwork 1960–68 |
| Dud | No name (DudhKund) | | 27°42′21.84″ N, 86°35′42.71″ E | Nepal: Survey Department (1996) | Photography 1992, field verification 1996 |
| Khu | Khumbu | | 27°57′6.16″ N, 86°49′14.35″ E | Nepal: Survey Department (1997e) | Photography 1992, field verification 1996 |
| Kya | Kyasar | | 27°45′25.95″ N, 86°47′22.90″ E | Nepal: Survey Department (1997e) | Photography 1992, field verification 1996 |
| Lan | Landak | | 27°55′37.33″ N, 86°34′32.42″ E | Nepal: Survey Department (1997c) | Photography 1992, field verification 1996 |
| Lang | Langtang | | 28°15′52.20″ N, 85°43′18.23″ E | OeAV (1990) | Photograph 1970/71, NASA Skylab mission 1973 |
| Lho | Lhotse | | 27°54′46.87″ N, 86°54′21.23″ E | Nepal: Survey Department (1997e) | Photography 1992, field verification 1996 |
| LhoN | Lhotse Nup | | 27°55′2.27″ N, 86°53′11.63″ E | Nepal: Survey Department (1997e) | Photography 1992, field verification 1996 |
| LhoS | Lhotse Shar | Imja | 27°54′32.08″ N, 86°56′49.93″ E | Nepal: Survey Department (1997e) | Photography 1992, field verification 1996 |
| Lir | Lirung | | 28°14′3.74″ N, 85°33′43.23″ E | OeAV (1990) | Photograph 1970/71, NASA Skylab mission 1973 |
| Lob | Lobche | | 27°57′21.03″ N, 86°48′25.17″ E | Nepal: Survey Department (1997e) | Photography 1992, field verification 1996 |
| Low | Lower Barun | Lower Barun | 27°47′55.23″ N, 87°5′5.98″ E | Nepal: Survey Department (1997b) | Photography 1992, field verification 1996 |
| Lug | Lugge | Lugge | 28°5′39.23″ N, 90°17′44.15″ E | | Field survey 2004 |
| Lum | Lumsumna | | 28°0′15.32″ N, 86°37′32.53″ E | Nepal: Survey Department (1997c,d) | Photography 1992, field verification 1996 |
| Mel | Melun (Pangbug) | | 27°58′48.82″ N, 86°33′26.30″ E | Nepal: Survey Department (1997c,d) | Photography 1992, field verification 1996 |
| Ngo | Nojumba* (Ngozumpa) | | 27°58′17.10″ N, 86°41′48.32″ E | Nepal: Survey Department (1997c,d) | Photography 1992, field verification 1996 |
| Nup | Nuptse | | 27°55′50.74″ N, 86°52′2.55″ E | Nepal: Survey Department (1997e) | Photography 1992, field verification 1996 |
| No | No name | | 28°14′47.35″ N, 85°41′8.79″ E | OeAV (1990) | Photograph 1970/71, NASA Skylab mission 1973 |
| Phu | Phurephu | | 28°22′32.32″ N, 85°37′50.78″ E | OeAV (1990) | Photograph 1970/71, NASA Skylab mission 1973 |
| PhuR | Phul Rangt-shan | | 28°13′43.77″ N, 85°38′47.43″ E | OeAV (1990) | Photograph 1970/71, NASA Skylab mission 1973 |
| Rip | Rolwalin (Ripimo Shar) | | 27°53′19.56″ N, 86°28′9.69″ E | Nepal: Survey Department (1997a) | Photography 1992, field verification 1996 |
| Ron | Rongbok | | 28°6′52.64″ N, 86°51′42.98″ E | Garrett (1988) | Space Shuttle Columbia 1983 |
| Qut | Qutar | | 28° 8′28.16″ N, 86°49′52.88″ E | Garrett (1988) | Space Shuttle Columbia 1983 |
| Tas65, Tas86 | Tasman | Tasman | 43°41′24.57″ S, 170°11′2.40″ E | Kirkbride and Warren (1999, fig. 5) | |
| Tas07 | Tasman | Tasman | 43°41′24.57″ S, 170°11′2.40″ E | Quincey and Glasser (2009) | ASTER satellite image 2007 |
| Tho | Thorthormi | Thorthormi | 28°6′10.52″ N, 90°15′51.85″ E | | Field survey in 2004 |
| Tra | Rolwalin (Trambau) | Tsho Rolpa | 27°50′33.32″ N, 86°29′47.66″ E | Nepal: Survey Department (1997a,c) | Photography 1992, field verification 1996 |

*Ngozumpa Glacier was measured up to a point located 6000 m from the terminus.

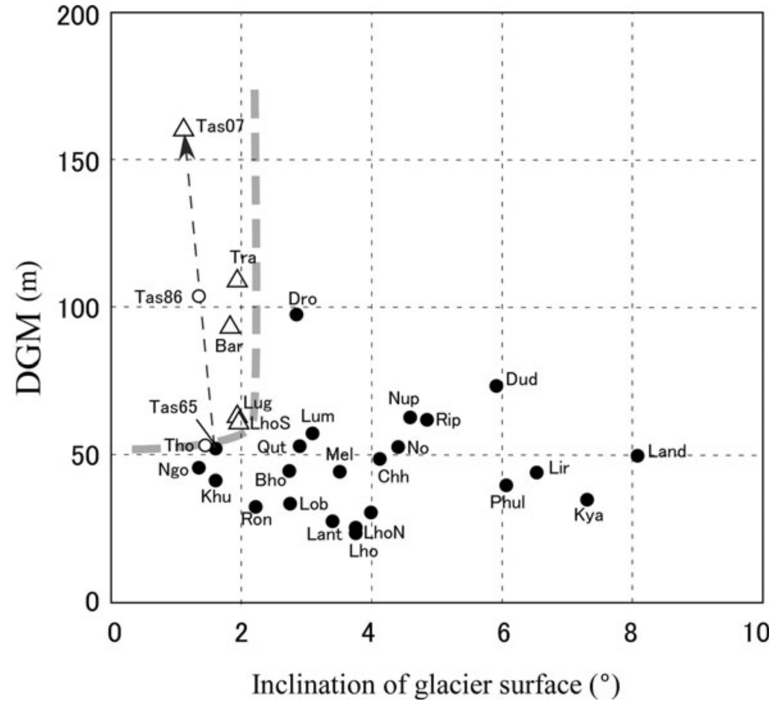


**Fig. 2.** Scatter diagram showing the difference in height between lateral moraine and the glacier surface (DGM) plotted against glacier surface inclination. White triangles indicate glaciers of the type 'with glacial lake' (lakes that have coalesced to form a single, continuous water surface). White circles indicate glaciers of the type 'with separate glacial lake' (a growing glacial lake at the terminus and a water surface >1 km in length, although the water surface is discontinuous, interrupted by glacier ice). Solid circles indicate glaciers of the type 'no glacial lake' (glacial lakes <1 km in length). The grey dashed line represents the boundary between glaciers with and without a glacial lake in the Himalayan debris-covered glaciers. The abbreviated glacier names are explained in Table 1. The arrow shows the trend observed at Tasman Glacier in 1965, 1986 and 2007.

develop at the terminus given lowering of the glacier surface and a reduction in the inclination of the surface, as observed at Tasman Glacier. Thus, we are able to predict the likely trends of glacial lake formation based on the above conditions required for the formation of glacial lakes.

Based on an analysis of glacier surface flow using interferometry and feature-tracking techniques, Quincey and others (2009) concluded that almost all the glaciers in the Everest region are in poor health, being characterized by low flow at high elevations, and long, stagnant, debris-covered tongues at lower elevations. Thus, a low rate of glacier surface flow, as determined from analyses of satellite images, is indicative of the future formation of a glacial lake.

At Tasman Glacier, lowering of the glacier surface has increased since the LIA, and the inclination of the glacier surface has decreased with the development of a glacial lake since 1965. Figure 2 shows that the DGM value at the commencement of expansion of the glacial lake at Tasman Glacier is greater than the value calculated for Himalayan glaciers, reflecting the difference in water level within the various glaciers. In the Himalaya, the altitude of the glacier terminus of debris-covered glaciers is 4000–5000 m a.s.l., and the annual temperature is <0°C (Yamada, 1998).

Observations of the distribution of buried ice at Imja Tsho and Tsho Rolpa using electrical resistivity and ground-penetrating radar indicate the occurrence of dead ice near the terminal moraine (Fujiwara and Gomi, 1995; Rana and others, 2000; Reynolds, 2006). In New Zealand, the glacier terminus can reach lower altitudes (~700 m a.s.l.) because the annual precipitation exceeds 3000 mm at the terminus. Hence, the average annual temperature near the glacier terminus is as high as 8.0°C (Röhl, 2008), meaning less dead ice is retained in moraine at Tasman Glacier, resulting, in turn, in high permeability within moraine and low water level inside the glacier compared with Himalayan glaciers. Therefore, expansion of the glacial lake at Tasman Glacier will begin after a pronounced lowering of the glacier surface. It may be necessary to identify different criteria regarding DGM-related glacial lake formation for glaciers in New Zealand.

Regarding the inclination of the glacier surface, Röhl (2008) reported a surface gradient of <2° in cases of glacial lake formation in New Zealand, consistent with the results of a previous study in the Bhutan Himalaya (Reynolds, 2000). The conditions of glacial lake formation at glaciers with a surface inclination of <2° may be common to all glaciers worldwide, as the surface gradient is related to ice dynamics. In contrast, the conditions of glacial lake formation expressed in terms of DGM will differ among glaciers, depending on the permeability of the moraine damming the glacial lake. In the Himalaya, the altitude of the terminus of debris-covered glaciers is generally 4200–5500 m a.s.l. Consequently, similar meteorological conditions may lead to similar water levels in Himalayan glaciers.

In summary, we have clarified that the formation conditions of a glacial lake can be clearly expressed in terms of the inclination of the glacier surface and the amount of lowering of the glacier surface since the LIA in the Himalaya. Using these criteria, it is possible to estimate the likelihood of glacial lake formation.

Figure 2 shows that debris-covered glaciers with a growing glacial lake have higher DGM values than do glaciers without a glacial lake. This relation can be explained by the contribution of disintegration of the terminus by ablation at supraglacial ponds and by glacier ice dynamics. In a study of Tasman Glacier, Röhl (2008) reported that supraglacial lakes contribute to disintegration of the glacier terminus by exposing ice faces at the surface. The formation of a terminal glacial lake results in reduced compression in the lower part of the glacier, as the glacier ice at the terminus receives no pressure from adjacent ice or the terminal moraine. This reduced compression results, in turn, in reduced emergence velocity, leading to further lowering of the glacier surface. Based on the results of field surveys at Thorthormi Glacier, N. Naito and others (unpublished information) reported intense compression at the glacier terminus and relatively high emergence velocities. Consequently, the level of the glacier surface has shown little change over time. This finding reflects the fact that only some of the small supraglacial lakes at Thorthormi Glacier are expanding, and no large water body has expanded to the side moraine. In contrast, Lugge Glacier records a rapid decline in the glacier surface, as the water surface has expanded to the side moraine, compression of glacier ice is relatively minor and the emergence velocity is low (N. Naito and others, unpublished information). These previous studies indicate that glacial lake formation at debris-covered glaciers will drive lowering of the glacier surface via both ablation and ice dynamics. Hence, glacial lake formation involves a positive feedback to lowering of the glacier surface, meaning that glacial lakes form in association with relatively large amounts of surface lowering. Furthermore, glacial lakes contribute to disintegration of the glacier terminus and acceleration of the rate of lowering of the glacier surface.

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