DISTRIBUTION OF SURFACE STRUCTURES OF THE ICE SHEET IN MIZUHO PLATEAU

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Abstract: Among the structural phenomena on the ice sheet, the structures with the dimensions of 10^1-10^4 m are called here "surface structures". The data of the surface structures obtained in Mizuro Plateau up to date were compiled and refined. The surface structures were classified into five major groups, according to their physical characteristics, A) flat surface, B) undulation (isolated), C) undulation (grouped), D) crevasse and crack, E) moraine and muddy band. These structures are made mostly by deformation of ice caused by movement of an ice sheet.

Thus the distribution of the surface structures would be a reflection of stress condition of the ice sheet; stress condition is controlled by ice thickness, flow velocity and bedrock topography. Referring to steepness and frequency of surface structures, Mizuho Plateau was divided into four subdivisional regions, coastal region, transitional region, inland region and mountainous region. The surface structures in the coastal region and in the vicinity of exposed land are steeper and more frequent than those of inland. Such variation of the feature of the surface structures is well explained by the distribution of the above-mentioned three factors which control the stress condition of the ice sheet.

This paper is an approach to a study on dynamics of the ice sheet.

1. Introduction

The Antarctic ice sheet is the largest ice mass on the present earth, and its areal extent is about 4500 km across. The real surface of the ice sheet is composed of many kinds of reliefs of various dimensions. Macroscale reliefs of the ice sheet have dimensions of 10^5-10^6 m (*e.g.* the shape of the Antarctic ice sheet, and shape of drainage basin of the local ice sheet), while mesoscale reliefs 10^1-10^4 m (*e.g.* undulated surface, ice mound, crevasse and moraine), and microscale reliefs less than 10^1 m (*e.g.* snow dune, sastrugi and ripple marks). Macroscale relief would show an equilibrium state of the ice sheet, while mesoscale relief and microscale relief would be formed by dynamics of the ice sheet flow and by deposition and erosion of snow. Mesoscale relief, called "surface structure" in this paper, is to be studied in relation with dynamics of the ice sheet.

Although several descriptive studies on the surface structures have been made separately in Mizuho Plateau, no systematic study on them was carried out. Here, available data are brought together to be refined and put in order. Then the distribution of the surface structures is discussed with reference to the relation between the surface structures and the dynamics of the ice sheet.

2. Classification of the Surface Structures in Mizuho Plateau

The available data on the surface structures in Mizuho Plateau comprised

Table 1. Sources of information on the surface structures.

Kind of information	References
Published papers	Yoshida and Fujiwara, 1963; Fujiwara 1964; Yoshida *et al.*, 1970; Fujiwara *et al.*, 1971; Watanabe and Yoshimura, 1972; Shimizu and Yoshimura, 1972; Naruse, 1975; Yokoyama, 1976a.
Field notes or personal communication	Ageta; Inoue; Nakawo; Naruse; Shimizu; Yokoyama; Watanabe.

Table 2. Classification of the surface structures in Mizuho Plateau.

	Bases of classification			Name of structure	Original description by previous observers
	Composing material	Structural feature	Configuration		
Surface structures	Snow or ice	Even		A. Flat surface	(Not recognized as a structure)
		Uneven	Isolated	B-1. Ice step	ice cliff, cliff-like step, transverse step, stairs-like structure, step, ice step, terrace
				B-2. Ice mound	dome, dome shape, mound, ice mound, independent dome
				B-3. Ridge	broad ridge-like rise, ridge
				B-4. Trough	valley, trough, valley-like structure
				B-5. Ice depression	ice depression
			Grouped	C. Undulation	scoop, broadly undulated surface features, broad undulation like terraces, broad undulations, small undulations, mounds, ice mounds, troughs, domes, rises, convex, concave, ice hills, hill, basin, hollow, depression
		Fissure		D-1. Crevasse	crevasse, crevasses, crevassed area, crevasse zone
				D-2. Crack	crack, cleavage
	Rock debris			E-1. Moraine	moraine, moraines, moraine field
				E-2. Muddy band	muddy bands, clay bands

published papers, field notes and personal communication as listed in Table 1. It was found after the compilation that these observers had not necessarily a common definition and terminology of the structure. Therefore, the work began with arranging the data to clarify the definition and terminology, by referring to the individual observers. Three bases for classification of the surface structures are as follows: (1) material composing the structure (*e.g.* snow, ice or rock debris), (2) structural feature (even, uneven or fissure), (3) configuration (isolated or grouped). According to these bases, all the surface structures observed were classified into five major groups A, B, . . . E, eleven sub-groups A, B-1, . . . E-2, as shown in Table 2. For Group A there is no original description, which may be due to the fact that Group A, flat surface, was seldom recognized as a structure.

The structures of Group B and C are that of uneven surface. When such structures existed in group, it was difficult to judge whether the structure had resulted from rising or lowering of the surface and to recognize each structure, so that the structures of Group C are collectively called "undulation" here. On the contrary, as for the isolated structure, it could be judged whether the structure was due to raised surface, lowered surface or stepped surface. The structure of Group B could be divided into five sub-groups B-1, B-2, . . . B-5 by the shape of the structure. They are explained as follows:

B-1. "Ice step" is composed of two flats with height difference of 50–200 m connected with a steep slope.

B-2. "Ice mound" is a dome-shaped rise of an ice sheet surface which attains a height of several tens meters up to one hundred meters.

B-3. "Ridge" is a crest-like rise which extends in some considerable length.

B-4. "Trough" is a valley-like lowering of the surface which has some considerable length.

B-5. "Ice depression" is a U-shaped hollow which has the dimensions of several kilometers across.

Group D is divided into two sub-groups, namely crevasse and crack, in the usual classification by their dimensions.

Group E is divided into two, moraine and muddy band, by the size of the composing material.

3. Mechanism of Formation of the Surface Structures

In the beginning, theories on the mechanism of formation of the surface structures are briefly summarized, then the formation of the surface structures observed in Mizuho Plateau is discussed in this section.

3.1. Theories on surface structures formation

3.1.1. Relation between surface structures of the ice sheet and bedrock undulation

NYE (1959) introduced a basic relation between bedrock undulation $p(x)$ and the ice sheet surface undulation $\varepsilon(x)$ as

$$\varepsilon(x) \simeq \frac{m+1}{m} \frac{\alpha_0}{h_0} \int_x^{x_0} p(x)dx \qquad (1),$$

where x-axis is in the direction of ice flow, m a constant in flow law of ice, α_0 slope angle of the surface of the ice sheet and h_0 thickness of ice.

ROBIN (1967) derived a relation between the stress deviation in the direction of flow σ_x^0, and the change of surface slope α_F, as

$$\alpha_F = -\frac{1}{\rho g} \frac{d\overline{\sigma_x^0}}{dx} \qquad (2),$$

where ρ is the density of ice, g the gravitational acceleration, and $\overline{\sigma_x^0}$ the average of σ_x^0 over the thickness of the ice sheet, where

$$\overline{\sigma_x^0} = b(\dot{\varepsilon}_x)^{1/4} \qquad (3),$$

$$\dot{\varepsilon}_x = \frac{1}{h}\left(\dot{a} - v\frac{dh}{dx}\right) \qquad (4),$$

where b is a constant, $\dot{\varepsilon}_x$ the longitudinal strain rate in the direction of flow, h ice thickness, $\dot{a}$ accumulation rate and v the velocity of ice flow.

Undulation explained by these theories is limited to stationary one, and is called "stationary wave" after NYE.

3.1.2. Kinematic wave

WEERTMAN (1958) pointed out the existence of kinematic wave on glacier. He described that a kinematic wave should break out when extremely heavy snowfall was brought on a glacier, and it should propagate with a velocity of several times faster than that of normal glacier flow.

3.1.3. Formation of crevasse

If one of the principal stresses in ice is tensile, and its value exceeds the tensile strength of ice, crevasse is formed transversely (NYE, 1952).

3.1.4. Formation of moraine

NYE (1951, 1967) derived two solutions for velocity of flow of ice from his generalized flow law: the one had a downward component of velocity, while the other upward. They correspond to Rankine's active and passive states of plastic equilibrium: they are called here "active flow" and "passive flow", respectively. In active flow, material is transported downwards in ice, and in passive flow upwards. Therefore, only by passive flow material can be taken into ice from bedrock. Existence of internal moraine and surface moraine which were brought from bedrock can be explained by this mechanism. This is "shear hypothesis".

WEERTMAN (1961) proposed "freezing-in process" on the basis of the observation in Greenland. This process is that debris is enclosed into ice by melting and re-freezing at the bottom of ice, which can occur near the margin of ice sheet.

3.2. Formation of the surface structures

3.2.1. The structures formed of snow and ice

In the theories summarized in Sections 3.1.1., 3.1.2. and 3.1.3., the movement of ice is considered as the forming agent of the surface structures. On the other hand, surface structures are related also to deposition and erosion of snow at the surface of the ice sheet. Surface structures and deposition-erosion process will interact on each other in two ways; one is the way in which deposition and erosion are the primary agent of surface structure, while in the other the secondary agent. Kinematic wave as stated in Section 3.1.2. is an example of the former case. In the latter case, deposition and erosion will magnify, maintain or shrink the original surface structure. This problem is not discussed further, because the process of deposition and erosion of snow is discussed in detail in the paper of this issue (p. 125–139, by YAMADA *et al.*).

Studies have been carried out on the relationship between bedrock and surface structure. ROBIN (1967), in his study of the Greenland ice sheet, obtained a good correlation between the calculated value and the observed value of surface slope change using eqs. (2), (3) and (4). A case study on the same subject in Mizuho Plateau was made by YOKOYAMA (1976b) with the same method as ROBIN. The result showed that the bedrock topography is fairly well reflected in the surface structures. Spectral analyses of bedrock and surface topography were made by BUDD and CARTER (1971) on the Greenland ice sheet and Wilkes ice cap, and by NISHIO and KUSUNOKI (1975) on the Mizuho Plateau ice sheet. They contended that the prevailing wavelength of bedrock undulation almost coincided with that of surface undulation. The results of these analyses support the idea that undulation of the surface is due to deformation of ice which is caused by stress deviation in ice.

The condition in which crevasse is formed is stated in Section 3.1.3. Such condition is satisfied when normal tensile stress is large or shear stress in horizontal plane is large. Such stress condition results from relatively high undulation of bedrock. Crack is formed in the same way. The difference of dimensions between crevasse and crack depends on the strain of the ice in the deeper part than the bottom of the fissure. The crack called "thermal crack" is supposed to be formed by cooling contraction of the surface of ice sheet. Such destruction will easily occur where tensile stress is dominant.

3.2.2. The structures composed of rock debris

Rock debris is taken into the ice body in two manners, that is, from exposed rock directly onto the surface of ice sheet by gravity, and from the bedrock across the bottom by "passive flow" of ice or "freezing-in process". The captured rock debris in the ice sheet is carried by the movement of ice. In the ice, the rock debris moves downward when the flow of ice is in "active state", while upward or remains on the surface of ice when "passive state". Therefore the existence of rock debris on the ice surface indicates that the ice flow is in "passive state", which is caused by relative rise of the bedrock to the ice surface.

Muddy band is generally formed in the same way as moraine. YOSHIDA *et al.* (1970) reported the muddy band which had been formed by a different mechanism, that is, the secondary deposition of the composing material of moraine field.

3.2.3. Relation between surface structures and dynamics of ice sheet

Regarding the above discussions, the characteristics of ice sheet which are concerned with surface structures are considered. The surface structures composed of snow and ice are formed by deformation of ice body. The manner of deformation is controlled by the stress condition in the area; deformation of ice does not occur where stress deviation is nil; deformation occurs in the form of undulation where stress deviation is smaller than the breaking strength of ice; destruction occurs where stress deviation exceeds the breaking strength of ice. The stress deviation in ice, and the surface structures composed of snow and ice as a result of the stress deviation, are controlled mainly by bedrock topography, ice thickness and flow velocity of ice (see eqs. (1)–(4)). Existence of moraine or muddy band is related to bedrock topography. Therefore, three factors noted above are considered to be the controlling factors of surface structures.

4. Distribution of the Surface Structures in Mizuho Plateau

4.1. Regional characteristics of the surface structures

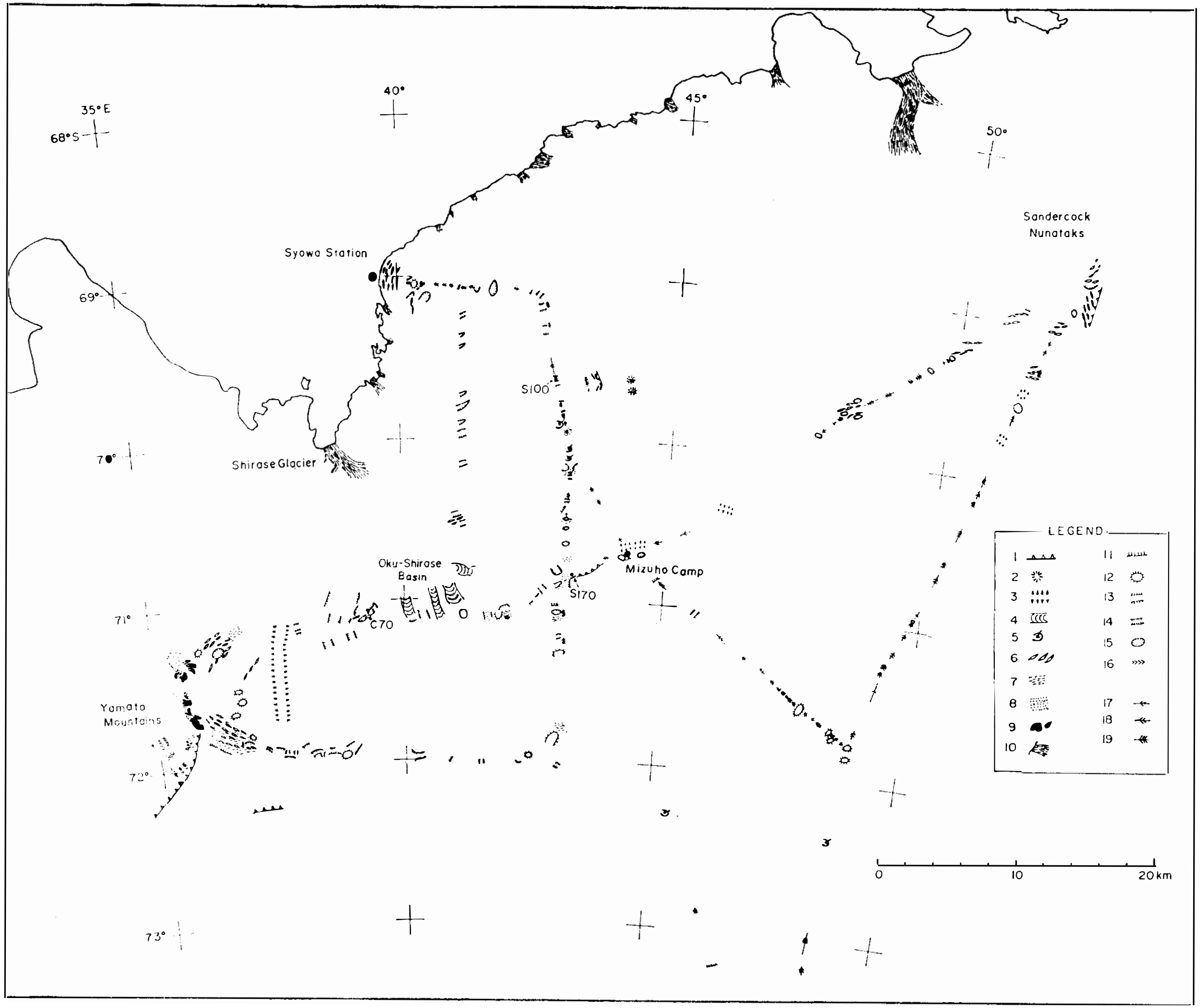
Fig. 1 shows distribution of the surface structures in Mizuho Plateau. The regional characteristics of the surface structures are summarized as follows:

(a) Near the coast, large crevasses and remarkable undulation were observed very often.

(b) In Oku-Shirase Basin, there extended four large troughs of 100–150 m deep, heading towards Shirase Glacier. FUJIWARA (1964) suggested that these troughs could be a reflection of the subglacial valley reported by ISHIDA (1961).

(c) Around C70, there were large crevasses running along the contour lines of the slope. To the north of C70, remarkable undulation was observed.

(d) To the east of the Yamato Mountains, a wide ridge was observed running along the meridian of 37°30′E approximately. FUJIWARA (1964) pointed out that this ridge could be the result of the subglacial rise extending parallel to the Yamato Mountains. The surface flow lines drawn by NARUSE and SHIMIZU (1978) indicated that the boundary of the ice flow existed around here, which



1: B-1, Ice step
2: B-2, Ice mound
3: B-3, Ridge
4: B-4, Trough
5: B-5, Ice depression
6: D-1, Crevasse
7: D-2, Crack
8: F, Moraine or muddy band
9: Exposed land area
10: Ice stream
11: Steep slope
12: Mound, dome or hill
13: Ridge or rise
14: Trough or valley
15: Basin, hollow or depression
16: Ice hills
17: Gentle slope
18: Medium slope
19: Steep slope
C, Undulation (grouped)

Fig. 1. Distribution chart of the surface structures in Mizuho Plateau. 1-5 are the undulation recognized as isolated one; 11-16 are the grouped undulation illustrated according to original description.

could be predicted from the above-mentioned ridge.

(e) To the east of S100, three moraine fields were observed (YOSHIDA *et al.*, 1970). In a region of 30 km east of the moraine, two large ice mounds with relative height of 100–150 m, diameter of 3–5 km were found, and to the north-east of the ice mounds, an ice step was found extending NW-SE (NARUSE, 1975).

(f) Around S170, intensive and complicated undulation was observed.

(g) In the circumference of exposed land areas, there was complicated undulation mostly accompanied by crevasses. To the southwest of the Yamato Mountains and south of the Sandercock Nunataks, there were observed ice steps with crevasses which extended over several kilometers. The ice step near the Yamato Mountains was supposed as a reflection of bedrock topography by YOSHIDA and FUJIWARA (1963) and by FUJIWARA (1964).

(h) To the south of the Yamato Mountains, two ice steps with relative height of 100 m running parallel to the contour lines were observed, at the elevation of about 2000 m and 2950 m above sea level.

(i) In Mizuho Plateau, except the particular regions mentioned above, wave-like undulation was generally seen, and the amplitude became smaller inlandwards.

4.2. Zoning of Mizuho Plateau regarding surface structures

Summarizing these observations, Mizuho Plateau was divided into four sub-divisional regions by the steepness and frequency of surface structures as shown in Fig. 2. Here "steepness" means relative height of structure and "frequency" means the number of structures in a certain area. The characteristics of these regions were the following:

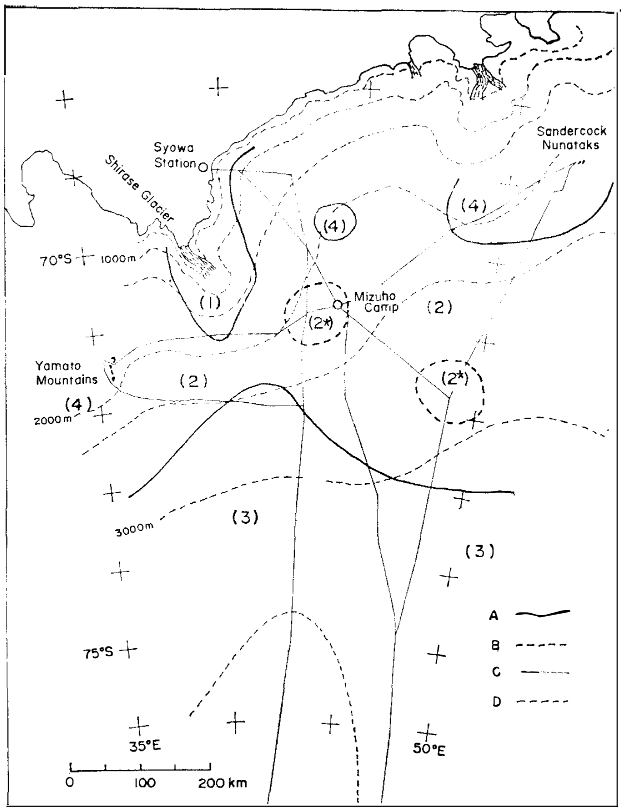
(1) Coastal region: In the region within about 100 km from the coast, very intricate topography with large crevasses and conspicuous undulation was seen.

(2) Transitional region: In the intermediate region between the coastal region and the inland region, moderate undulation was usually seen, while some complicated topography was also seen occasionally.

(3) Inland region: In the region farther than several hundreds of kilometers from the coast, gentle undulation was commonly seen.

(4) Mountainous region: In the surrounding region of the exposed land area, even in the inland, many kinds of remarkable structures such as crevasse and ice step were seen; undulation was as distinguished as in the coastal region.

Then we turn to the regional features of the controlling factors of surface structures noted in Section 3.2.3. As for a simple model of ice sheet, ice thickness increases and flow velocity of ice decreases from margin to center of ice sheet. This tendency accounts for the fact that steepness and frequency of surface structures decrease from margin to center. This is considered a general feature of distribution of surface structures of ice sheet, and bedrock topography should



(1) Coastal region; (2) Transitional region; (2*) The part of transitional region with relatively complicated surface structures; (3) Inland region; (4) Mountainous region. A: Boundary of subdivisional regions. B: Sub-boundary in the subdivisional region. C: Traverse route. D: Contour line (interval: 500 m).

Fig. 2. Subdivisional regions of Mizuho Plateau with regard to steepness and frequency of surface structures.

give variation to the feature. From this view point, the distribution of surface structures in Mizuho Plateau is explained as follows: increase in ice thickness and decrease in flow velocity of ice towards inland resulted in decrease in steepness and frequency of surface structures from the coastal region towards the inland region: decrease in ice thickness in the vicinity of exposed land area resulted in complicated surface structures in the mountainous region: relatively thin ice or complicated bedrock topography resulted in considerably complicated surface structures in several parts of the transitional region (see Fig. 2).

5. Conclusion

Available data on the surface structures collected in Mizuho Plateau were compiled. After refining and adjusting the original data, the structures were classified anew, and distribution of the surface structures in Mizuho Plateau was studied. Finally, Mizuho Plateau was divided into four subdivisional areas by the steepness and frequency of the surface structures, referring to the previous studies on the formation of the surface structure. However, the discussion was limited to qualitative one because of the lack of quantitative data.

Now let us consider the peculiarity of surface structures among the other phenomena of the ice sheet, and reveal the remaining problems. First, it is noticeable that surface structure is a topographical phenomenon superimposed on the macroscale form of the ice sheet. Next, the distribution of surface structures can be regarded as a reflection of dynamic condition of the ice sheet, according to the process of their formation as discussed in the preceding sections. Though the discussions made in this paper were based upon the assumption that the ice sheet is in a steady state, it could not be confirmed whether this assumption was strictly applicable to the Mizuho Plateau ice sheet or not. Detailed and quantitative discussion of surface structure should be made relating to the dynamic characteristics of the ice sheet.

It has been known that the earth has experienced several ice ages, and the ice sheets expanded, shrinked and some of them disappeared in times past. Furthermore, of importance is the interaction between cryosphere and lithosphere, that is, ice sheet and its bedrock; the form and flow of ice sheet are strongly influenced by its bedrock, and at the same time the flow of ice sheet acts as an agent which changes the form of its bedrock continuously.

After all, only through the study on both spatial and time-dependent change in the form of surface structure and that of ice sheet, the structural characteristics of ice sheet, dynamic property of ice sheet and the interaction between cryosphere and lithosphere would be clarified. This method may be an effective way to study ice sheet as a dynamic phenomenon.

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