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SNOW SURFACE FEATURES ALONG THE TRAVERSE ROUTE FROM THE COAST TO DOME FUJI STATION, QUEEN MAUD LAND, ANTARCTICA

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Abstract: Frequencies of snow surface features such as sastrugi, dunes and thermal cracks were measured along the traverse route from the coastal region to the summit of the Queen Maud Land ice sheet, Dome Fuji Station, East Antarctica. The study route can be clearly divided into three regions on the basis of the regional characteristics of snow surface features: coastal region, katabatic wind region and inland plateau region. The coastal region is characterized by high frequency of small sastrugi and low frequency of dunes. The katabatic wind region is characterized by the co-existence of small and large sastrugi, dunes and glazed surface. The inland region is characterized by low frequencies of small sastrugi and dunes. These regional characteristics of snow surface features reflect the deposition-erosion process affected by surface topography of the ice sheet. Especially, a glazed surface zone where snow accumulation is small develops on relatively steep slopes above the relatively large convex bedrock topography. This indicates that bedrock topography is one of the factors controlling snow accumulation patterns in the katabatic wind region on the Antarctic ice sheet.

1. Introduction

There exist many types of snow surface features, such as sastrugi, dunes and pitted patterns on the Antarctic ice sheet. To clarify the characteristics of distribution and the duration of snow surface features is very important in estimating distribution of surface mass balance on the ice sheet. Especially, a glazed surface is thought to indicate a hiatus stage on deposition-erosion processes at ice sheet surface lasting several years (WATANABE, 1978). Mass loss exceeding 5 g cm^{-2} per year occurs at the glazed surface due to sublimation (FUJII and KUSUNOKI, 1982). However, we don't have enough information to discuss the duration and the mechanism of formation of the glazed surface.

Several studies of the distribution of snow surface features have been done on the Antarctic ice sheet. FUJIWARA and ENDO (1971) observed characteristics of snow surface features along a traverse route from the coast to the South Pole. WATANABE (1978) observed snow surface features along the traverse routes and divided the Mizuho Plateau, Antarctica, into three regions on the basis of regional characteristics of the surface condition. He discussed the characteristics of snow surface features and their significance in the process of surface snow layer formation. FURUKAWA *et al.* (1992) compiled data on snow surface features collected by the Japanese Antarctic Research Expeditions (JARE) along traverse routes in Enderby Land and East Queen Maud Land, Antarctica, and indicated that large scale (several hundreds km) topography of the ice sheet surface is related to the distributions of snow surface features.

However, previous studies on snow surface features lack common definitions and terminology, and too few use quantitative methodology. One quantitative study was by TAKAHASHI *et al.* (1984), who measured the frequency distributions of sastrugi along the traverse route, and discussed the relationship to the ice sheet surface topography. GOODWIN (1990) measured the type, size and orientation of surface microrelief and snow surface characteristics in eastern Wilkes Land.

We observed snow surface feature distribution along a traverse route from Dome Fuji Station to the coastal region in 1992 following the method of TAKAHASHI *et al.* (1984), and discuss the relationship between snow surface features and depositional regime on the ice sheet.

2. Observation Method

Snow surface features were morphologically classified into three types: "sastrugi", "dunes" and "glazed surface" representing erosional, depositional and equilibrium stages in deposition-erosion processes respectively according to the classification by WATANABE

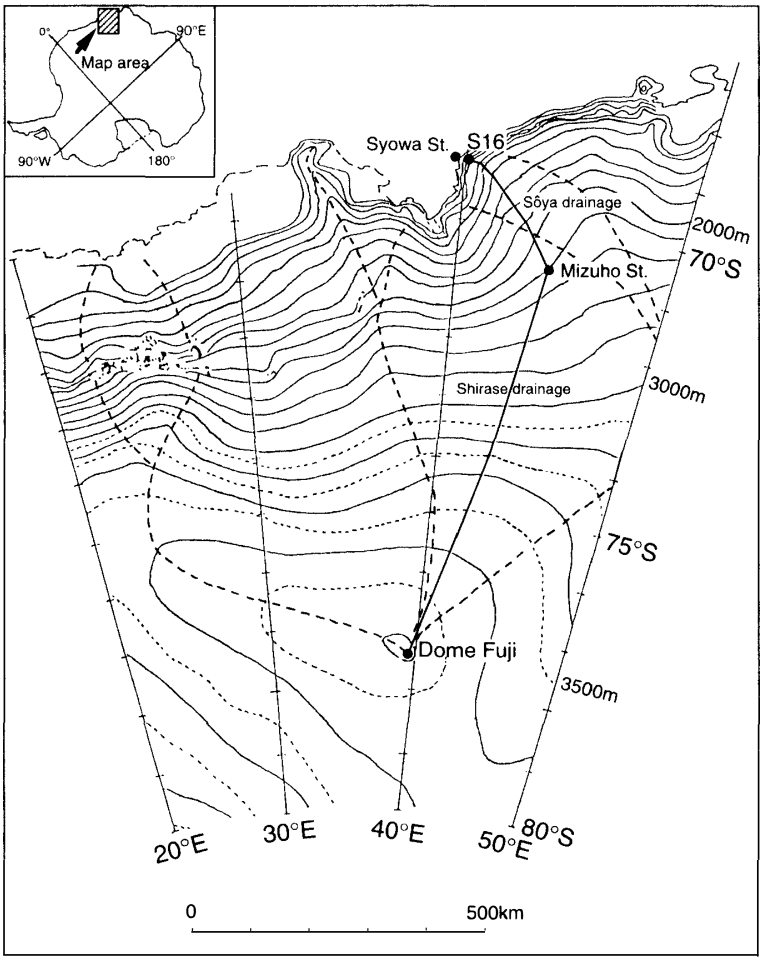

Fig. 1. Location map of the study route. Broken lines indicate drainage boundaries. The study route crosses Shirase drainage and the Sôya drainage.

(1978). Sastrugi were divided into two types, large and small ones with the height higher and lower than 30 cm respectively. On a glazed surface, thermal cracks are usually visible, therefore the frequency of thermal cracks is assumed to represent the existence of a glazed surface in this study.

As snow surface features on the ice sheet change successively and often co-exist, it is difficult to describe quantitatively the distribution of each surface feature. Here we visually counted numbers of each surface feature occurrence from an oversnow vehicle along the traverse route during an oversnow traverse in spring/summer (October–December) 1992. The number of each type of surface feature between snow stakes at 2 km intervals was recorded. Therefore, the frequency of each type of snow surface feature occurrence per 2 km was obtained along the traverse route.

The study route is from the coast, S16 (69°01'47" S, 40°03'49" E, 591 m a.s.l.), to the summit of the Queen Maud Land ice sheet, Dome Fuji Station (77°22'24" S, 39°36'50" E, 3807 m a.s.l.) as shown in Fig. 1. The study route is approximately perpendicular to the prevailing wind direction. In addition to the surface feature observation, we measured the surface and bedrock topography by both the barometric altimetry and differential GPS method, and radio echo sounding respectively (Kamiyama *et al.*, 1994). Net snow accumulation distribution from October 1992 to January 1994 was also measured by the snow stake method along this route as reported by Motoyama *et al.* (1995).

3. Results

3.1. Distribution of snow surface features

Figure 2 (a), (b) and (c) show frequencies per 2 km of sastrugi, dunes and thermal cracks along the study route from S16 to Dome Fuji Station. There are some areas where the frequencies of snow surface features could not be measured; these are hatched in Fig. 2 (a), (b) and (c). We could measure the frequencies of snow surface features along the route except in the hatched areas. Figure 2 (d) shows net snow accumulation distribution along the study route at every 2 km by snow stake method from October 1992 to January 1994. Here net snow accumulation data are given in snow depth. Figure 2 (e) shows the surface and bedrock topography and Fig. 2 (f) shows surface slope distribution at every 2 km along the S16 – Dome Fuji Station axis. Striped areas in Fig. 2 show glazed surface zones where thermal cracks were observed.

Small sastrugi existed all over the study route. The frequency of small sastrugi occurrence is large around the coastal region and small around 2000 m a.s.l. From 2400 m to 3600 m a.s.l. frequency of small sastrugi occurrence fluctuates; it is relatively small in areas where glazed surface was observed. Above 3600 m a.s.l. around Dome Fuji Station small sastrugi occurrence decreases.

Large sastrugi exist in the area above about 2000 m a.s.l. Frequency of large sastrugi occurrence reaches a maximum around 2400 m a.s.l. It is smaller than that of small sastrugi occurrence and also relatively small in areas where glazed surface was observed. Above 3600 m a.s.l., frequency of large sastrugi occurrence decreases; few large sastrugi were observed near Dome Fuji Station.

Frequency of dune occurrence has a similar trend to that of small sastrugi except in the coastal region, where dunes occur less frequently than small sastrugi.

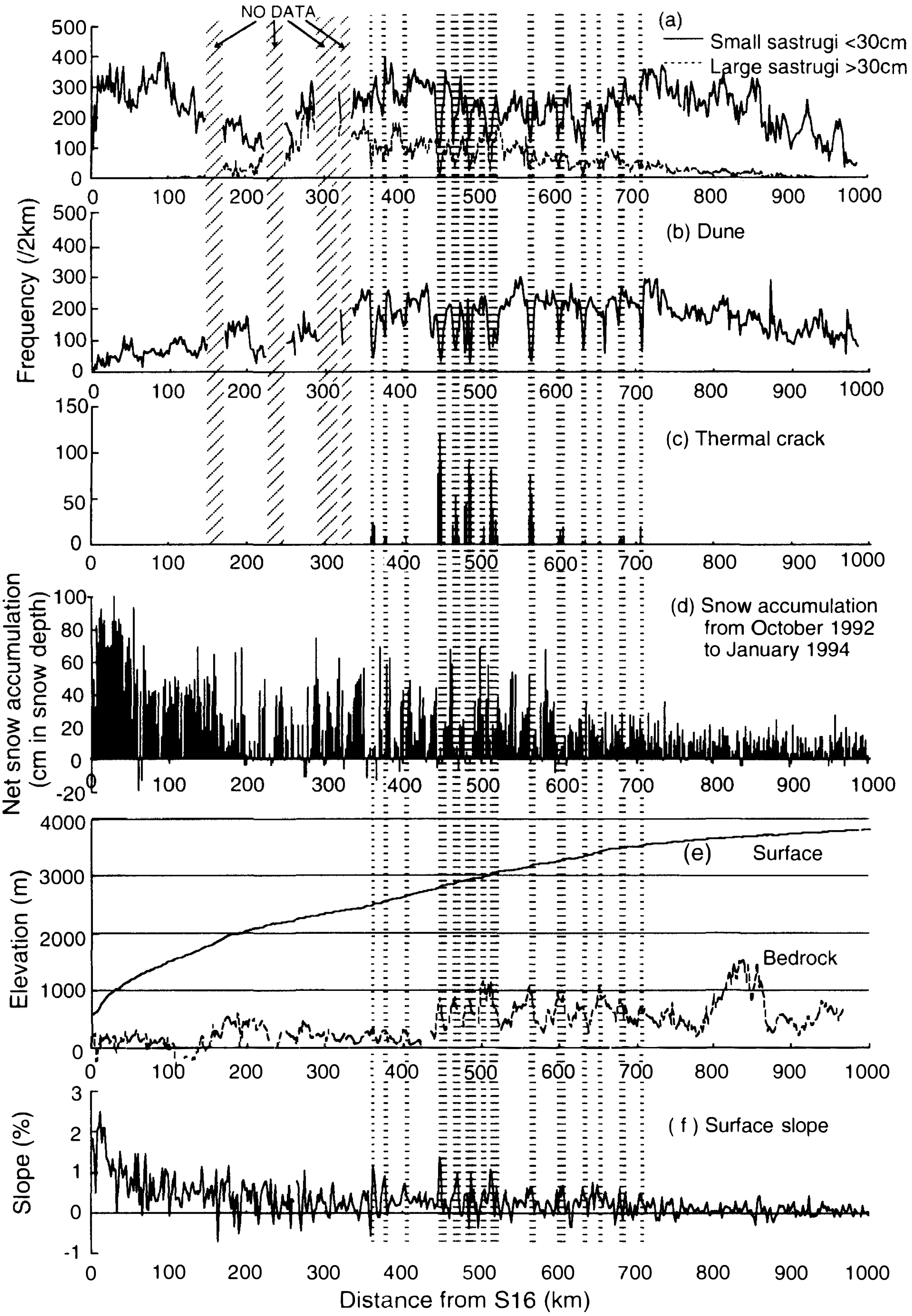

Fig. 2. Frequency distributions of snow surface features, net snow accumulation distribution and surface and bedrock topography, (a) small and large sastrugi, (b) dunes, (c) thermal cracks, (d) net snow accumulation in snow depth from October 1992 to January 1994, (e) surface and bedrock altitude, (f) surface slope at intervals of 2 km. The striped areas indicate the glazed surface zone observed in this study. The hatched areas indicate the area where frequencies of snow surface features occurrences could not be measured.

The glazed surface zone where thermal cracks were observed was found at intervals of 20–30 km along the study route from 2400 m to 3600 m a.s.l. In this study route, the upper limit of the area where glazed surface exists is about 3600 m a.s.l. Unfortunately the lower elevation limit cannot be determined because there are some coastal areas without data. However, from WATANABE (1978) the lower limit of the glazed surface can be estimated as 1800–2000 m a.s.l.

On the basis of these characteristics of surface feature distribution, the study route from S16 to Dome Fuji Station can be divided into three sections. Section 1 is the region under about 2000 m a.s.l., where glazed surface and large sastrugi are rarely observed while small sastrugi and dunes are observed. Section 2 is the region from 2000 m to 3600 m a.s.l. characterized by the glazed surface. Section 3 is the region above 3600 m a.s.l. characterized by low frequency of large sastrugi and high frequencies of small sastrugi and dunes.

3.2. Snow surface features and spatial variability of net snow accumulation

Snow surface features are regarded as forms to represent stages in deposition-erosion processes on the ice sheet surface. From Fig. 2 (d), net snow accumulation is relatively small in the area where glazed surface exists, and high snow accumulation corresponds to the large frequencies of sastrugi and dunes. Here we compare spatial variabil-

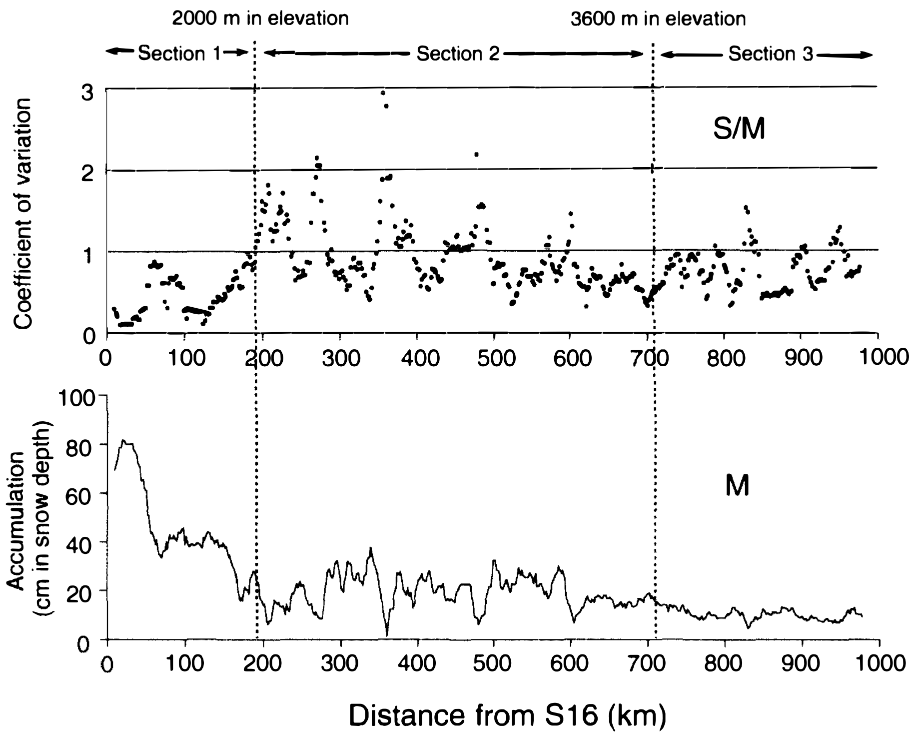

Fig. 3. Running means of net snow accumulation over 10 stake sites, M, and coefficients of variation, S/M where S is the standard deviation of the ten values. (The coefficient of variation was introduced by YAMADA and WAKAHAMA (1981).) Section 1 is from the coast to 2000 m a.s.l., Section 2 is from 2000 m to 3600 m a.s.l., Section 3 is above 3600 m a.s.l.

ity of snow accumulation with snow surface feature distributions for each section.

Figure 3 shows 10 point running means of net snow accumulation, M, and the coefficient of variation defined by S/M, in which S is the standard deviation of the 10 point values. This coefficient of variation was introduced by YAMADA and WAKAHAMA (1981). This value gives the spatial variability of net snow accumulation averaged over 20 km section along the study route.

In Section 1, net snow accumulation is relatively large and spatial variability is small. In Section 2, net snow accumulation decreases relatively, and spatial variability is relatively large and fluctuates. In Section 3, net snow accumulation and fluctuation of spatial variability decrease. The trends of net snow accumulation and its spatial variability coincide with that observed along the traverse route from S16 to South Pole by

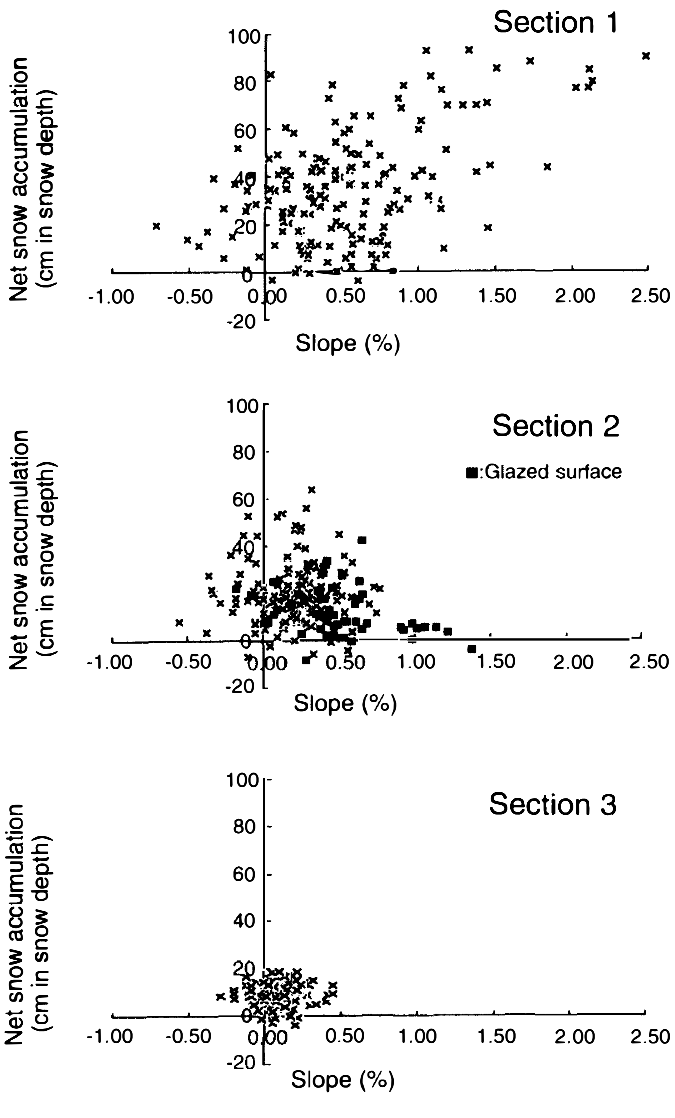

Fig. 4. Relationship between surface slope and net snow accumulation for Section 1, Section 2 and Section 3. Squares indicate the existence of glazed surface.

YAMADA and WAKAHAMA (1981). Sections 1, 2 and 3 respectively correspond to "continuous accumulation zone", "sporadic accumulation zone" and "calm accumulation zone" as called by YAMADA and WAKAHAMA (1981).

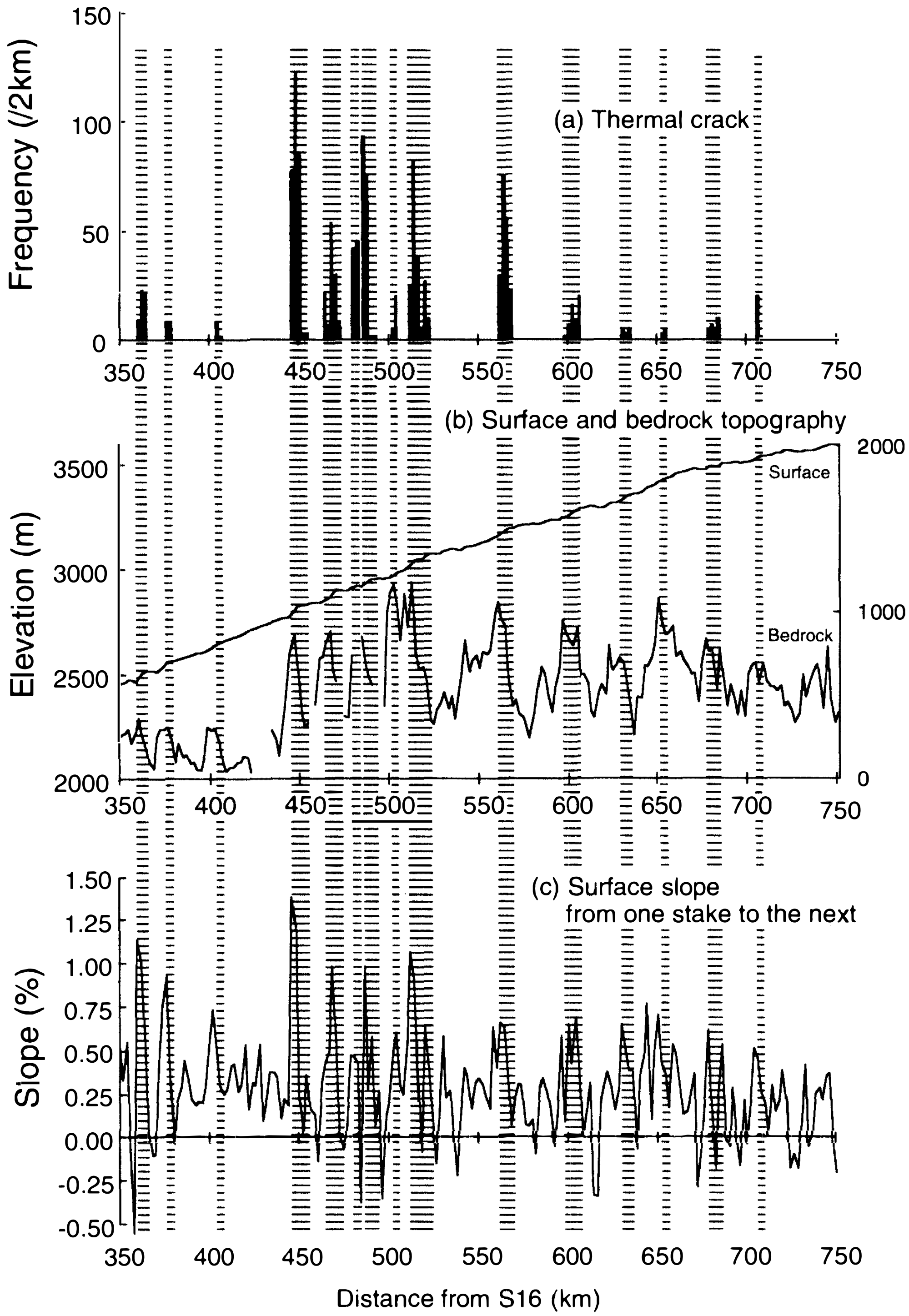

Fig. 5. Frequency distributions of (a) thermal cracks, (b) surface and bedrock topography and (c) surface slope for the section where glazed surface was observed in this study.

In the continuous accumulation zone, small sastrugi and dunes exist. In the sporadic accumulation zone, small and large sastrugi, dunes and glazed surface co-exist. Large spatial variability in Section 2 is mainly due to the existence of glazed surface where net snow accumulation is relatively small. In the calm accumulation zone, small sastrugi and dunes exist. In this way, the variety of snow surface features reflects spatial variability of snow accumulation on a small scale of several tens km.

3.3. Snow surface features, surface and bedrock undulations

Snow accumulation patterns are strongly influenced by topography on both large and small scales (BLACK and BUDD, 1964). There are surface undulations of wavelength of a few tens of km along this study route. Figure 4 shows the relationship between surface slope and net snow accumulation at intervals of 2 km. Here net snow accumulation is the average of 2 values of snow accumulation at neighboring snow stakes. Squares indicate values in the area where glazed surface was observed between snow stakes.

In Section 1, net snow accumulation is larger in steep slope areas, though the relationship between surface slope and net snow accumulation is not clear in gradual slope areas. In Section 2, the larger the absolute value of slope the smaller the net snow accumulation. The most remarkable characteristic is that on slopes steeper than about 0.75% areas where glazed surface was observed exist and net snow accumulation is small in these areas. Large values of net snow accumulation on a glazed surface may reflect the co-existence of sastrugi and dunes. In Section 3, the surface slope is less than 0.5% and net snow accumulation is small.

In this way, surface undulation on the ice sheet is a main factor in formation of a glazed surface except in Section 1, where glazed surface was not observed even on slopes steeper than those of Section 2. This indicates that redistribution of drifting snow is related to the formation of snow surface features and the distribution of snow accumulation as pointed out by TAKAHASHI *et al.* (1994).

Surface undulation on the ice sheet is affected by ice flow on bedrock undulations (BUDD and CARTER, 1971). Figure 5 shows distributions of thermal crack frequency, surface and bedrock topography, and surface slope in the section where glazed surface was observed from 2500 m to 3600 m a.s.l. Glazed surface appears on relatively steeper slopes above convex bedrock topography. Therefore, glazed surface formation is related to surface undulation affected by bedrock undulation. This indicates that bedrock undulation is also one of the factors controlling the formation of glazed surface and snow accumulation patterns.

4. Discussion

Distributions of snow surface features reflect local snow accumulation patterns, and they are controlled by surface undulation affected by bedrock undulation. Here we discuss the regional characteristics of snow surface feature formation and the relationship between snow surface features and ice sheet topography.

Glazed surface was observed in the katabatic wind region defined as Section 2. Glazed surface develops on a relatively steeper slope, where katabatic wind accelerates, the drift-transport rate increases and the surface snow layer is eroded (TAKAHASHI *et al.*, 1994). On the snow surface in such an accumulation-free area, sublimation of snow particles and condensation of water vapor to the surface occur, and glazed surface with multi-layered ice crust is easily formed (FUJII and KUSUNOKI, 1982). On the other hand, on a relatively gentle slope snow particles are easily deposited in the form of dunes. Sastrugi are formed from dunes exposed to constant katabatic wind. Although sastrugi is classified as an erosion form, high frequency of sastrugi occurrence coincides with high net snow accumulation. This indicates that sastrugi is formed by the deposition process.

In the coastal region defined as Section 1, glazed surface was not observed, though the surface slope in some areas is steeper than that in Section 2. This is due to continuous snow accumulation by offshore cyclones and redistribution of drifting snow transported by wind from inland over the ice sheet (TAKAHASHI *et al.*, 1988). This accumulation covers surface roughness and makes it difficult to form glazed surface. The low frequency of dune occurrence is also due to this uniform snow accumulation. Small sastrugi are easily formed from new deposited snow exposed to wind.

In the inland plateau region defined as Section 3, snow accumulation is small and redistribution of drifting snow is also small because of weak wind. In this area, the snow drift form during precipitation was observed as dunes. Small sastrugi are easily formed from softly deposited snow exposed to wind.

Snow surface feature distributions depend on the surface topography on a large scale over several hundreds of km (FURUKAWA *et al.*, 1992). A snow accumulation anomaly in Shirase drainage, which is a valley shaped drainage, was revealed by using NOAA AVHRR data (SEKO *et al.*, 1993). Also in this study, areas where glazed surface develops were confined to the Shirase drainage. This indicates that the snow accumulation anomaly observed by satellite images is due to the existence of glazed surface formed by convergence of katabatic wind (PARISH and BROMWICH, 1987).

Snow surface features reflect redistribution of drifting snow controlled by surface topography on both small and large scales which are affected by bedrock topography. This suggests that glazed surface zones do not move if the ice sheet is in a steady state. And local snow accumulation patterns will be altered by change in surface undulation. If the surface slope above a ridge of bedrock undulation becomes steeper due to change of ice thickness, that will offer a suitable condition for the formation of a glazed surface. It will be followed by increase in low snow accumulation area in the katabatic region on the ice sheet. This process is important in investigating how surface mass balance patterns will response to ice sheet changes.

5. Concluding Remarks

Summarizing the results of this paper we present Fig. 6. From the viewpoint of snow surface features, we can divide the route from the coast to Dome Fuji Station into three regions.

The coastal region below 2000 m a.s.l. is an area where the frequency of large sastrugi is low, and that of small sastrugi is high. Although the surface slope is steep, glazed surface does not develop because of high snow accumulation due to offshore cyclones and redistribution of drifting snow from inland over the ice sheet. The katabatic wind

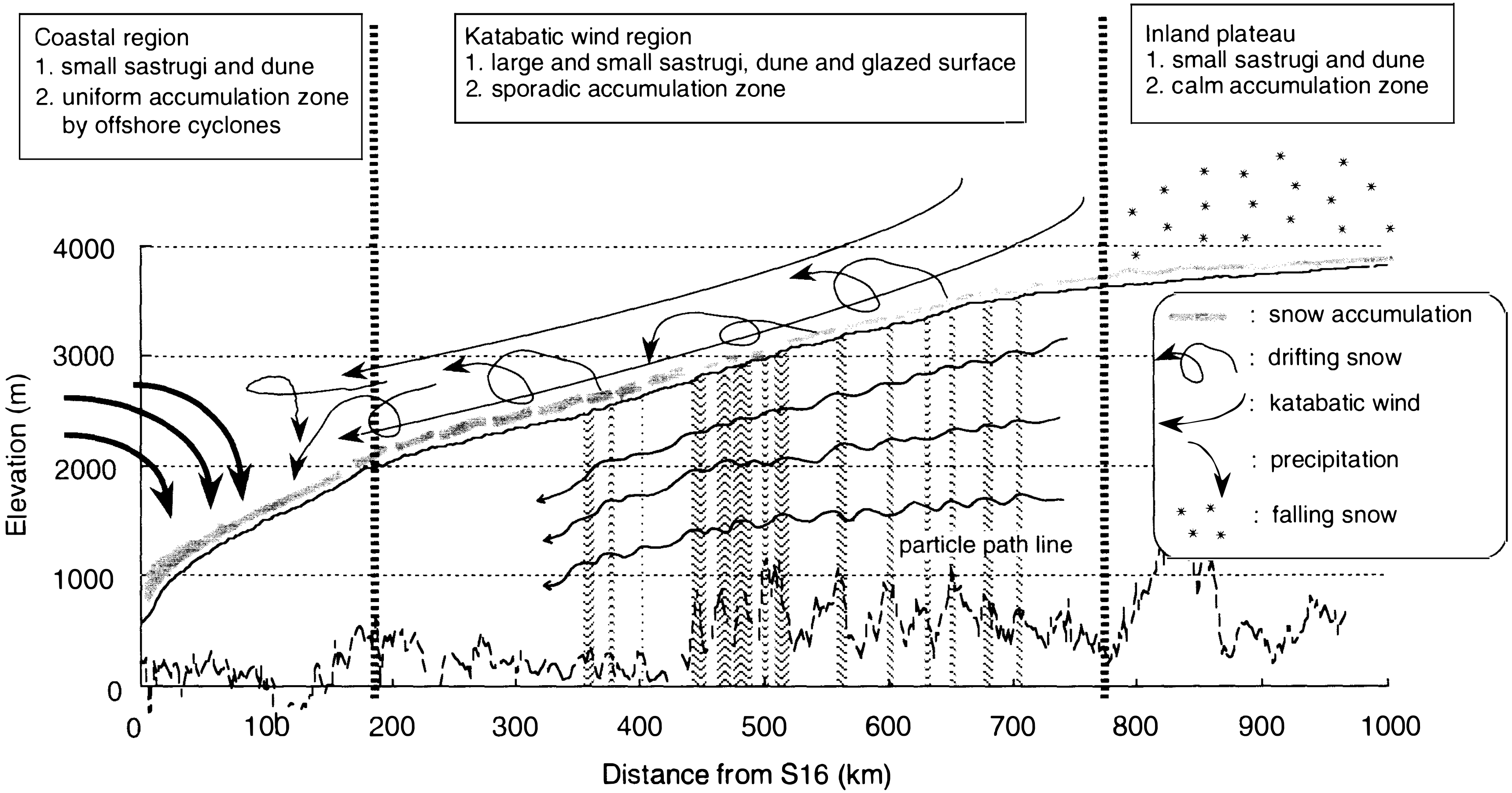

Fig. 6. Schematic model of the depositional regime along the study line. The hatched areas indicate the glazed surface zone observed in this study.

region from 2000 m to 3600 m a.s.l. is the area where sastrugi, dunes and glazed surface alternately appear. Glazed surface develops on steeper surface slopes where katabatic wind accelerates. Around 2200 m a.s.l. frequencies of sastrugi and dunes and net snow accumulation are relatively small. This reflects erosion of surface snow by divergence of snow on convex topography at around 2200 m a.s.l. (TAKAHASHI *et al.*, 1994). In the region above 3600 m a.s.l., frequencies of small sastrugi and dunes are small because of inactive snow accumulation. Erosion of surface snow by wind is small in this region.

Snow surface features reflect redistribution of drifting snow controlled by surface undulations and shape of drainage of the ice sheet, that is affected by bedrock topography on both small and large scales. This is important in the sense that local snow accumulation patterns are controlled by not only surface topography but also bedrock topography. This suggests that local snow accumulation patterns on the ice sheet will be altered by change in surface topography due to ice sheet change. However, more quantitative studies will be needed concerning some factors such as ice sheet flow over bedrock undulation and redistribution of drifting snow on the ice sheet.

The present study was done along a specific route on the Antarctic ice sheet. Characteristics of snow surface feature distributions in this study may reflect the difference of drifting snow redistribution processes between Shirase and Sôya drainages. It is necessary to observe the distribution of snow surface features, surface and bedrock undulation and to study redistribution of drifting snow and surface undulation over a wider area. Not only ground survey but also microwave remote sensing such as scatterometer and altimetry will be useful in these observations. The method used in this study for measuring snow surface features does not directly represent surface roughness on the ice sheet. However, comparing these data with satellite image data will provide useful information for interpreting active or passive microwave images by satellites.

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