IDENTIFICATION OF BEDROCK TYPES BENEATH THE ICE SHEET BY RADIO ECHO SOUNDING IN THE BARE ICE FIELD NEAR THE YAMATO MOUNTAINS, ANTARCTICA

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Abstract: From December 1982 to January 1983 an oversnow traverse party of the 23rd Japanese Antarctic Research Expedition carried out radio echo sounding of a bare ice area near the Yamato Mountains in Antarctica. On the basis of photographs of A-scope recorder which were taken every 1 km along the traverse routes, the reflection intensity of the radio echo signals from the ice/bedrock interface was calculated by correcting the effect of the attenuation loss of electromagnetic waves within the ice sheet. Rock specimens collected from Massif A of the Yamato Mountains, the Minami-Yamato Nunataks and the nearby moraine field, and dielectric constants of the rocks were measured in a frequency range from 3 to 50 MHz. According to the measurements, the values of dielectric constant of the rock samples varied from 2 to 5. To identify bedrock types beneath the ice sheet in the bare ice area, the reflection intensity of the bedrock is compared with the echo strength calculated from the measured dielectric constant of rock samples. It is found that the bedrock is granitic gneiss in the region near Massif A of the Yamato Mountains, and there are a few areas along the traverse route where the bedrock gives a strong echo between −10 and −20 dB.

1. Introduction

Many radio echo sounding flights have been carried out in Antarctica, especially in the regions of Victoria Land, Wilkes Land and Ross ice shelf. These radio echo sounding data have been used to investigate mainly the thickness of ice and to detect small roughness of bedrock, roughness beneath an ice shelf and to discover a sub-ice water area (OSWALD, 1975). STEED and DREWRY (1982) compiled radio echo sounding data and depicted the Antarctic ice sheet surface and bedrock topography of 500000 km^2. In addition to depicting maps, internal and sub-ice characteristics have been also studied. ROBIN *et al.* (1969) calculated the reflection coefficient from the dielectric constant of typical rock types, such as granite and sandstone, but no data of radio echo sounding were compared with the reflection coefficient.

From October 1982 to January 1983, an inland traverse party of the 23rd Japanese Antarctic Research Expedition carried out glaciological investigation in the Shirase Glacier drainage basin and in the southern part of the bare ice area around the Yamato Mountains. During the inland traverses, radio echo sounding was carried out to measure the ice thickness and to investigate the electrical and dielectrical properties of the ice/bedrock interface. In the present study, for the purpose of calculating the reflection coefficient of rocks, rock samples were collected from Massif A and the Minami-Yamato Nunataks and dielectric constants of the sampled rocks were measured. To identify the rock type beneath the ice sheet, the reflection intensity of the bedrock echo obtained by the present radio echo sounding system was compared with the echo strength calculated from the reflection coefficient of the sampled rocks.

2. Field Survey and Morphological Characteristics of the Bare Ice Area

2.1. *Field survey*

Radio echo sounding was carried out along the traverse route of about 50 km between Massif A of the Yamato Mountains and the Minami-Yamato Nunataks (Fig. 1). The radio echo sounding system was operated at 60 MHz, and the sounder used in the present study consists of transmitter and receiver, 3-element Yagi antenna, and Z- and A-scope recorders. A-scope recorder is used to describe one-dimensional display on synchroscope, and Z-scope recorder is the two-dimensional display of the modulated signals along the direction of the traverse route. Records of radio echo sounding were obtained in the oversnow vehicle towing an antenna-installed sledge, and radio echo sounding information was recorded continuously on a 35-mm film by Z-scope recorder during the traverse, and every 1 km by A-scope recorder. Figure 2 shows photographs recorded by Z- and A-scope recorders. The intensity of bedrock echo is digitized from A-scope photographs (Fig. 2a).

Surface elevation was measured by a Pouline altimeter every 1 km and was connected to the positions determined by the satellite navigation system at about 60 km intervals. Bedrock topography was determined by subtracting the thickness of ice from the surface elevation. Figure 3 shows the bedrock topography along the lines of the investigation. Surface topography of the ice sheet near Massif A is rather steep, and bedrock elevation near Massif A and nunataks is higher than that in other areas.

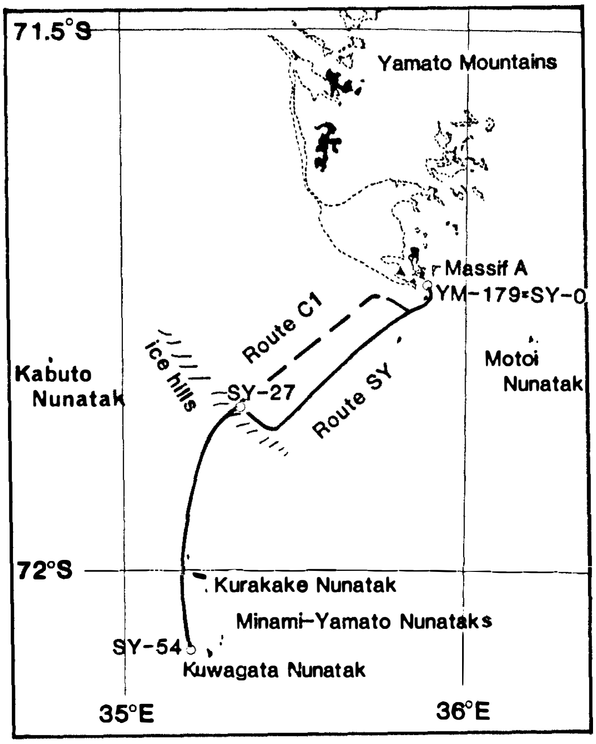

Fig. 1. Map of the investigated area and the traverse routes. Solid line indicates route SY and dashed line route C1.

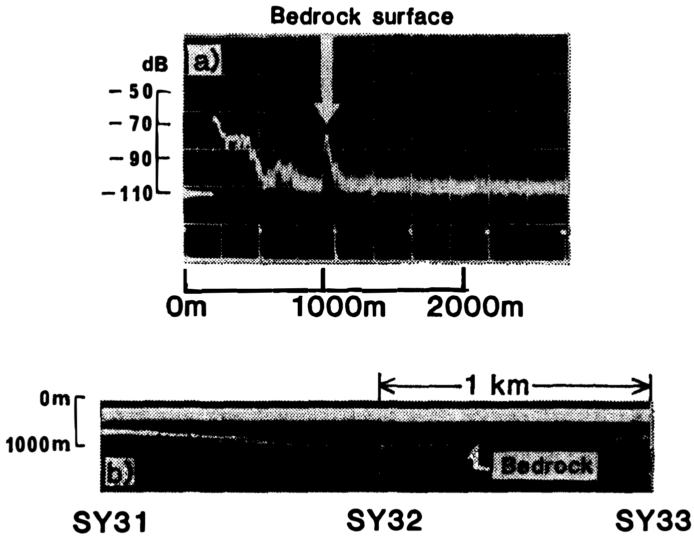

Fig. 2. Examples of radio echo sounding record. a. Photograph of A-scope record at SY-32. b. Photograph of Z-scope record between SY-31 and SY-33. Arrows indicate the bedrock surface.

2.2. Bedrock characteristics of the bare ice area

The strength of the bedrock echo measured by the radio echo sounding system includes attenuation loss, which was caused by absorption in ice and scattering by air bubbles. Therefore, for the purpose of obtaining the reflection intensity of bedrock, it needs to eliminate the effect of attenuation from the bedrock echo.

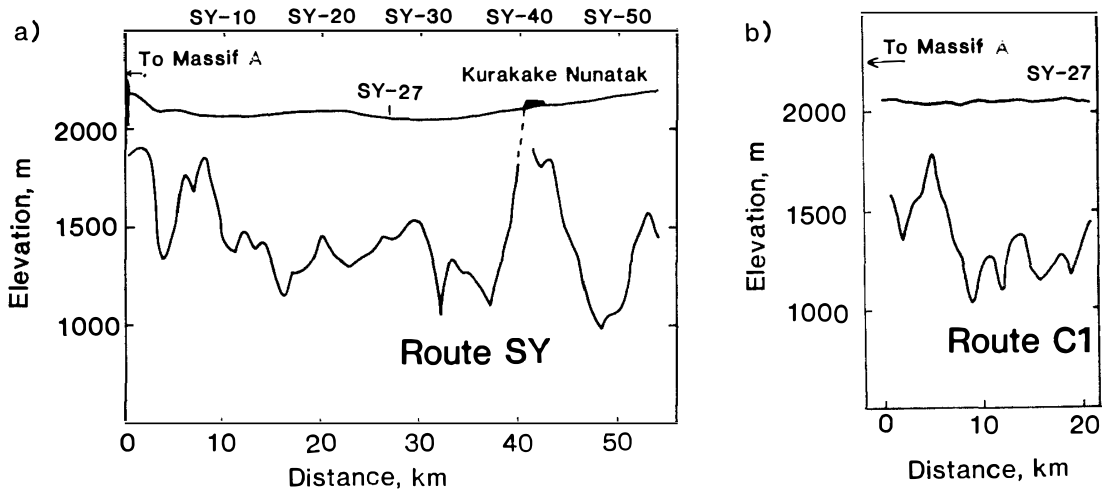

Fig. 3. Bedrock topography and surface elevation. a. Along route SY. b. Along route C1.

The method of calculating the attenuation loss within the ice sheet is as follows: The signals on A-scope records include bedrock echo and internal echo, whose origin has been attributed to density variation, dust and volcanic ash, impurities in the ice and anisotropy of dielectric constant of the ice. Internal echoes from the depth less than about 1000 m have been generally observed, and the strength of internal echo on A-scope photographs decreases as depth increases. The attenuation coefficient is calculated from the gradient of the fitting line of internal echo strength with depth on A-scope photograph. The attenuation coefficient, α_1, is the value of attenuation of echo strength for every 100 m depth (dB/100 m). By using α_1, the ice thickness and the strength of bedrock echo, the reflection intensity of bedrock (g_0) is calculated as in the following equation,

$$g_0 \text{ (reflection intensity)} = g_r + 2 \times \alpha_1 \times \frac{z}{100}, \tag{1}$$

where g_r is the strength of bedrock echo obtained by radio echo sounder which is related to the dielectric constant of bedrock, and z is the ice thickness in meters. Reflection intensity (g_0) is also related to the dielectric constant of bedrock and ice.

2.3. *Dielectric constants of rocks from Massif A of the Yamato Mountains and from the Minami-Yamato Nunataks*

The dielectric constants were measured on the rocks collected from Massif A of the Yamato Mountains, from the Minami-Yamato Nunataks, and from the moraine field around the Minami-Yamato Nunataks. Round plate specimens, about 30 mm in diameter and about 2 mm in thickness, were polished and their capacitance and conductance were measured to obtain the dielectric properties. The instruments used are a conductance bridge (Ando Denki, TR-210) and an oscillator with a null-detector (Wayne Kerr, SR 268). Measurements were made at several frequencies, 3, 5, 10, 20, 30 and 50 MHz at about 20°C of room temperature.

Frequency dependence of dielectric constant of rock samples, garnet-biotite gneiss, is shown in Fig. 4. Values of dielectric constant decrease with frequency

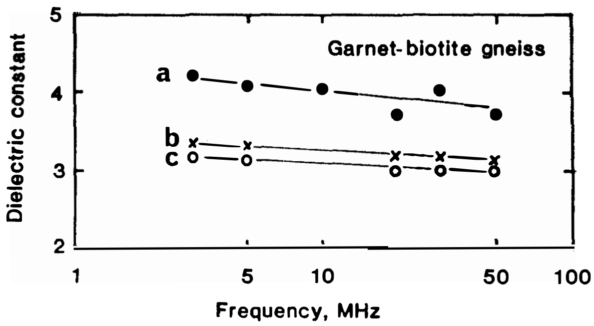

Fig. 4. Frequency dependence of dielectric constant of garnet biotite gneiss sampled at the Minami-Yamato Nunataks.
a. The direction of foliation of rock is 45° to the electric field direction.
b. Foliation is parrallel with the electric field.
c. Foliation is perpendicular to the electric field.

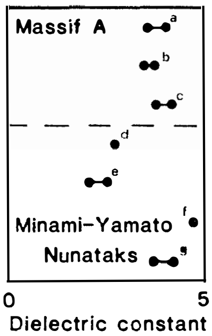

Fig. 5. Dielectric constants of various rocks measured in frequency range from 3 to 50 MHz.
a. Quartz monzonite. b. Quartz syenite charnockite. c. Biotite gneiss. d. Granitic gneiss. e. Granite. f. Biotite gneiss. g. Garnet-biotite gneiss.
a–c: Collected from Massif A,
d–g: from the Minami-Yamato Nunataks.

increase, and the difference in the direction of foliation relative to the electric field gives different dielectric constants.

The measured dielectric constants were summarized in Fig. 5. These values were the results of measurements of specimens with a foliation direction of 45° to the electric field direction. They were less than 5. The value of dielectric constant of granite is the smallest, but granite is not a typical rock in the investigated area. The typical rock of the Minami-Yamato Nunataks is granitic gneiss, whose dielectric constant is about 3 at frequencies from 3 to 50 MHz. Therefore, granitic gneiss can be distinguished from other rock types because of its smaller value of dielectric constant than that of other rocks.

3. Results

3.1. Bedrock topography and surface topography

Figure 3 shows the bedrock topography along routes SY and C1 measured by radio echo sounding. Surface elevation of the survey area is about 2100 m above sea level, but a corrugated bedrock topography was observed between 1000 and 1800 m above sea level. SY-27 is located near the ice hill chain which is 1 km in width and about 100 m in height as reported by YOKOYAMA (1976). Though YOKOYAMA (1976) concluded that the direction of these ice hills seems to coincide with that of ice flow, the bedrock topography along the investigated line shows no such characteristic feature as to decide the direction of ice flow.

3.2. Signals reflected at ice/bedrock interface

The attenuation coefficient (α_1) differs from place to place in the bare ice area.

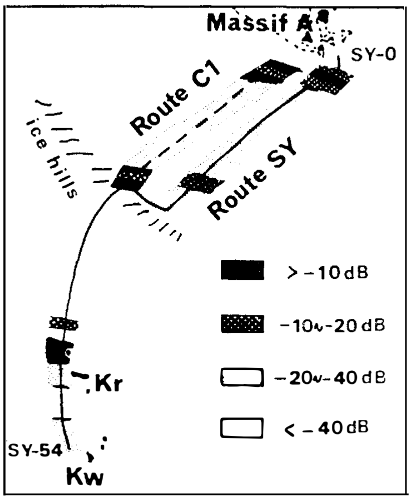

Fig. 6. Distribution of reflection intensity calculated with eq. (1) in the bare ice area. Reflection intensities of bedrock are divided into 4 classes, over −10, −10 to −20, −20 to −40 and below −40 dB. Kr and Kw indicate the Kurakake and the Kuwagata Nunataks, respectively.

According to the result of calculation of α_1, the values of α_1 vary between 2 and 4.5, with an arithmetical mean value being 3.8 dB/100 m.

Figure 6 shows the reflection intensity (g_0) calculated with eq. (1) along routes SY and C1; the values are divided into 4 classes, smaller than −40, −40 to −20, −20 to −10 and higher than −10 dB. Relatively strong reflection intensity was obtained near Massif A, near the Kurakake Nunatak, and near SY-22. It seems that the region with strong reflection intensity on route SY is connected to the region with strong reflection intensity on route C1.

4. Discussion

A simple ice and bedrock layer model is considered assuming the normal reflection of radio wave at the bedrock surface. Reflection coefficient (R) of bedrock is

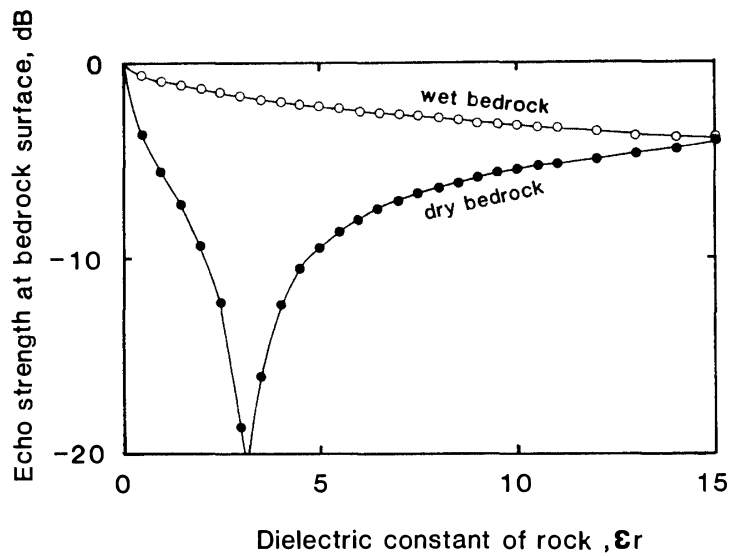

Fig. 7. Echo strength calculated from measured dielectric constants of rocks. Solid circles indicate echo strength of dry bedrock, and open circles wet bedrock.

calculated from measured values of dielectric constants (ε_r) of bedrock types and that of ice (ε_i), that is

$$R=\left|\frac{\sqrt{\varepsilon_i}-\sqrt{\varepsilon_r}}{\sqrt{\varepsilon_i}+\sqrt{\varepsilon_r}}\right|^2 . \tag{2}$$

Figure 7 shows the echo strength, calculated with eq. (2), at the bedrock surface as a function of ε_r. However, in principle, it is impossible to distinguish the rock with dielectric constant of 2 from the rock with that of 5. In both cases the echo strength by eq. (2) comes to have the same value of -9.4 dB. Figure 7 shows the echo strength from dry and wet bedrocks.

Geological survey around the Minami-Yamato Nunataks showed that the granitic gneiss is dominant (SHIRAISHI, 1975). If the bedrock beneath the ice sheet in the Minami-Yamato Nunataks is granitic gneiss with the dielectric constant of about 3, the echo strength is to be -15 dB from dry bedrock and -2 dB from wet bedrock. In the present study, reading error is less than 2 dB. Therefore, these two cases, wet and dry, are distinguished by the present radio echo sounding system in consideration of error in digitizing. And according to the result shown in Fig. 7, if the value of g_0 in eq. (1) is near 0 dB, it is concluded that the bedrock is wet, but bedrock types are not identified.

The strong echo of about -5 dB was received around SY-2 near Massif A. The reason is as follows: Surface slope near SY-2 is rather steep, and the bedrock is uprising. Therefore, radio wave did not reflect normal at the bedrock surface, and reflection from a wider bedrock surface than normal reflection was received by the radio echo sounding system. Thus, it is considered that the bedrock echo becomes strong near SY-2. But it is possible that ice is melting so that an abrupt change of bedrock topography would produce a strong stress at the ice/bedrock interface.

According to the results of the measurement of dielectric constant of collected rocks, the obtained values have no large difference. But from a geological interpretation, it can be concluded as follows: According to the present radio echo sounding, the bedrock is dry and its type is granitic gneiss when the reflection intensity of bedrock (g_0) in eq. (1) is between -10 and -20 dB. Thus, near Massif A, near SY-22, around the Kurakake Nunatak, and in a few places along route C1, the bedrock is considered to be granitic gneiss.

It is concluded that the present radio echo sounding system can detect the existence of a water layer at the ice/bedrock interface, because in this case the reflection intensity is higher than -5 dB (Fig. 7), although the bedrock type is not identified. In the bare ice area between Massif A and the Minami-Yamato Nunataks, granitic gneiss is identified from other bedrock types. But it is difficult to apply the present result to other regions without geological study, and further analysis of radio echo sounding is necessary and a model for calculating echo strength should be prepared.

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