ESTIMATION OF THE ICE THICKNESS OF CIRQUE GLACIERS BY THE GRAVIMETRIC SURVEY AT THE YAMATO MOUNTAINS, EAST ANTARCTICA

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Abstract: As part of geophysical investigations by the 22nd Japanese Antarctic Research Expedition (JARE-22), the gravity measurements were carried out along the inland traverse route and in the Yamato Mountains region in 1981. In the latter area, the depth of subglacial rock surfaces under two peculiar cirque glaciers and one outlet glacier was estimated by gravity measurements, in addition to the investigation of the gravity field in ice-free areas. The results are as follows: 1) On the west side of Massif B, the bedrock height decreases steeply with a gradient of 300 m/1000 m from the shallow cirque glacier bottom to the west, 2) the deepest bedrock in the cross profile near the terminal part of the Nizi-no-kubo cirque glacier in Massif D reaches 265 m, 3) the relationship among depth of cirque bottom, depth of the neighboring ice sheet, and surface features of cirque glaciers and the ice sheet suggest that the cirques were formed mainly prior to the ice sheet cover, and that the tectonic displacement might have been responsible for the deep subglacial bottom of the surrounding area, 4) the subglacial bedrock topography suggests that the fault line runs along the southern foot of Massif G, and the surface configuration of the outlet glacier between Massifs F and G seems to be influenced not only by snow accumulation controlled by surface topography but also by subglacial rock topography.

1. Introduction

The Yamato Mountains are situated 200 km southwest of the head of Lützow-Holm Bay, East Antarctica. The earth sciences feature in this region has been investigated by several field parties of the Japanese Antarctic Research Expedition (JARE) since 1960. For example, the characteristics of landforms and geomorphic development were discussed (YOSHIDA and FUJIWARA, 1963; YOSHIDA, 1983), and geological and petrological studies were carried out (KIZAKI, 1965; SHIRAISHI *et al.*, 1983). Glaciological and glacio-meteorological investigations were also done (ISHIDA, 1962; SHIMIZU *et al.*, 1978; KOBAYASHI, 1979).

It is important to know topographic features not only of ice-free areas but of ice-covered areas for elucidating geomorphic development and also for discussing the crustal nature of the mountainous region. Three methods are used to reveal the subglacial topography; the seismic reflection, the radio-echo sounding, and the gravity measurement. The seismic reflection method had been used widely in inland traverse surveys in the 1960s, supplemented by gravity measurements. But in some cases this method has some difficulty to obtain clear reflection records obstructed by a thick firn layer of the ice sheet, and requires laborious field operation. The air-borne radio-echo sounding took over the seismic reflection in the latter part of the 1960s and has yielded fruitful results. The radio-echo soundings from the ice surface (NARUSE and YOKOYAMA, 1975; OMOTO, 1976) and from the air (WADA and MAE, 1981) were conducted in and around the Yamato Mountains region by JARE. This method, however, has also some problems in determining ice thickness. It is sometimes difficult to identify a real echo by subglacial rock surface from multiple radar echos (MAE, 1978). In addition, a specific characteristic of an ice-radar used by JARE is not suitable for sounding of shallow subglacial rock surface. Furthermore, the rugged subaerial and subglacial topography of the Yamato Mountains and the moraine-covered ice surfaces obstruct the use of seismic and radio-echo methods. On the other hand, determination of ice thickness by gravity measurement is an indirect method and calls for the assumption that the Bouguer anomaly (crustal structure) is equal at the observation sites for the estimation of ice thickness. But the gravity method is much more convinient in the field in comparison with other methods. Therefore, it is thought to be an adequate method for preliminary investigation and for the use in areas of rugged topography.

The gravity measurements by the JARE-22 traverse party from Syowa Station to the Yamato Mountains region were carried out with the use of LaCoste-Romberg gravimeter Model-G (G-183) in November and December, 1981. Gravity stations were 68 in number along the inland traverse route and 50 (21 in ice-free areas and 29 on the ice) in the Yamato Mountains region including the Minami-Yamato Nunataks and the Kabuto Nunatak areas. All the results of gravity measurements were reported by KAMINUMA and NAGAO (1984). They tabulated gravity values, free air anomalies and simple Bouguer anomalies after instrumental drift and earth tide corrections using the system of the Japan Gravity Standardization Net 1975 (SUZUKI, 1976). The ice thickness estimation on two peculiar cirque glaciers and one outlet glacier in the Yamato Mountains is reported in the present paper.

2. Data Analysis

Figure 1 shows the locations of the whole gravity stations in the Yamato Mountains region. The name of gravity station is referred to KAMINUMA and NAGAO (1984). The stations of YMT03–1 ~6, YMT04, YMT07–1 ~4, YMT15 and YMT16–1 ~9 are concerned with this study.

For the estimation of ice thickness, the following parameters were adopted.

Density of the bedrock; $\rho_1=2.67$ g/cm^3

Density of the ice; $\rho_2=0.90$ g/cm^3 .

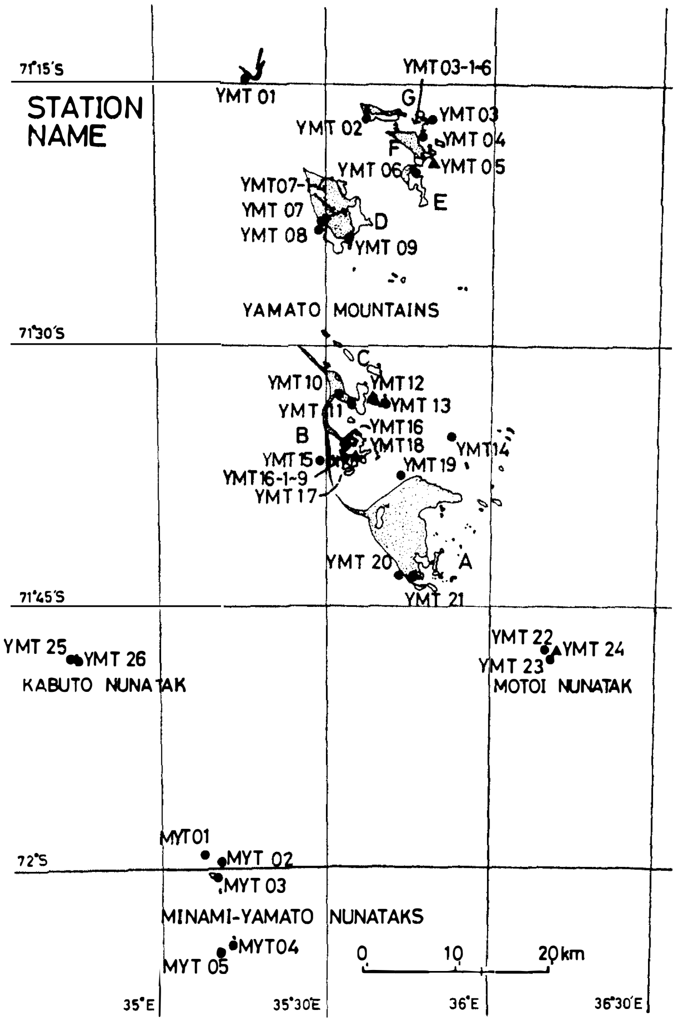

Fig. 1. The location of the gravity station. Station names correspond to those in KAMINUMA *and* NAGAO *(1984).*

The method of ice thickness estimation is as follows. In an ice-free area, after the gravity value determination, we calculated both free air and simple Bouguer anomalies, adopting the model of infinite plain. In order to estimate the ice thickness at the observation site, we assumed that the simple Bouguer anomaly of the nearest ice-free area station was identical within this limited observation area. If we assume the above condition, the ice thickness at the observation site is expressed by the following equation:

$$IC=[(g_b-g_o)-(\gamma_b-\gamma_o)+(0.3086-0.0000965)(H_b-H_o)$$
$$-2\pi G\rho_1(H_b-H_o)]/[2\pi G(\rho_1-\rho_2)]\ ,$$

where IC is the ice thickness of the observation site in meter, g the observed gravity value in mgal, γ the normal gravity value in mgal, G the universal gravitation constant, and H the altitude in meter, respectively. The subscripts of b and o indicate the referred base station in the ice-free area and the station at which we want to know the ice thickness. 0.3086 and 0.0000965 are a free air gravity gradient and a term

Table 1. The results of gravity measurements and estimation of ice thickness.

Station name	Gravity value (mgal)	Normal gravity (mgal)	Free air anomaly (mgal)	Bouguer anomaly (mgal)	Latitude deg. min.	Longitude deg. min.	Height (m)	Ice thickness (m)	Remarks
	982	982							
YMT03	247.400	681.616	121.0	−80.0	71 17.0	35 49.0	1797	0.0	Massif G
03–1	243.175	681.800	110.8		71 17.2	35 48.5	1778	109.8	
03–2	241.244	682.076	108.8		71 17.5	35 48.0	1779	137.2	
03–3	243.251	682.352	111.5		71 17.8	35 47.5	1782	105.6	
03–4	232.223	681.892	94.5		71 17.3	35 42.5	1761	303.8	
03–5	227.201	682.076	88.3		71 17.5	35 42.5	1758	382.0	
03–6	216.163	682.260	77.7		71 17.7	35 42.5	1760	528.0	
YMT04	251.827	682.536	119.3	−79.8	71 18.0	35 47.0	1780	0.0	Massif F
YMT07	265.340	686.941	105.0	−85.7	71 22.8	35 29.0	1704	0.0	Massif D
07–1	252.443	686.849	92.2		71 22.7	35 30.0	1704	172.7	
07–2	245.387	686.666	87.1		71 22.5	35 31.2	1710	249.4	
07–3	244.442	686.483	85.8		71 22.3	35 32.4	1708	265.0	
07–4	256.620	686.391	99.3		71 22.2	35 33.6	1712	88.9	
YMT15	198.113	704.220	67.0		71 41.8	35 29.7	1855	640.8	Base camp
YMT16	252.184	698.972	107.8	−93.0	71 36.0	35 38.5	1795	0.0	Massif B
16–1	253.684	698.972	108.4		71 36.0	35 38.5	1792	−12.3	
16–2	252.831	698.972	105.1		71 36.0	35 38.5	1784	20.4	
16–3	247.063	698.972	103.7		71 36.0	35 38.5	1798	61.0	
16–4	244.884	698.972	104.2		71 36.0	35 38.5	1798	66.6	
16–5	244.249	698.972	104.8		71 36.0	35 38.5	1811	64.6	
16–6	244.295	698.972	105.2		71 36.0	35 38.5	1812	61.3	
16–7	244.063	699.426	103.9		71 36.5	35 32.0	1810	75.8	
16–8	223.985	699.426	95.5		71 36.5	35 32.0	1848	245.8	
16–9	212.158	699.426	84.6		71 36.5	35 32.0	1851	397.3	

of atmospheric correction by the Gravity Formula 1967 in mgal/m. In the Gravity Formula 1967, γ is expressed by the equation:

$$\gamma=(A\cdot GE\cdot\cos^2\phi+B\cdot GP\cdot\sin^2\phi)/\sqrt{(A^2\cos^2\phi+B^2\sin^2\phi)}\ ,$$

where A is the equatorial radius of the earth (6318.14 km), B the polar radius of the earth ($B=A(1-1/298.257)$), GE the gravity value at the equator (978031.846 mgal), GP the gravity value at the poles (983217.728 mgal), and ϕ the geographic latitude, respectively. The results of this study are shown in Table 1.

3. Accuracy

In these gravity measurements, it is considered that the relative accuracy of the gravity values between the stations is less than 0.1 mgal, because the observation of each area was carried out within several hours. The tear did not occur and instrumental drifts were less than a few tens of microgal in each measurement. The leveling was made with the use of Paulin System Model MM-1 altimeters. The accuracy of relative height determination between two neighboring stations would be less than 2 m. An error of 0.1 mgal of gravity value causes 1.3 m of ice thickness error and an error of 2 m in relative height does 5.3 m error.

Terrain correction at gravity stations was not made in this investigation. As shown in Table 1, the minus ice thickness value was obtained at the YMT16–1 station. This is an unrealistic result. This station is located very close to Aka-kabe Bluff of Massif B. The large mass of Aka-kabe Bluff might have affected the measured gravity value.

4. Results and Discussions

Figure 2 shows the location of gravity stations and the ice thickness profile in the Massif B area. Stations YMT16–1 ~ 6 are located on a small cirque glacier. It has a flat or slightly depressed ice surface which continues smoothly to the ice sheet in the west. The cirque bottom is covered with thin ice up to 67 m thick, and the bedrock surface inclines steeply to the west through the break of slope. This profile seems to indicate that the cirque had been formed prior to the inundation of the ice sheet or in the early stage of the ice sheet shrinkage. The abrupt decrease in elevation of the subglacial bedrock in the west also suggests that the mountains have been tectonically uplifted.

Figure 3 shows the result of measurements in Massif D. The measuring line was set across the terminal part of the Nizi-no-kubo cirque glacier. The surface of the glacier is rather flat and continues smoothly to the ice sheet to the northwest. The northwestern half of the glacier surface is covered with thin morainic debris where low wavy relief and pitted patterns develop suggesting a slight movement and ablation of ice. The cirque wall is steep and several precipitous horns soar at the head wall. The estimated profile shows a gentle cirque bottom covered by ice with the maximum thickness of 265 m. The longitudinal profile is not known, but the bedrock 7 km northwest of the glacier terminal descends steeply to the depth of 1180 m

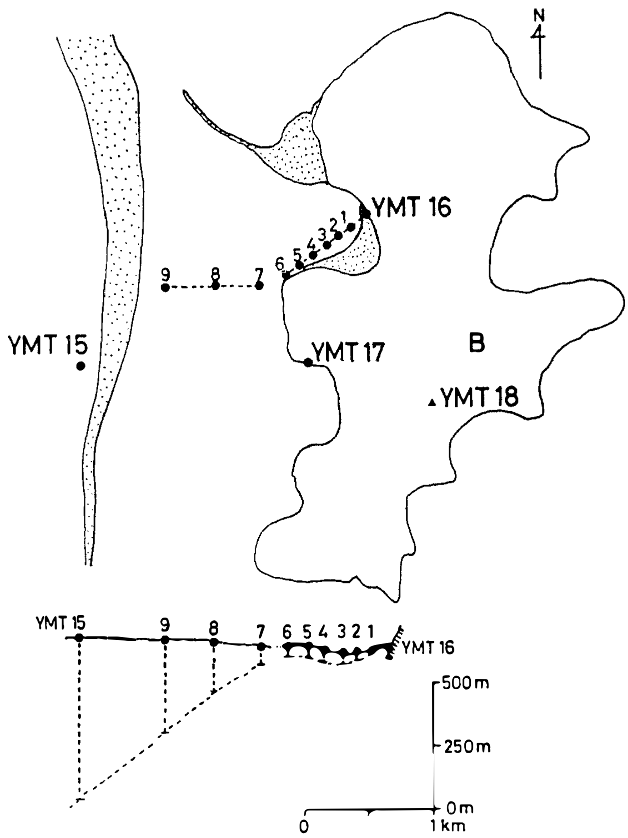

Fig. 2. *The result of the estimated ice thickness at Massif B. Dotted areas are the moraine fields.*

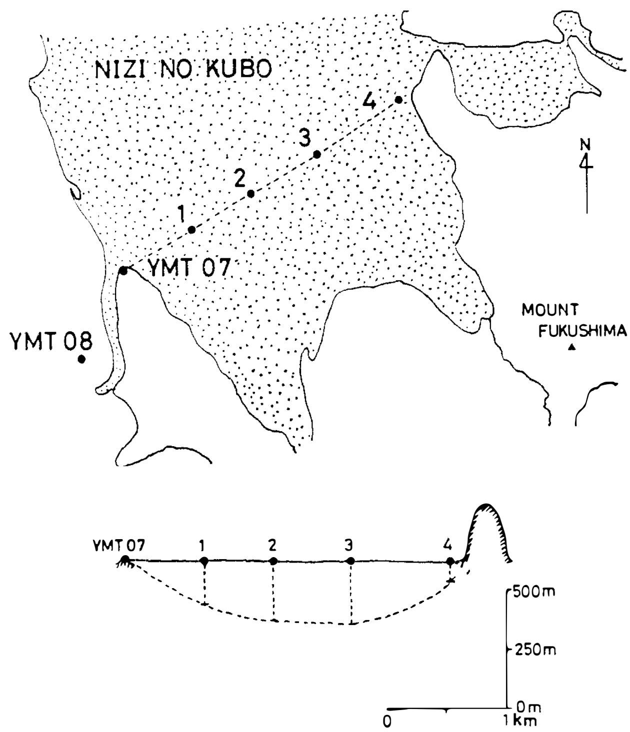

Fig. 3. *The result of the estimated ice thickness at Massif D (Nizi-no-kubo).*

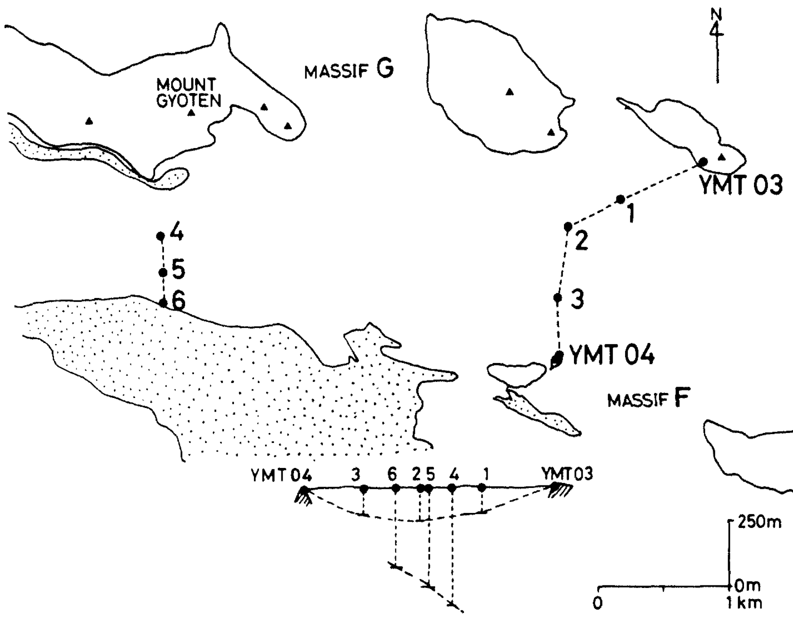

Fig. 4. The result of the estimated ice thickness of an outlet glacier between Massifs F and G.

(457 m above sea level) (NARUSE and YOKOYAMA, 1975). These facts also suggest that the cirque configuration had been formed mainly prior to the ice sheet cover.

Figure 4 shows the result of measurements on an outlet glacier between Massifs G and F. The ice thickness was calculated by referring to the gravity value of station YMT03. Two measuring lines were set in the upper and the lower reaches, respectively. But the measurement at stations close to Massif G in the lower reaches was interrupted by a huge wind scoop on the glacier.

The glacier bottom in the upper reaches shows a rather shallow and gentle cross profile. On the other hand, the bottom in the lower reaches, though not fully measured, seems to indicate the cross profile of a valley floor which inclines steeply towards Massif G in the north with a gradient of 200 m/1000 m.

These facts and the geological structure (YOSHIDA and ANDO, 1971) suggested that a subglacial folding axis exists under this glacier. Furthermore, the subglacial topography may indicate that a fault line was in the E-W direction near the southern foot of Massif G.

5. Summary

Our concluding remarks are as follows: On the west side of Massif B, the bedrock height decreases steeply with a gradient of 300 m/1000 m from the shallow cirque glacier bottom to the west. The deepest bedrock in the cross profile near the terminal part of the Nizi-no-kubo cirque glacier in Massif D reaches 265 m. The subglacial bedrock topography suggests that the fault line runs along the southern foot of Massif G and the surface configuration of the outlet glacier between Massifs F and G seems to be influenced not only by snow accumulation controlled by surface topography but also by subglacial rock topography. The relationship among depth of cirque bottom, depth of the neighboring ice sheet, and surface features of cirque glaciers and the ice sheet suggests that these cirques were formed mainly prior to the ice sheet cover, and that the tectonic displacement might have been responsible for the deep subglacial bottom of the surrounding area. And we should like to emphasize through this study that the gravity measurement is the most convenient method for estimating subglacial topography as a preliminary study.

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