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Ground penetrating radar sounding on an active rock glacier on James Ross Island, Antarctic Peninsula region

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Abstract: This study used ground penetrating radar soundings to examine a tongue-shaped rock glacier (64°04'S 58°25'W) on James Ross Island, Antarctic Peninsula, in January 2005. The rock glacier studied has multiple well-developed transverse ridges and approximately 800 m long from the talus of its head to its frontal slopes and is 300 m wide in the middle. The longitudinal ground penetrating radar profile identified debris bands which dip up-glacier, similar to the thrust structures in the compression zone of a valley glacier. Transverse ground penetrating radar profiles indicated a layered structure which is inclined towards the central part of the rock glacier and which resembles the transverse foliation of a valley glacier. Consequently, the internal structure of the rock glacier is revealed as being similar to the "nested spoons" common in the interior of valley glaciers. We concluded that this rock glacier has been created by the deformation of a glacier ice core and a thick and continuous debris mantle.

Key words: Antarctic Peninsula, James Ross Island, rock glacier, ground penetrating radar.

Introduction

Rock glaciers are tongue- or lobate-shaped debris landforms which resemble small valley glaciers and which move downslope due to the deformation of internal ice or frozen sediments (*e.g.* Haeberli 1985; Benn and Evans 1998). Rock glaciers commonly have multiple transverse ridges on their surfaces and steep frontal slopes. They are widely distributed in the permafrost zones of high mountains and polar regions (*e.g.* Barsch 1996; Humlum 1998).

The Antarctic Peninsula has numerous rock glaciers, and several studies have investigated the formation of rock glaciers in this region (Chinn and Dillon 1987; Strelin and Malagnino 1992; Lundqvist *et al.* 1995; Strelin and Sone 1998; Humlum 1998; Serrano and López-Martínez 2000). Strelin and Malagnino (1992) studied the rock glaciers in James Ross Island and divided them into two types: lobate (mainly ice-cemented) and ice cored types, determining their frequency, dimension, orientation, altitude and ratio of the accumulation and ablation zones, lithological composition, and discussed their possible genesis. Strelin and Sone (1998) studied in detail the morphometry and morphogenesis of ice cored rock glaciers (Lachman II rock glacier) and protalus lobes in Lachman Crags area, NW James Ross Island. Serrano and López-Martínez (2000) proposed that over half of the rock glaciers in South Shetland Islands have originated from the deformation of the lower parts of frozen talus slopes. Previous studies have partially examined the internal structure and the dynamics of the rock glaciers in the Antarctic Peninsula region (Strelin and Sone 1998), however formation mechanisms remain unclear.

In January 2005, a joint research team from Argentina and Japanese "Grupo Criología" used ground penetrating radar (GPR) to determine the internal structure of a rock glacier on James Ross Island. This paper reports the results of these GPR soundings and discusses the formation of the rock glacier.

Study area

James Ross Island (aprox. 64°S 58°W) is located on the eastern side of the Antarctic Peninsula (Fig. 1). A single ice cap, having a central dome reaching 1650 m above sea level (a.s.l.), covers the main part of the island. Only 20% of the

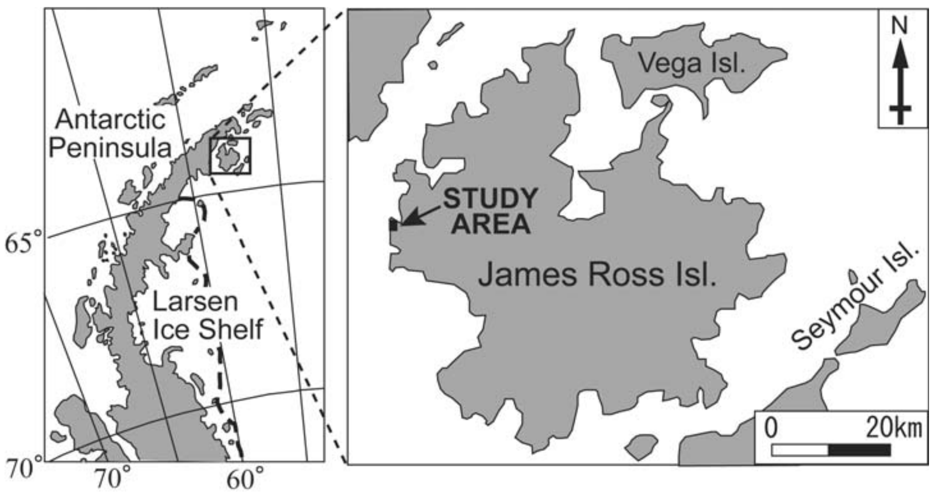

Fig. 1. Location of James Ross Island and study area.

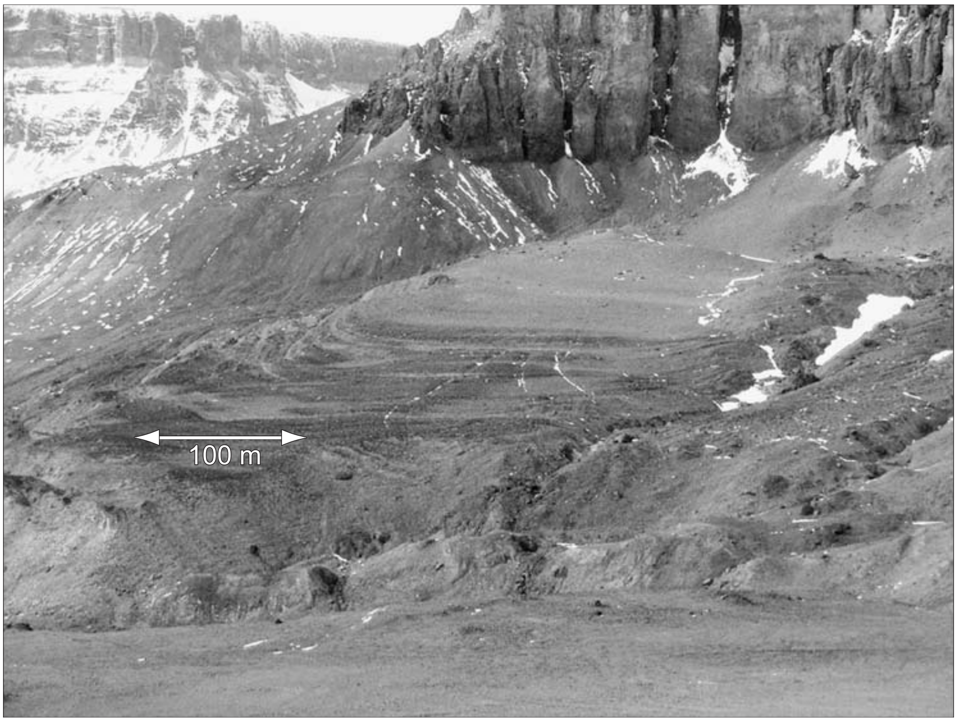

Fig. 2. Tumbledown Norte Rock Glacier (50–190 m a.s.l.).

island is ice-free. Large ice-free areas are situated in the northwestern part of the island and along the western coast, and many rock glaciers and periglacial landforms occur here (Strelin and Malagnino 1992; Fukuda *et al*. 1992; Sone and Strelin 1997). The bedrock of the ice-free areas is mainly Cretaceous sediments and Tertiary volcanic rocks (Bibby 1966).

The rock glacier studied is located in the western coastal area (Tumbledown Crags area; Fig. 1) and is referred to as the Tumbledown Norte Rock Glacier (Strelin and Malagnino, 1992). This is a tongue-shaped rock glacier that is almost completely covered with debris; it is connected to a talus slope (Figs 2 and 3) and is approximately 800 m long and 300 m wide. The altitude of the rock glacier toe and top are 50 and 190 m a.s.l., respectively, and the surface inclination is around 10°. Multiple transverse ridges on the surface of the rock glacier are arranged in a concentric circle pattern (Fig. 2). An unpublished geodetic survey between 2001 and 2004, carried out by our research team, found horizontal surface movements at the center of the rock glacier of approximately 16 cm/yr. The movements of the marginal part of the rock glacier were relatively slower than those at the center. Strelin and Malagnino (1992) described that this rock glacier is a glacier-derived genesis. Lundqvist *et al.* (1995), on the other hand, pointed out that the origin of this rock glacier favors a talus-derived genesis.

The mean annual air temperature from 2003 to 2005 was –6.2°C; the air temperature has been measured by an automatic meteorological station situated on the front (89 m a.s.l.) of the rock glacier. The equilibrium line altitude (ELA) in James Ross island vary very much because of the wind drifted snow accumulation and insulation (among other factors) and reach 200 to 500 m a.s.l., some parts descending to the sea level (in the calving glaciers of the southern part).

Methods

We used a Noggin 250 GPR system (Sensor and Software Inc., Mississauga, Ontario, Canada). The device consists of a transmitter unit, receiver antenna, controller, and data logger. The frequency of the transmitter unit and the receiver antenna is 250 MHz. We measured one longitudinal and three transverse GPR profiles in January 2005 (Fig. 3). The longitudinal GPR profile (647 m long) extended along the central flow line of the rock glacier. The transverse GPR profiles were taken in the lower (124 m long), middle (205 m long), and upper (118 m long) sections of the rock glacier.

The GPR profiles were processed and topographically corrected using Radpro software for Windows (Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea). Surface topographic data for the rock glacier were obtained from

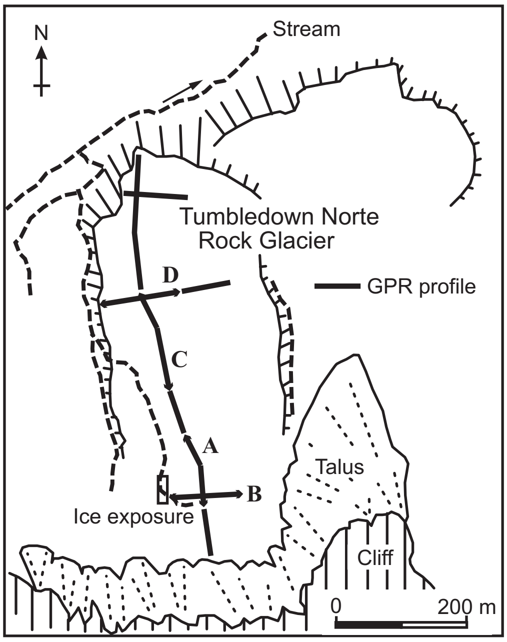

Fig. 3. Main geomorphological features and location of the GPR profiles in the study area.

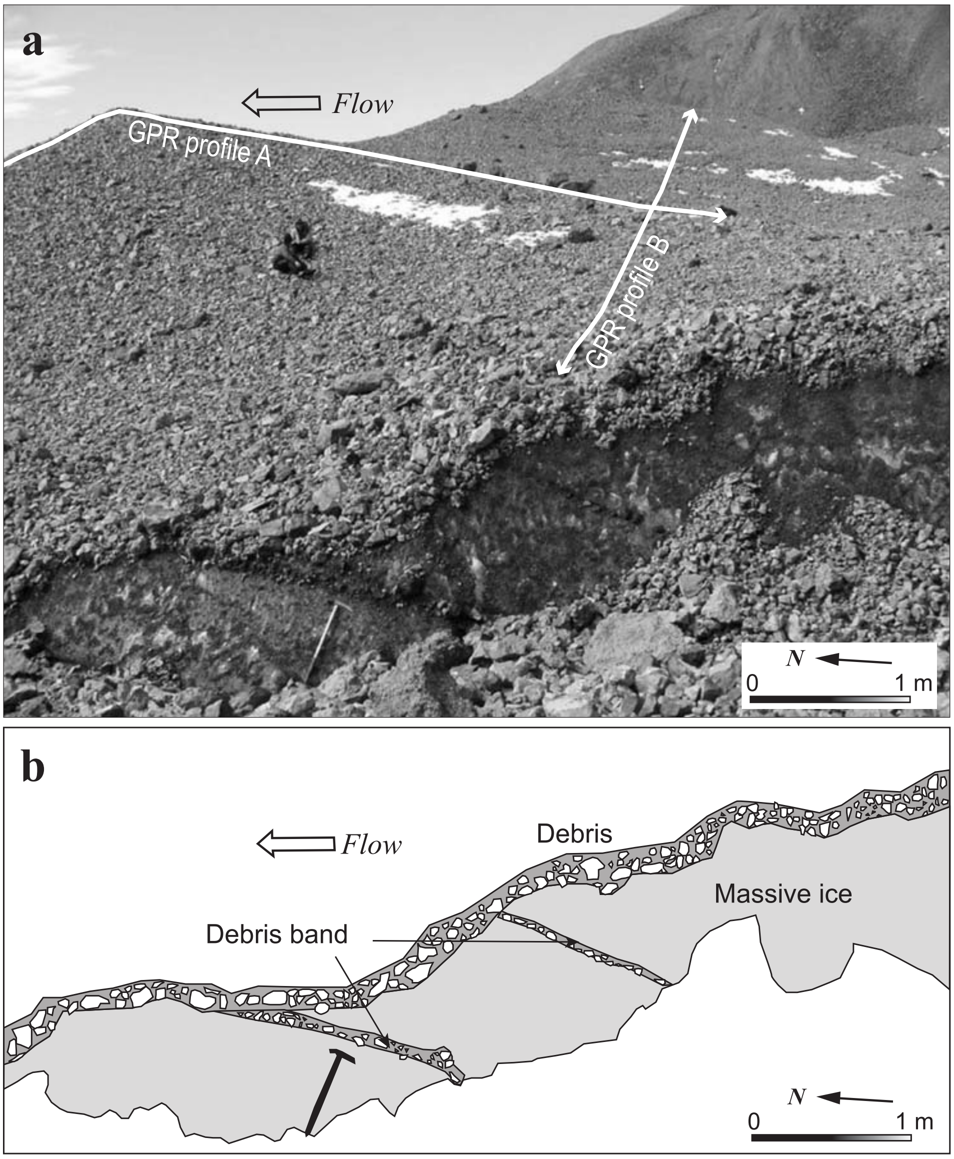

Fig. 4. Photograph (**a**) and sketch (**b**) of the ice exposure. The location of GPR profiles A and B is indicated.

our unpublished geodetic survey. In the upper part of the rock glacier, we identified an ice exposure approximately 50 m long and 1 m high running parallel to the longitudinal GPR profile A (Figs 3 and 4). The ice exposure has been created by erosion of a stream flowing on the upper part of the rock glacier. We sketched the stratigraphical features of the ice exposure in January 2005. Similar ice exposures were observed in the Lachman II rock glacier (Strelin and Sone 1998).

Results

Stratigraphical features of the ice exposure. — The surface layer of the ice exposure is a 10–30 cm thick debris layer composed of sand and angular gravel (Fig. 4). White massive ice rich in trapped air bubbles (0.5–2 mm in diameter) lies underneath the surface debris layer. The massive ice has homogenous crystals 5–6 mm in diameter. Debris bands approximately 5–10 cm thick dip up-glacier in the massive ice (Fig. 4), and two gentle transverse ridges extend across the ice exposure. The debris bands run toward these gentle ridges (Fig. 4).

The GPR profiles. — Profile A was a longitudinal profile in the upper part of the glacier (Fig. 3). A large transverse ridge runs across the profile (Fig. 5). Reflec-

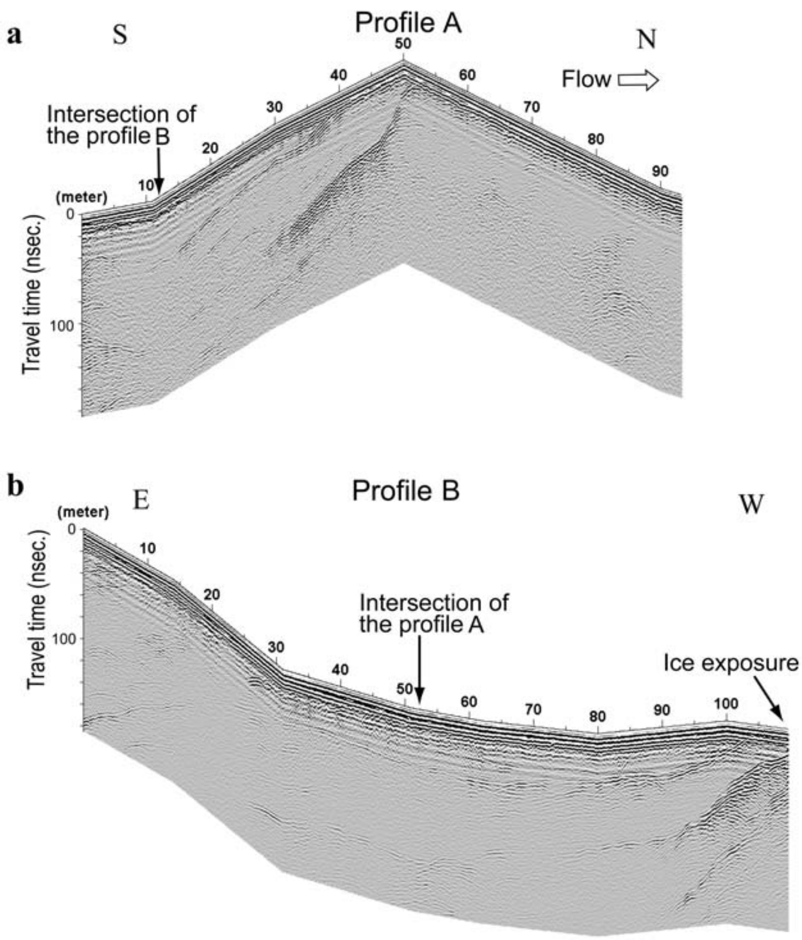

Fig. 5. GPR longitudinal profile A (a) and transverse profile B (b) in the upper part of the rock glacier. For location see Figs 3 and 4.

tions dipped up-glacier in the first 55 m of the profile, and one reflection ran toward the top of the ridge.

Transverse profile B was taken in the upper part of the glacier (Fig. 3). The topography shows a knoll in the first 30 m and a hollow from 30 to 100 m in distance of the profile (Fig. 5). The ice exposure is located at the end of the profile. In the first 30 m, reflections dipped toward the east. From 30 to 110 m, reflections dipped toward the center of the hollow. In the last 20 m, the reflections ran toward the ice exposure (Fig. 5).

Profile C was a longitudinal profile in the central part of the glacier (Fig. 3). Several reflections dipped up-glacier in this profile (Fig. 6). Outstanding transverse ridges were found at approximately 70 and 120 m in distance. Some of the reflections ran toward these ridges (Fig. 6).

Transverse profile D also focused on the central part of the glacier (Fig. 3). The main part of the surface topography of the profile was convex in shape (Fig. 6), and reflections sank toward the profile center.

Discussion

Rock glacier formation. — Debris bands dipping up-glacier were identified in the massive ice of the ice exposure (Fig. 4). Profile A showed clear reflections dipping up-glacier (Fig. 5). Because profile A ran parallel to the ice exposure (Fig. 3) and the debris band reflections had similar dip directions, we interpreted the main part of profile A to be massive ice and the reflections to be debris bands.

The ice exposure was located at the end of profile B (Fig. 3). The reflections ran toward the ice exposure in this profile (Fig. 5), indicating that the main part of profile B was massive ice and the reflections were the debris bands. Based on profiles A and B, profiles C and D were also considered to consist primarily of massive ice with reflections indicating the debris bands.

Hooke and Hudleston (1978) suggested that the internal ice structure of a valley glacier resembles "nested spoons" due to the sedimentary stratification of ice and ice modification by strain during flow. The schematic diagram in Fig. 7 illustrates the internal structure of the study rock glacier based on the GPR profiles. The internal structure of the rock glacier also resembles "nested spoons", suggesting that the glacier originated through the deformation of a glacier ice core and a thick and continuous debris mantle.

Development of the rock glacier ridges. — Reflections interpreted as indicators of debris bands ran toward the transverse ridges in the longitudinal GPR profiles (Figs 5 and 6). This pattern indicates that transverse ridge formation is related to debris band formation.

The debris bands and the movements of the rock glacier suggest the following mechanism for the development of the ridges on the rock glacier. Our unpublished

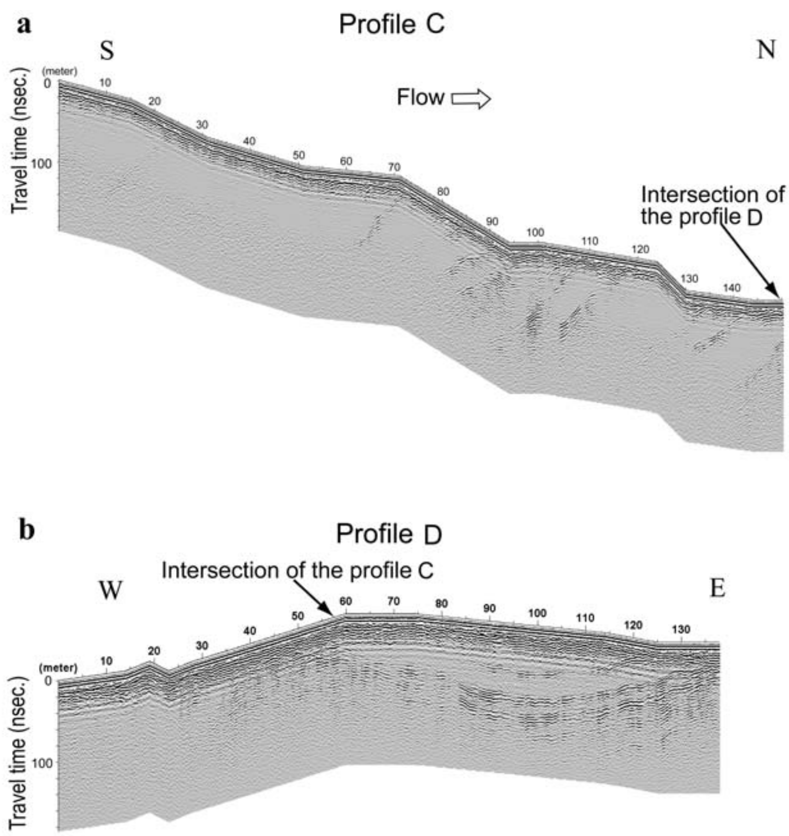

Fig. 6. GPR longitudinal profile C (a) and transverse profile D (b) in the central part of the rock glacier. For location see Fig. 3.

geodetic survey of the rock glacier has confirmed that movements of the marginal part of the rock glacier were relatively slower than those of the central part. Such heterogeneous movements would cause longitudinal compression within the rock glacier and form thrusts in the internal ice. These thrust movements would then create the debris bands by uplifting debris from the bottom of the glacier. Pushing of the upstream ice against the downstream ice would bend the surface layers, forming transverse ridges on the rock glacier surface (Fig. 7). Strelin and Sone (1994 and 1998) proposed a similar origin for the transversal ridges (pressure ridges) formation in Lachman II rock glacier.

Conclusions

The GPR soundings showed that the rock glacier has an internal structure similar to that of the “nested spoons” structure common in valley glaciers. This result

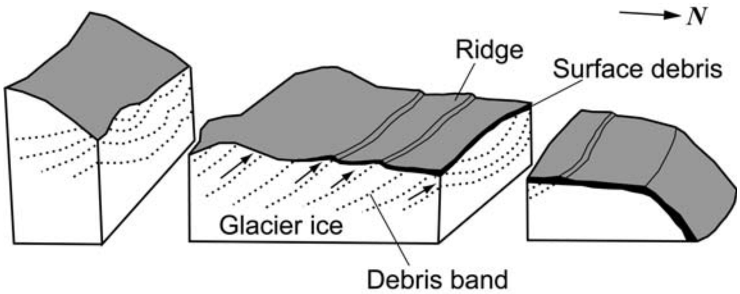

Fig. 7. Schematic diagram of the internal structure of the study rock glacier.

indicates that the rock glacier was formed through deformation of a glacier ice core and a thick and continuous debris mantle. Reflections interpreted as indicative of debris bands ran toward the transverse ridges in the longitudinal GPR profiles. They are likely to have formed by thrust movements in the rock glacier. Movement of upstream ice slow flowing or stagnate against downstream ice would have bent the surface layers of the rock glacier, forming the transverse ridges.

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