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Variation and lake expansion of Chubda Glacier, Bhutan Himalayas, during the last 35 years

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Abstract

Chubda Tsho (Chubda Glacial Lake), located in the headwater of Chamkhar River, is one of the largest glacial lakes in the Bhutan Himalayas. To assess the Glacial Lake Outburst Flood (GLOF), map and satellite image analyses, and field investigations were carried out. The results showed the past and present features of the glacier and the glacial lake. The horizontal location of the front of Chubda Glacier has not changed, at least during the last 35 years, and the present surface elevation of the debris-covered part of the glacier has obviously dropped. The area of Chubda Tsho expanded by about threefold through the years from 1967 to 2001. This expansion rate is slightly slower than those of other glacial lakes in the Eastern Himalayas. Assuming that the pace of expansion was constant, the initial water area would have appeared in the late 1950s to the early 1960s. The features of the lower end of the glacier are gravitationally stable under current conditions. However, the existence of collapse scars and the remaining ice core in the terminus suggest the potential danger of failure. In addition, the situation of the rocks and glacial ice on the upper part of the lake, which can be a trigger of GLOF, has not been understood. Therefore, detailed investigations of both the lower part of the glacial lake and the upstream of the glacier are required.

1. Introduction

Severe floods caused by outbursts of glacial lakes have occurred at frequency in many mountain areas of the world during the last half-century due to climatic changes (*e.g.* Lliboutry *et al.*, 1977; Vuichard and Zimmermann, 1987; Xu and Feng, 1994). Glacial lake outburst floods (GLOF) have also occurred in Bhutan in the eastern Himalayas (*e.g.* Gansser, 1970, 1983; Geological Survey of Bhutan, 1999). The last outburst flood in Bhutan originated from Lugge Tsho (Lugge Glacial Lake) in the Lunana region, headwater of Pho Chhu (Pho River), in October 1994. The GLOF killed over 20 people, and caused damage to property on the river (Watanabe and Rothacher, 1996). There are many dangerous glacial lakes similar to Lugge Tsho in Bhutan (*e.g.* Gansser, 1970; Takada, 1992; Ageta and Iwata, 1999; Mool *et al.*, 2001a; Iwata *et al.*, 2002). Hence, investigation of the glaciers and glacial lakes is necessary for disaster prevention in the Bhutan Himalayas.

A large and dangerous glacial lake is plotted in the upper part of the Chamkhar Chhu basin, central Bhutan (Geological Survey of Bhutan, 1999; Mool *et al.*, 2001a). The Geological Survey of Bhutan reported the results of the first field investigation of the lake (Karma *et al.*, 1999). The report recommended investigating the glacier and glacial lake in more detail. The lake was called Churapokto Tsho (code number GLC-5) by the Geological Survey of Bhutan (1999) and Chubda Tsho by Karma *et al.* (1999). In the present study, the lake was called Chubda Tsho. If Chubda Tsho is a dangerous glacial lake, the fertile basin downstream and Chamkhar Town, a major town in Bhutan, remain exposed to risk of severe disaster. Urgent assessment of the danger of GLOF is important not only for Chamkhar basin but also throughout Bhutan. The present study was performed to elucidate the variation in the Chubda Glacier and Chubda Tsho during the last 35 years based on the information from satellite data and field investigations to assess the possibility of an outburst. Previously, the authors reported the variations in Chubda Tsho during the last 11 years (Iwata *et al.*, 2003). The present report provides additional results regarding variations over a longer period in Chubda glacier and glacial lake using other satellite data.

2. Research area and method

The Chamkhar Chhu, also called Bumthang Chhu, flows from north to south in central Bhutan and

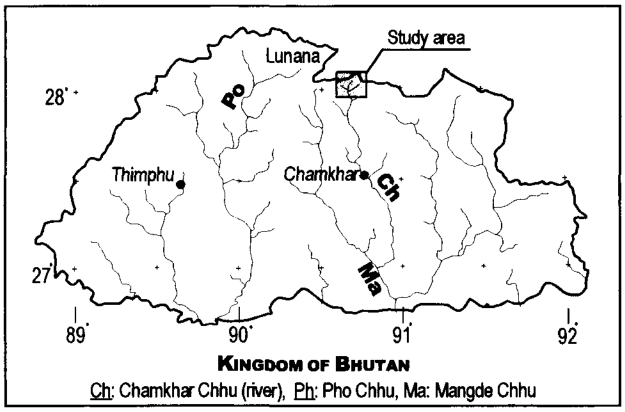

Fig. 1. Map showing the study area and main rivers in Bhutan

confluences with Mangde Chhu in southern central Bhutan (Fig. 1). The northern limit of the Chamkhar Chhu basin, which is comprised of over 6000 m peaks, is bordered on the north by Tibet. The present glacier fronts in this area are located at 4200-4500 m a.s.l. (Gansser, 1983). There are a total of 94 glaciers and 557 glacial lakes in the basin (Mool *et al.*, 2001a). Chubda Glacier (area: 26 km^2) the largest glacier in the eastern branch of the basin, contains Chubda Tsho, the largest lake in the basin.

Topographic maps of the area (1:50,000 in scale, 40 m contour interval) were plotted from aerial photographs taken in the late 1950s and the ground survey carried out in 1961-1963 by the Surveyor General of India (Karma *et al.*, 2003). These maps were used as base maps for this survey. Features of the lake and glacier were investigated using CORONA satellite photographs (40-30 m digitized resolution, taken in January 1967/November 1968) and SPOT satellite images (nominal resolution of 20 m, taken in December 1991/December 2001) in stereoscopic views. Furthermore, the detail shoreline of the Chubda Tsho was obtained from SPOT images and digitally scanned CORONA photos (scanning resolution: 720 dpi), using the Deneba Canvas 7 image-editing program.

The field investigation was carried out in late September 2002, with the cooperation of the Geological Survey of Bhutan. The Base Camp was set up for 5 days, September 23-27, at Domjyon (*ca.* 4400 m a.s.l.), 5 days walk from the northern end of Chamkhar Town (*ca.* 2600 m a.s.l. midstream of Chamkhar Chhu). The field investigation in Chubda glacier was carried out on two days, September 24 and 26. It took 3-4 hours to walk from Base Camp to the lower end of the glacier. Throughout the two days, the weather was not good, cloudy, and it sometimes rained or snowed. However, the geological and topographical survey for the lower part of the glacier was completed.

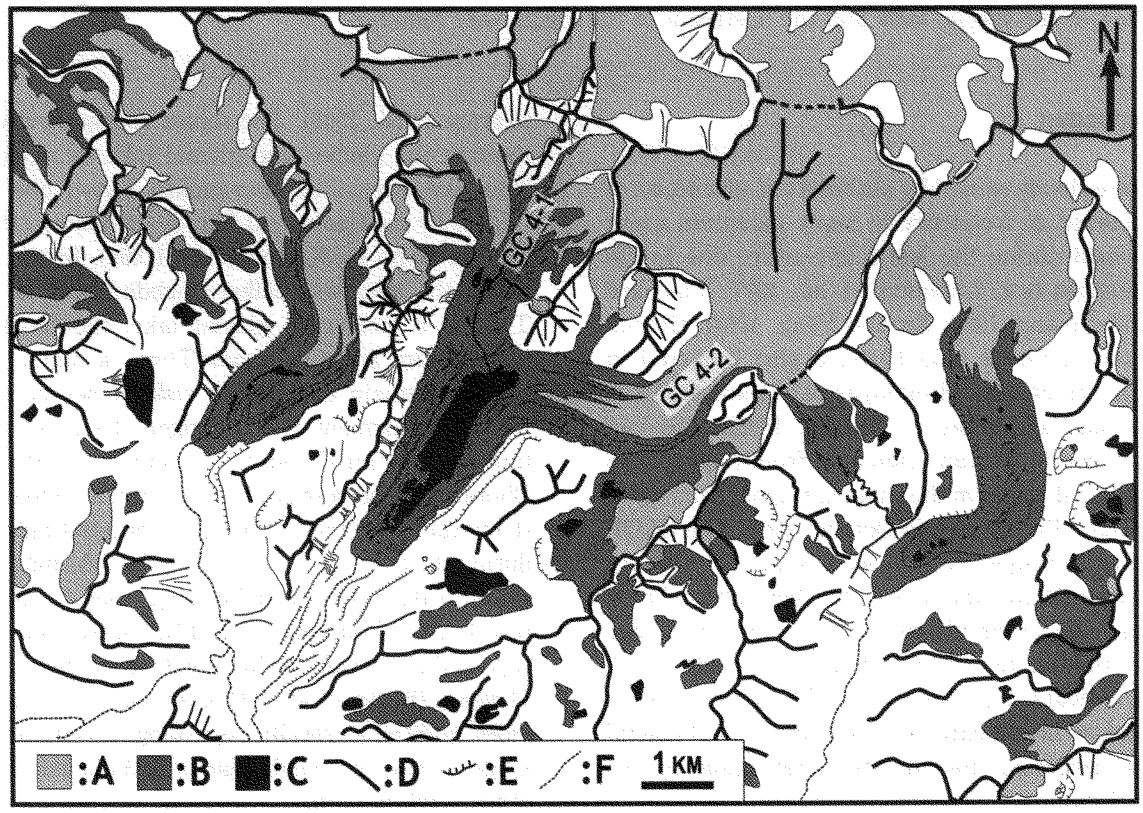

Fig. 2. Chubda Glacier and the surrounding area, the headwater of Chamkhar Chhu. The rectilinear and crank-shaped glaciers join forming Chubda Glacier (center). Chubda Tsho is located on the debris-mantled area of Chubda Glacier. Mapped from SPOT images taken on December 23, 2001. A, Snow and Ice area; B, Debris-mantled area and glacier; C, Lake; D, Ridge; E, moraine; F, Stream.

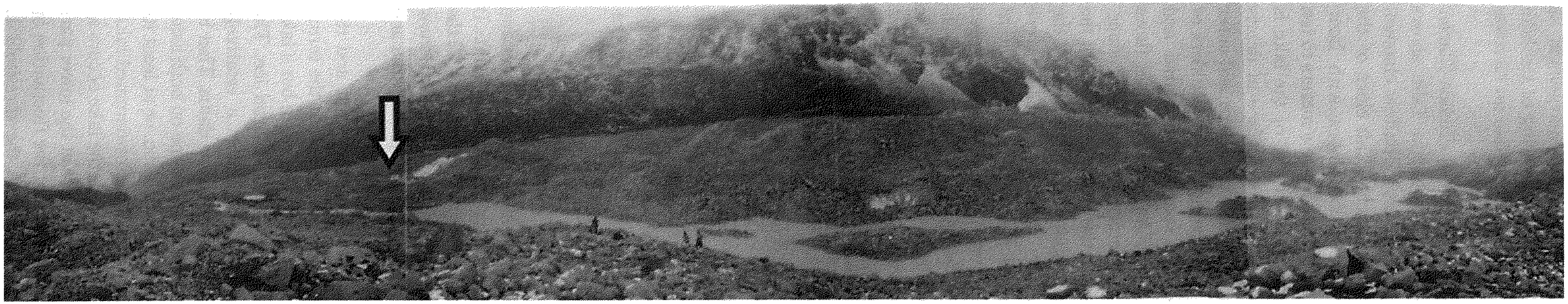

Fig. 3. View from the left bank of the lower part of Chubda Tsho. The flat terminal threshold forms the outlet of the lake water (left). Small islands are distributed in the lower reaches of the lake (center and right). The fresh supraglacial debris-mantled slope borders on sparsely vegetated Holocene/Little Ice Age moraines (far back of center) with a clear boundary. The white arrow indicates the location of Figure. 4. Photo taken on September 26, 2002.

Fig. 4. Ice core exposed below the supraglacial debris 0.5 – 1.0 m in thickness. The location is indicated by the white arrow in Figure 3. Photo taken on September 26, 2002.

Fig. 5. Upstream view from the threshold. Eastern mainstream and western tributaries of the Chubda Glacier can be seen on the far back. The white arrow indicate the boundary between present glacier and shrank its (light color), and basement rock and moraine (dark colored). The black arrow point to an icefall on the eastern mainstream. Photo taken on September 24, 2002.

3. Results and discussion

3.1. Chubda Glacier

Chubda Glacier is a compound glacier with a rectilinear-shaped tributary glacier (GC 4-1, coded by Karma *et al.*, 1999) that stretches down from the north-northeast and joins a crank-shaped main glacier (GC 4-2) that stretches down from the northeast (Fig. 2). The upstream part is the debris-free glacier, while the lower part is covered with a thin debris mantle. The glacier ice is exposed in the faces of small cliffs in the downstream part of the right bank of the glacier (Fig. 3) with a thin covering of surface-debris 0.5-1.0 m in thickness (Fig. 4). The debris in the debris-covered area which were observed by the field investigation, are comprised of light-gray fresh granitic and gneiss boulders with no plant or lichen cover. The debris-covered area could be identified on SPOT images as a light gray area, with distinct borders from the surrounding area composed of dark-colored basement rocks and older moraines. Chubda Tsho occupies the central part of the debris-covered area, which is a nearly flat glacier tongue with some hummocky hills (Figs. 3 and 5). The glacial front of Chubda Glacier forms a steep slope covered with surface debris.

Based on comparison of the topographic maps (late 1950s), CORONA photos (1967/1968) and SPOT images (1991/2001) the lower end of Chubda Glacier has not changed its position between the late 1950s and 2001. Thus, during the last 40 years, the terminus has not experienced any major advance or retreat that could be identified from these data.

3.2. Chubda Tsho and outlet flow

The CORONA photos taken in 1967 and 1968 show that Chubda Tsho already existed as a small lake at this time. Analysis of satellite data from 1967, 1968, 1991 and 2001 showed that Chubda Tsho has expanded in size by threefold over the last 35 years (Fig. 6). The lake has mainly expanded upstream. Extrapolation of the expansion rate during the last 35 years indicated that the initial water area of the lake appeared in the late 1950s to early 1960s. The expansion rate of Chubda Tsho ($0.027\ km^2 a^{-1}$) is slightly slower than those of other glacial lakes in the Eastern Himalayas (Fig. 6). The timing of the appearance of the initial water areas of each glacial lake converge with 1950s to early 1960s similar to Chubda Tsho. Comparison between SPOT images taken in 1991 and those taken in 2001 indicated differences in the shorelines at both the lower and upper parts of the lake. On the other hand, no changes were observed in the middle part of the lake in 1991 to 2001 (Fig. 7). If the water level of the lake increased during the last 10 years, the shorelines should have changed not only in the upper and lower parts of the lake, but also in the middle part. Thus, the lake area enlargement is thought to have occurred due to lowering of the lake bottom caused by ice melting rather than an increase in water level.

The furthest downstream part of Chubda Glacier that functions as threshold of Chubda Tsho shows very complicated features. It has a shallow channel-like water area with many inlets. Both sides of the lake have gentle debris-mantled slopes with hummocky hills ranging in height from a few meters to ten meters (Figs. 3 and 5). The lower end of the lake is bounded by an almost flat narrow surface of debris mantle. This flat surface bounds on the terminal outer slope. Figure 8 shows that the light-gray boulders of the outer side overlie the sparsely vegetated and dark-colored older moraine. An outlet channel flows on the flat surface and stretches to the outer slope. The outlet water seeps into the debris at the end of the flat surface, and emerges again at the lower end of the terminal slope. Shallow debris channels were identified on the terminal slope below the point of disappearance, and the channel beds were composed of unstable and slippery boulders. The sound of submerged water flow could clearly be heard beneath the boulders in the dry channel. The emergence point corresponds to the boundary of the present glacier and the older moraine (Fig. 8). Karma *et al.* (1999) reported the continuous surface flow on the terminal slope in summer, 1999. The difference in the outlet flow between 1999 and 2002 may be due to differences in the outlet discharge amount. Two alluvial cones exist at the lower end of the terminal slope (Fig. 8). The riverbed debris from these alluvial cones was most likely transported by outlet flows from the lake and mass movement, such as debris flow and small collapse due to failures of the threshold.

3.3. Assessment of danger of GLOF

The following points are important in discussion of the risk of an outburst from Chubda Tsho: 1) stability of the lower end of the glacier and lake, 2) the possibility of bedrock, debris, glacier ice and snow avalanches into the lake from the catchment area and ice calving at the upper end of the lake.

1)-1. The features of the glacial front and the lower end of the Chubda Tsho suggest that the terminal part of the glacier is not a moraine dam but a lake threshold composed of debris-mantled dead ice. The wide threshold of Chubda Lake shows a relatively stable form compared to other moraine dams. That is, fresh debris has covered the gentle slope on both sides of the lake indicating that Chubda Tsho, or at least its lower part, is not an unstable moraine-dammed lake, but supra-glacial lake. Expansion of the lake occurs at the upper and lower end, but the rate at the lower part is not high. It can safely be said that the fluctuation of the lake water is stable. Although the threshold is

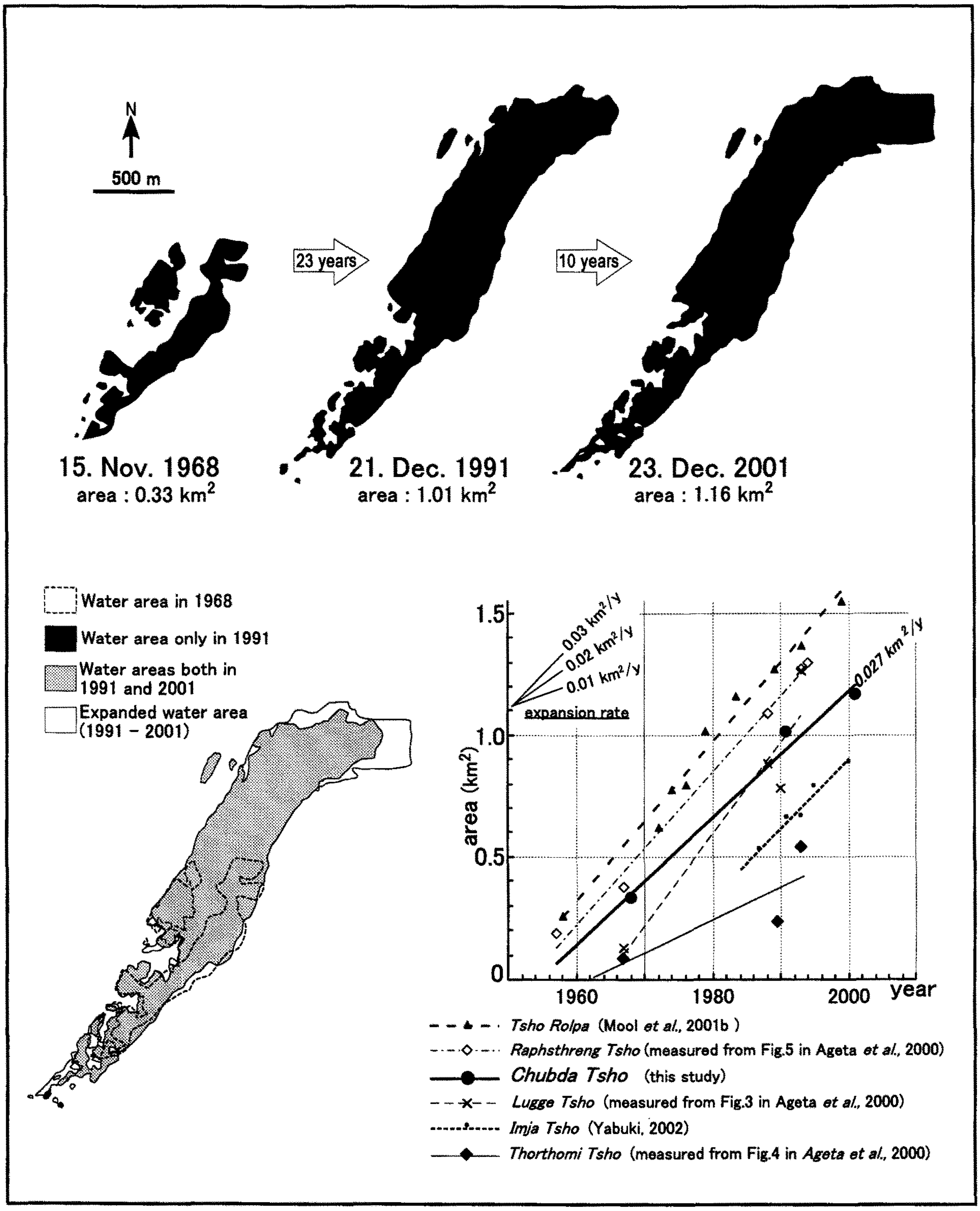

Fig. 6. Top: Changes of Chubda Tsho between 1968 1991 and 2001. The shorelines were determined from CORONA photos and SPOT images. Bottom left: Superimpose display of Chubda Tsho in the same periods. Bottom right: The scatter graph of area - time variation of the lakes in the Eastern Himalayas. The area of Raphsthreng Tsho, Lugge Tsho and Thorthomi Tsho, glacial lakes in the Lunana region are digitized and measured from the figures in Ageta *et al.* (2000). Tsho Rolpa and Imja Tsho in Nepal Himalayas are referred from Mool *et al.* (2001b) and Yabuki (2002).

gravitationally stable under current condition, the existence of past collapse scars on the terminal slope and ice core remaining in the terminus suggest that there is a potential danger of threshold failure.

1)-2. In the area where the debris is thick, the surface flow disappears. The submerged outlet water that gently emerges from the boundary between the debris-mantled and older moraines flows beneath the glacier surface just below the debris-moraine (Fig. 8). The audible sound of submerged water flow and

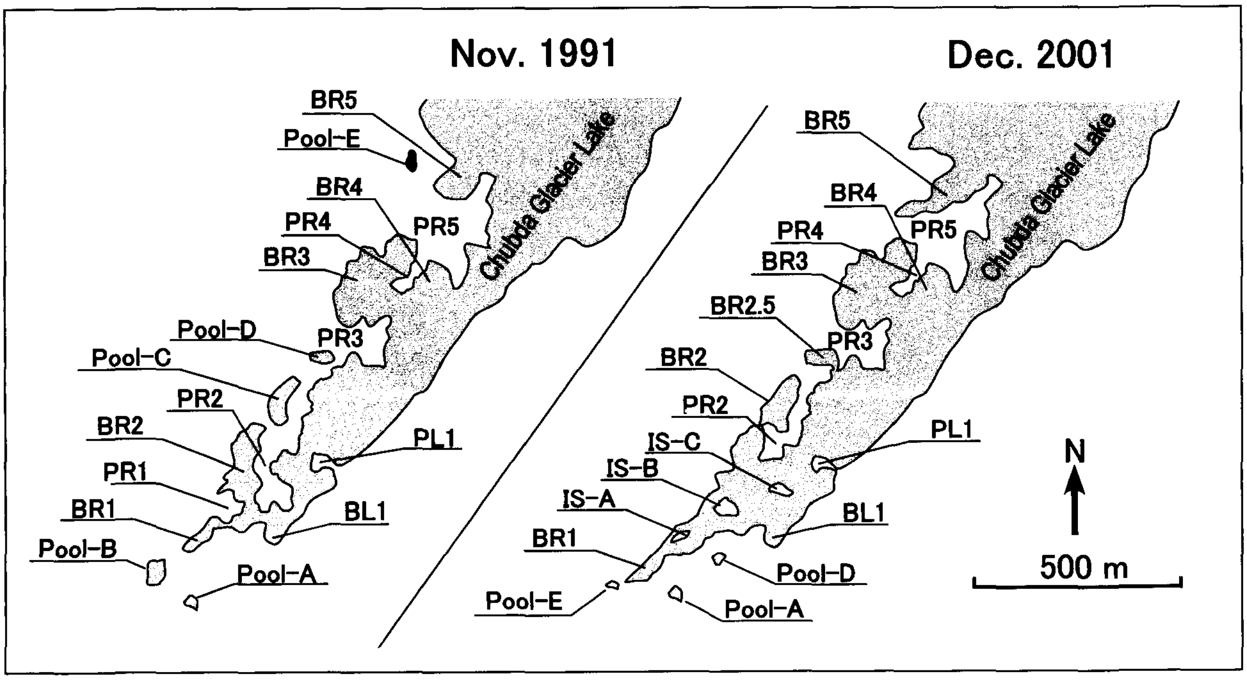

Fig. 7. The middle and lower parts of Chubda Tsho, 1991 and 2001. The peninsulas (PR1 and 2 in 1991) changed to small islands (IS-A and B in 2001) and two ponds (Pool-B, C and D) became small bays (BR 1, 2 and BR2.5) in the lower part of the lake. In contrast, in the middle part of the lake (upper right of figures) no changes were detected in the shorelines over the last ten years.

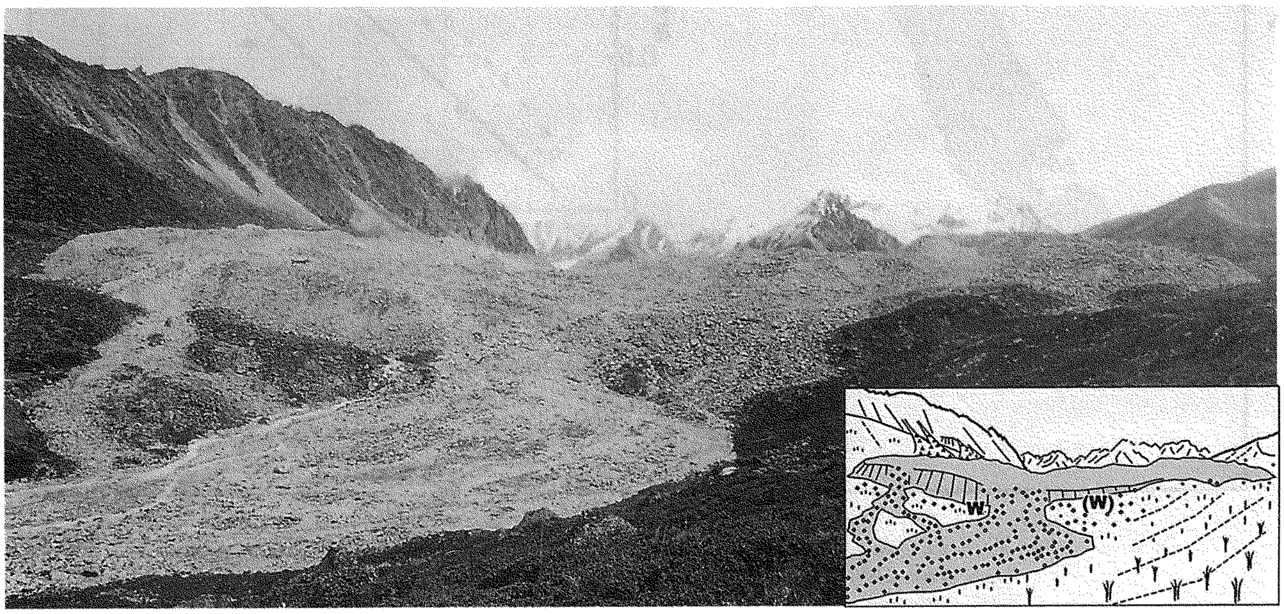

Fig. 8. View of the frontal part of Chubda Glacier forming terminal slopes and flat threshold. Two collapsed scars and associated deposits can be seen on the center and right bank side of the threshold. Seepage water emerges between the older moraine (dark-colored) and younger debris. Photo taken on September 26, 2002. A sketch of the same outline is shown on the lower right. W, emerges point; (w), emerged point in September 1999 (Karma *et al.*, 1999).

gentle emergence as the outlet indicate that the groundwater is not pressurized. Thus, the outlet water could not be a direct trigger of failure of the threshold.

2). The distributions of the bedrock, debris and glacial ice in the surrounding area of the lower part of Chubda Glacier indicate that they may not fall into the lake directly. An icefall in the eastern tributary of Chubda Tsho (GC 4-2) was recognized in a field survey (Fig. 5). Avalanche and ice-block fall seem to pose less of a danger because of the considerable distance between the icefall and the lake. However, there are large taluses on the lake bank at the ridge between the GC 4-1 and GC 4-2 glaciers (Fig. 5) indicating that frequent rock falls have occurred. Moreover, glacial ice facing the uppermost part of the lake directly as an ice wall was recognized on SPOT images. A large rock fall and calving in the upstream may become triggers of a large surge wave and/or a sudden rise in the lake level.

4. Conclusions

The results of the present study indicated that the position of the terminus of Chubda Glacier has not changed during at least the last 40 years, while the area of Chubda Tsho has expanded constantly, increasing in size by threefold, during the last 35 years. The lower end of the lake is relatively stable under current conditions as the threshold of the Chubda Tsho. However, the existence of collapse scars and the remaining the ice core in the terminus indicate the potential danger of failure. Therefore, the lack of detailed information about the rocks and glacial ice around the upper part of the lake needs to be addressed. In conclusion, Chubda Tsho does not pose an urgent risk of GLOF, but detailed inspections of the threshold and upstream region of the lake by glaciologists with knowledge of debris glaciers are necessary.

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