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Topographical survey of end moraine and dead ice area at Imja Glacial Lake in 2001 and 2002

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Abstract

A survey was carried out at the end moraine and the dead ice area of the Imja Glacial Lake in October 2001 and in April 2002 using a digital theodolite with a laser distance meter and differential Global Positioning System (d-GPS). The survey points covered the whole dead ice area and end moraine of the Imja Glacier, and map contours were produced at 5-m intervals. This topographical map will be a significant means to analyze the time variation of the dead ice area and end moraine in future re-mapping. Changes in the lake level and the spillway on the dead ice area since 1994 were also analyzed in comparison with the measurements in 1994 by Watanabe *et al.* (1995).

1. Introduction

There are many glacial lakes in the world, for example in South America, New Zealand and Himalayas (Lliboutry, 1977; Lliboutry *et al.,* 1977a; Lliboutry *et al.,* 1977b; Kirkbride, 1993). Since there are many debris-covered glaciers there, those glaciers can build relatively huge moraines, and moraines tend to dam up meltwater after decline in the glacier surface level.

There are two types of glaciers in the Himalayas (Moribayashi, 1974); one is debris-free and the other is debris-covered. Debris-free glaciers in the Himalayas are shrinking more rapidly than glaciers in other regions of the world (Fujita *et al.,* 1997). Moreover, the shrinkage of debris-free type glaciers accelerated in the 1990s (Fujita *et al.,* 2001a; 2001b). Debris-covered glaciers have also been shrinking because their surfaces are declining (Inoue and Yoshida, 1980), and there are many glacial lakes at the terminus of the glaciers. Yamada (1993) estimated that some glacial lakes have expanded at the glacier terminus of the debris-covered glaciers since the 1950s or 1960s. Those were surrounded by end and lateral moraines and dead ice area (Yamada, 1998; Ageta *et al.,* 2000; Iwata *et al.,* 2002; Komori *et al.,* 2004). The dead ice may have remained beneath the moraine, and the strength of the moraine would decrease due to the melting of the dead ice.

From compared bathymetric maps made in 1992 and in 2002, Sakai *et al.* (2003) concluded that the surface area of the Imja glacier lake in 2002 has grown to become 30% larger than in 1992. The stored water volume has become 28% more than in 1992, although the average depth has decreased.

Glacier ice remained between end moraine and lake at the Imja glacial lake. And the lake was dammed by the glacier ice (dead ice) directly. Based on the survey at Imja Glacial Lake, Watanabe *et al.* (1995) reported that the lake level fell and was close to ground level, and the possibility of outburst from the lateral moraines has diminished now from the survey of one cross section. However, they also said that it is necessary to assess the lowering of the surface of

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the dead ice area since the spillway on the dead ice area underwent a dramatic change.

In this study, field surveys of the moraine and dead ice area have been carried out to clarify the positional relationship among the moraine, dead ice area and Imja Glacial Lake. The relative height between the lake level and river bed was analyzed to clarify the portion where there was the possibility of outburst. Change of spillway on the dead ice area was also analyzed in comparison with the measurements in 1994 by Watanabe *et al.* (1995). After several years, the variation in the lowering of the moraine and dead ice area can be clarified by re-survey.

2. Study area

A survey was carried out on Imja Glacial Lake located in the Khumbu region of the Nepal Himalayas as shown in Fig. 1. The lake is located 6 km south of Mt. Everest (Sagarmatha in Nepalese; Qomolungma in Chinese) and the south foot of the Mt. Island Peak as shown in Fig. 2. The lake formed at the terminus of Imja Glacier. The Imja Glacier is a debris-covered type glacier and the Lhotse Shar Glacier has con-

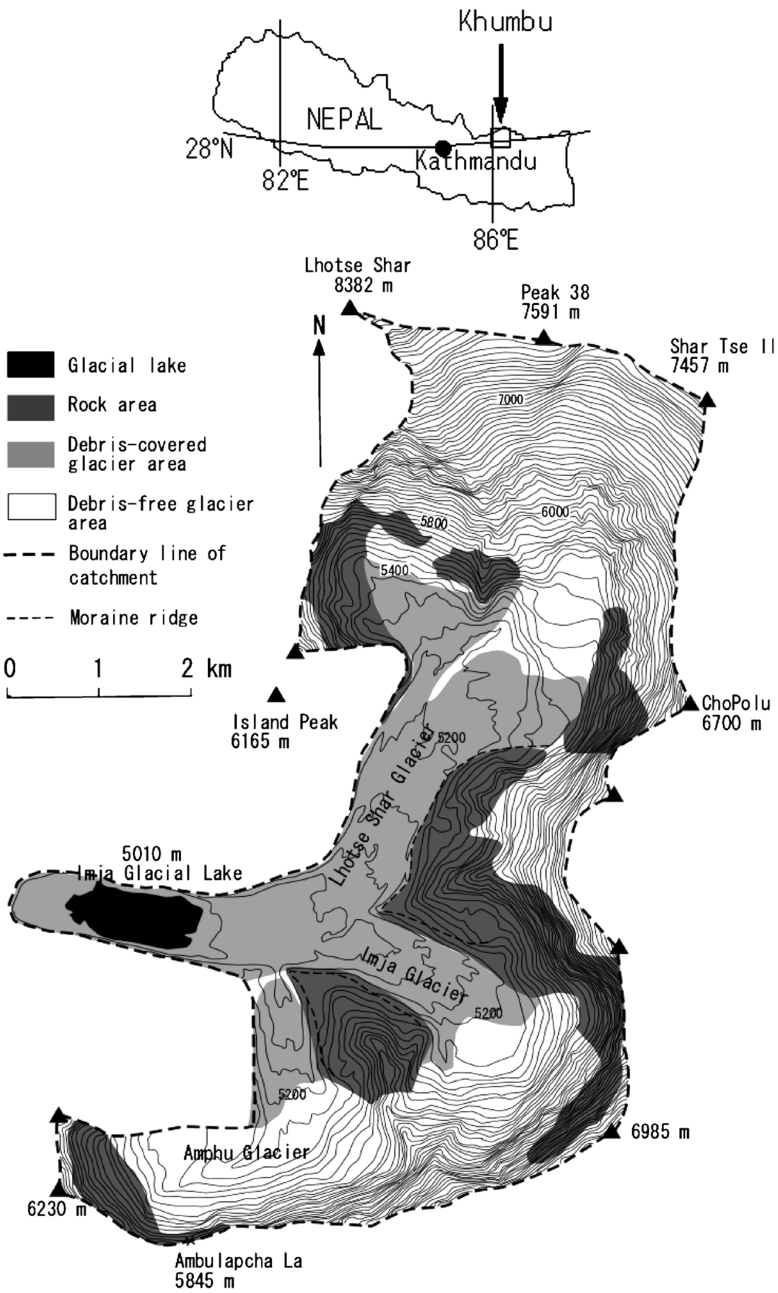

Fig. 1. Location of Khumbu region (above). Topographical map of the basin of Imja Glacial Lake (below), modified from map produced by the Survey Department of His Majesty's Government of Nepal in co-operation with the Government of Finland (Sheet No. 2786 04, SAGARMĀTHĀ). Map compiled from 1: 50 000 scale aerial photograph of 1992. Field verification done in 1996.)

Fig. 2. Photograph of Imja Glacial Lake from left side, BM 20. 'Island Peak' can be seen in front.

verged with it. The Ampbu Glacier also converged with the Imja Glacier, but now no longer is in contact with it.

Watanabe *et al.* (1995) reported that glacier ice was exposed in 1994 between the end moraine and Imja Glacial Lake, which they termed "Dead ice" in their paper. Therefore, we call this the "dead ice area" between the end moraine and Imja Glacial Lake.

There were several supra-glacial ponds in 1955 near the terminus of Imja Glacier (Watanabe and Hammond, 1994; Yamada, 1993), and they became one huge lake from 1975 to 1984 based on aerial photographs (Quincey *et al.,* 2005). Yamada (1993) measured the depth distribution of the lake and made a bathymetric map in 1992. Watanabe *et al.* (1995) carried out a survey of the cross sections at the dead ice area and moraines. They concluded that the possibility of outburst from the lateral moraine has diminished based on their survey of the relative height between the lake level and ground level at the side of the lateral moraine. But, they reported another possibility, namely that the outburst will occur by meltdown of the dead ice area, particularly along the spillway.

3. Survey

Surveys of the dead ice area and end moraine of Imja Glacial Lake were carried out from 26 October to 6 November, 2001 and from 7 to 8 April, 2002. A digital theodolite with the laser distance meter (SOKKIA SET2100) was used in 2001, and a differential Global Positioning System (d-GPS) (CMC Co., Ltd.) was used for the survey in 2002.

The error of the digital theodolite with the laser distance meter was $\pm(2+2\,\mathrm{ppm}\times\mathrm{D})$ mm in distance, where D is the measured distance, and the accuracy of azimuth and elevation angles were 2 seconds. All measured distance was less than 1000 m, so the error was less than 10 mm. However, the error of measurements taking into account the mirror setting and network of benchmarks would be ± 0.1 meter.

The digital theodolite with the laser distance meter was settled at a benchmark and measured the azimuth, elevation angle and distance of the measurement point on the basis of another benchmark. We did not measure survey points on the basis of magnetic north since it is difficult to fit the digital theodolite with the laser distance meter to magnetic north with sufficient accuracy. Therefore, the measured data were based on benchmarks with no concern with deviation from magnetic north.

The survey using the digital theodolite with the laser distance meter was conducted as follows: One person engaged in operation of the digital theodolite with the laser distance meter set one of the benchmarks, and the other one or two persons, who carried a reflector, decided the points to be measured, moving along on the dead ice area, end moraine and at the foot of the moraines. Measured points included remarkable topographical features such as peaks, cols, ridges, bottom lines of trenches, pond edges, and edges of spillways.

A Global Positioning System (GPS) measures absolute positions on the earth with low accuracy (more than 10 meters), although the accuracy of a relative position between fixed master receiver and remote receiver (mobile station) using d-GPS is on the order of cm. If the master station is removed once, it is necessary to measure the benchmark again.

Instrumental error of the d-GPS depends on the distance between the base station and the reference station. The maximum distance was less than 1 km, so the error was within 0.2 m since the error was 0.2 m when measured distance was 1km according to CMC Co., Ltd.. Those measurement errors within 0.2 m are accurate enough to discuss the variation in topography of the dead ice area and end moraine in future measurement, and those data can be treated as the same data observed by a digital theodolite with a laser distance meter.

One GPS receiver was fixed at the top of the pole in the Base Camp as a reference station, and the other was the mobile station in the backpack of the person who walked on the dead ice area and moraine. The data logging interval was one second. Therefore, the trail of a person with a mobile GPS receiver can be measured with high density. It can not be measured by d-GPS in a dangerous area, such as a steep slope since a person with a mobile receiver can not walk there.

Data processing of d-GPS measurement from those data obtained at removal and reference stations was performed using GrafNav software (Waypoint Consulting Inc.). Processed data are represented by the Universal Transverse Mercator system (UTM) (Zone: 45): north, east, and altitude. Measured data can not be processed when the number of receivable Satellites becomes less than 4. Some measured data at the foot of the end moraine could not be processed using GrafNav software because of the insufficient of number of data received from satellites. On the other hand, all data measured on the dead ice area could be processed.

Nine benchmarks were set on and around the Imja Glacier to measure the topography of moraine

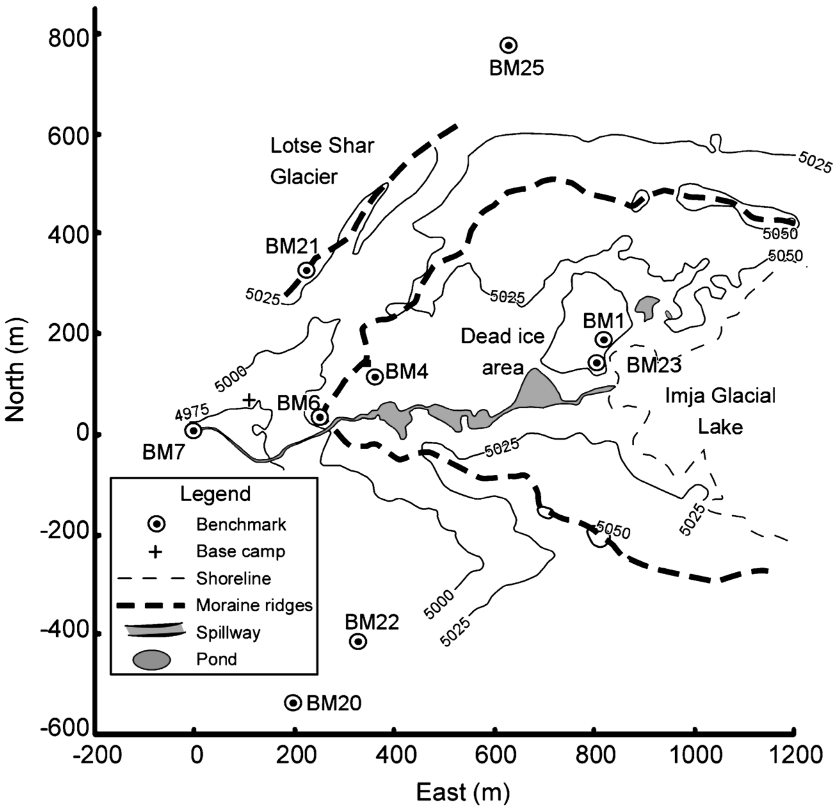

Fig. 3. Location of benchmarks on and around dead ice area and end moraine. Coordinate is represented with BM7 as zero.

Table 1. Locations of benchmarks in the Universal Transverse Mercator (UTM) (Zone 45).

	UTM position (zone: 45) Projection: Transverse Mercator, Datum: India-India, Ellipoid: Everest 1956			Relative location from BM7		
	East (m)	North (m)	Elevation (m)	East (m)	North (m)	Elevation (m)
BM1	491594.29	3085976.33	5031.99	815.53	183.11	67.17
BM4	491138.17	3085898.76	5018.83	359.41	105.54	84.64
BM6	491029.52	3085819.57	5015.75	250.76	26.36	50.93
BM7	490778.76	3085793.22	4964.82	0.00	0.00	0.00
BM20	490973.95	3085254.44	5141.78	195.19	−538.78	176.96
BM21	491004.21	3086110.41	5039.27	225.45	317.19	74.45
BM22	491106.91	3085378.66	5065.00	328.15	−414.56	100.18
BM23	491585.42	3085928.58	5028.93	806.66	135.36	64.11
BM25	491402.34	3086560.95	5049.46	623.58	767.74	119.63

and dead ice area in 2001. Locations of all benchmarks in the Universal Transverse Mercator (UTM) (Zone: 45) projection were summarized in Table 1 and shown in Fig. 3. The relative distance and direction of each measurement point from the network of benchmarks were calculated. BM7, BM23 and BM4 were measured again by d-GPS in 2002. Then, the survey data using the digital theodolite with the laser distance meter obtained in 2001 overlapped the data surveyed using d-GPS in 2002 by the Universal Transverse Mercator system. As mentioned above, the accuracy of the relative position was within 0.2 m, although the accuracy of the absolute position was several meters. Therefore, relative positions of all points from the benchmark, BM7, are also listed in Table 1.

The four benchmarks of BM1, 4, 6, and 23, were on the dead ice area or moraine. Therefore, there is the possibility that those 4 benchmarks will be removed in the future by melting glacier ice under debris. On the other hand, presumably there is no ice under BM7, 20, and 22, so, those 3 benchmarks can be used as fixed points in the re-survey.

Measurements were done at 1,338 points and 41,547 points by laser distance meter and by d-GPS, respectively. Contours of the map were created using Geographical Information System (GIS) software (TNTmips ver. 6.7; Micro Images Inc.) based on the observed data. The Minimum Curvature method was applied to surface fitting. This method applies a two-dimensional cubic spline function to fit a smooth surface to the set of input elevation values. The computation requires a number of iterations to adjust the surface so that the final result has a minimum amount of curvature.

The west side of the shoreline of Imja Glacial Lake was also surveyed in 2001 using digital theodolite with the laser distance meter in order to connect the bathymetric map and the map of end moraine and dead ice area. The spillway on the dead ice area has been surveyed at more than 50 points and by photographed in order to be incorporated into the topographical map.

4. Results

Figure 5 shows the completed topographical map of the dead ice area and end moraine of Imja Glacier. The scale of the original map is 1: 10000. The contour intervals are 5 m. A bathymetric map of Imja Glacial Lake was also combined based on d-GPS measurement at BM 4, 7 and 23.

Densities of measurement points were shown in Fig. 4. A survey using d-GPS was carried out on the right side of the dead ice area since the surface can not be seen from all benchmarks because of the rugged topography. Therefore, high-density areas are concentrated on the right side. The precision of the map shown in Fig. 5 depends on the density of the measured points (Fig. 4). The precision is high where the measurement density is high, and *vice versa*. The area where measurement was carried out using d-GPS was very high, since the logging time of the d-GPS was 1 second. d-GPS was used to measure the rough terrain because of impenetrability by the digital theodolite with the laser distance meter. d-GPS was also useful in this regard since the logging interval of d-GPS was one second, and we could observe many measurement points. However, one should note the bias in the measurement point density because with d-GPS observation the measurement points concentrate along accessible area.

The roughness of the surface at the dead ice area was high at the end moraine side and low at the lake side from the range of the contour line. The spillway was located at the lowest portion of the dead ice area and moraine area, and the slope surrounding the spillway was relatively steep. There was, however, no exposed ice at the dead ice area of Imja Glacier during the survey period in 2001 and 2002. There was much exposed ice contacting the lake water in 1973, to judge by a photograph taken by Japanese Glaciological Expedition of Nepal mentioned by Watanabe *et al.* (1994). Exposed ice can melt very rapidly since the surface is not insulated by rock debris (Sakai *et al.,* 2002). It is important to check for possibility exposed ice on a dead ice area or moraine in forthcoming studies.

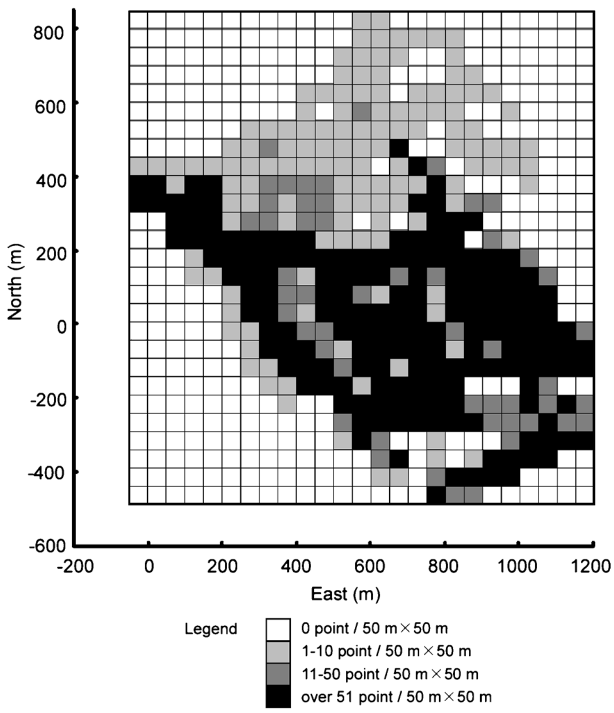

Fig. 4. Density of points for topographic measurements of dead ice area and end moraine. Coordinate is the same as in Fig. 3.

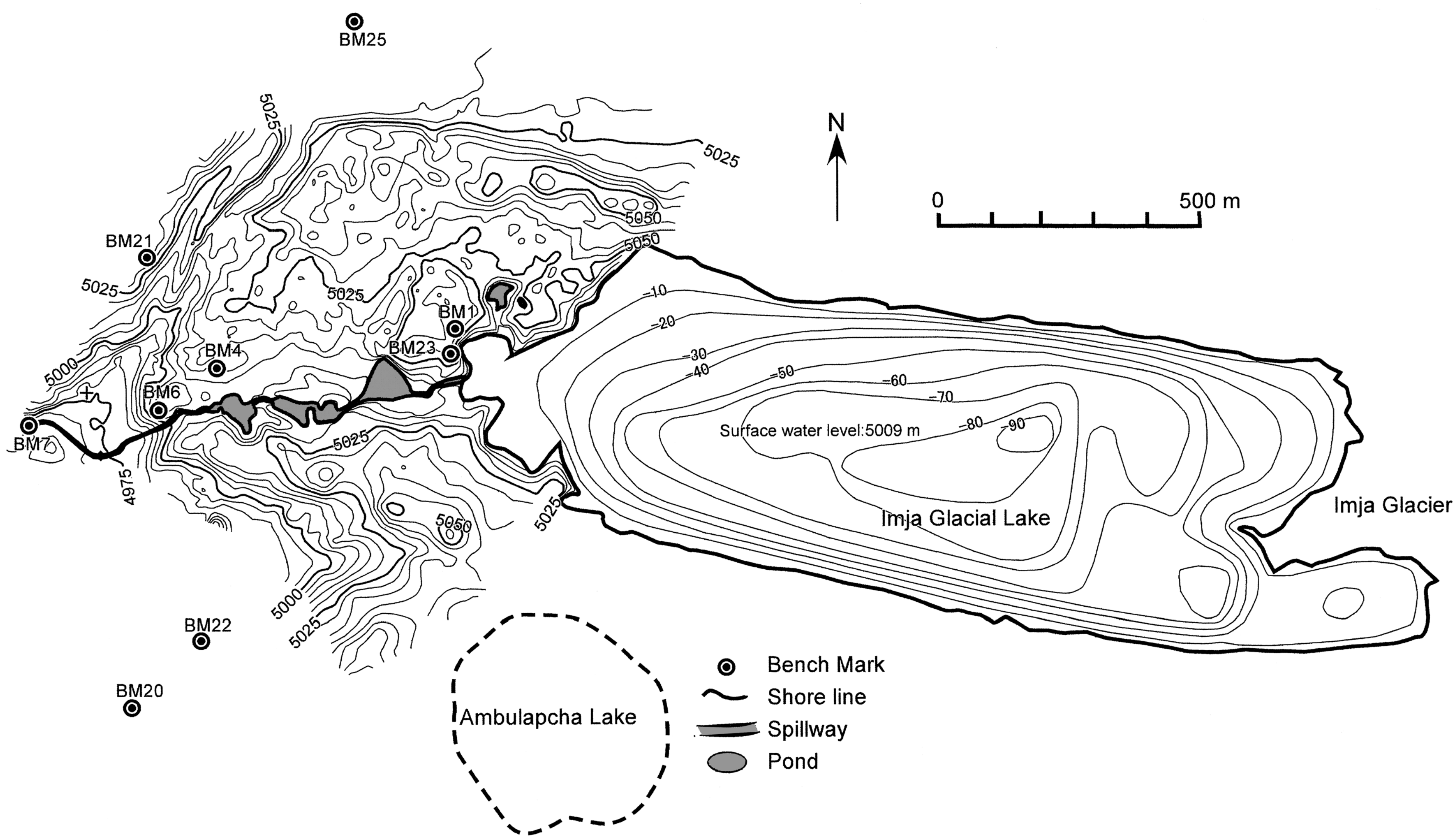

Fig. 5. Topographical map of dead ice and end moraine of Imja Glacier and bathymetric map of Imja Glacier. Contour of moraine and dead ice area was at 5-m intervals. Depth contour of the lake is expressed as relative height to water surface level (5009 m a.s.l.) at 10-m intervals.

5. Discussion

Watanabe *et al.* (1995) reported that the water level declined 10.3 m from 1989 to 1994, assuming that the BM-B did not move during that period. Unfortunately, the BM-B could not be found during our field surveys in 2001 and 2002. The altitude of BM-B was 5035±5 m a.s.l. as shown in Fig. 6, which overlapps Fig. 8 in Watanabe *et al.* (1995) based on the location of the end moraine. The water level of the lake was 5009 m a.s.l. in 2001 by our observation. Therefore, the relative height between BM-B and the water level was 26±5 m ((5035±5)-5009 m) in 2001. Watanabe *et al.* (1995) found that the relative height was 25 m in 1994. Then, the change in water level of the lake was in the range of error.

The spillway in 1994 (Fig. 8 in Watanabe *et al.* (1995)) also overlapped the topographical map in 2001 as seen in Fig. 6. The spillway on the dead ice area in 2001 flowed along the southern side of the cone (indicated as "C" in Fig. 6), as opposed to its northern side in 1994. The spillway changed the path of flow from 1994 to 2001. The area where there had been a spillway in 1994 was at a relatively low altitude and flat in 2001, as shown in Fig. 6. Unfortunately, Watanabe *et al.* (1995) did not measure the cross section around the cone, 'C', in Fig. 6. Therefore, we have no information on the topography there in 1994. There was no other change in the path of the spillway from 1994 to 2001.

A Glacial Lake Outburst Flood (GLOF) can occur where the height of the lake surface is higher than the river bed i.e., the foot of the moraine. The level of Imja Glacial Lake was 5009 m a.s.l. Thus, the area with an altitude less than 5010 m a.s.l. was shaded in Fig. 6. There was no area below the lake level on the right (north) side of the moraine of Imja Glacier as indicated by Watanabe *et al.* (1995). Therefore, there is no possibility that a GLOF occurs by collapse at the right of the moraine at the present lake level. On the other hand, the relative height of the foot of the end moraine in relation to the lake surface level was 30 m at the left. Thus, were the left side of the end moraine or dead ice to melt or collapse, a GLOF would occur. And if the left side of the moraine and dead ice area were to completely collapse, the lake water up to 30 m depth would flow away. The water volume reached $20.6 \times 10^6\,m^3$. It is necessary to continue to observe carefully the topographical change of the moraine and dead ice and the change in the Imja Glacial Lake level.

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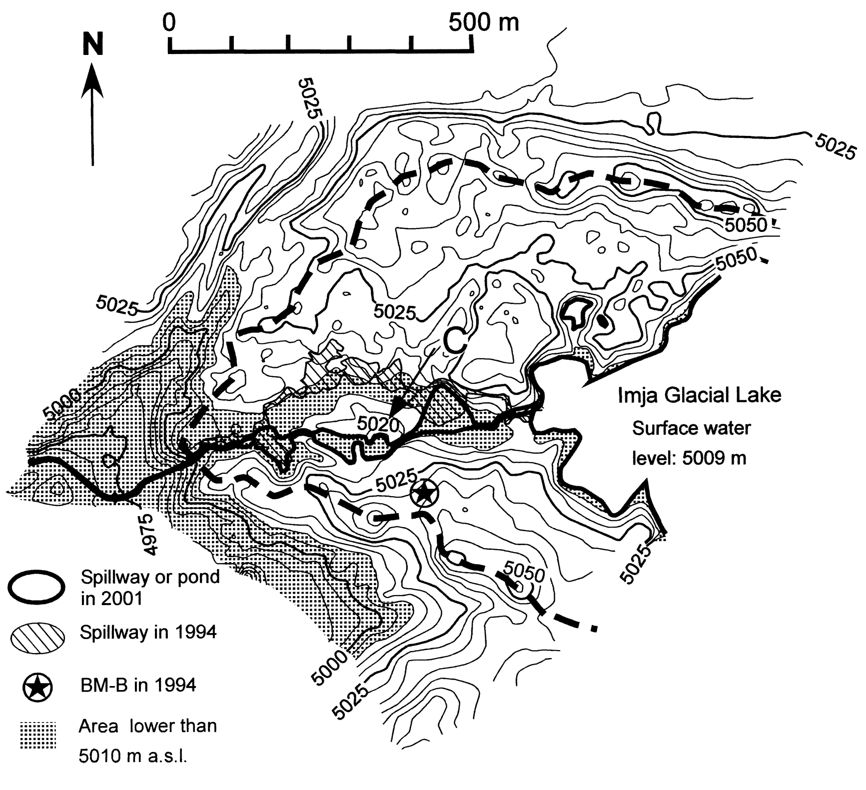

Fig. 6. Topographical map of dead ice and end moraine of Imja Glacier. Shaded area indicates altitude is less than 5010 m a.s.l. Hatched area indicates spillway in 1994 and star mark shows BM-B, with reference to Fig. 8 in Watanabe *et al.* (1995).

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