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# High-centered polygons in the Sør Rondane Mountains, East Antarctica: Possible effect of ice wedge sublimation

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***Abstract:*** Small high-centered polygons, 3–15 m in diameter, dominate moraine fields in an inland cold desert of the Sør Rondane Mountains, Antarctica. They mainly occur on moraine fields at two stages younger than 1 Ma. The polygons on the younger moraine ($<$0.5 Ma) generally have an ice wedge surrounded by ice-cemented permafrost, although the ice wedge cracking is inactive or too slow to be detectable. The polygons on the older moraine (0.5–1 Ma) have either an ice wedge or ice-free wedge. The ice-free wedge underlies a subsided trough and consists entirely of loose and coarse sediments with vertically-oriented clasts, which represents an ice-wedge cast probably originating from long-term sublimation of an ice wedge. These observations suggest that flat-top polygons with ice wedges form in wet permafrost when located close to the ice sheet surface, but that the subsequent ice sheet lowering separates the polygons from the moisture source, and finally long-term ice sublimation leads to domed polygons with ice-wedge casts enclosed in dry permafrost.

**key words**: Antarctica, permafrost, patterned ground, ice wedge, sublimation

## 1. Introduction

Polygons accompanied by ice or soil wedges (frost wedges) widely occur in terrestrial polar regions underlain by continuous permafrost (*e.g.* French, 1996; Mackay, 2000), including cold deserts in inland Antarctica (*e.g.* Berg and Black, 1966). Particular attention has recently been paid to similar features on the Martian surface, because they possibly indicate the existence of present or past ground ice (*e.g.* Mellon, 1997; Seibert and Kargel, 2001).

In broad terms, frost wedges are classified into *ice wedges* composed mainly of ice and *ice-free wedges* filled with sediments (soil, sand or gravel). The latter group involves active layer soil wedges, primary sand wedges and ice-wedge casts. In previous research on the Antarctic polygons, sand wedges were first highlighted (Péwé, 1959) since the hyper-arid climate is considered to prevent the formation of ground ice. Later excavations demonstrated that ice wedges are also common even on this dry permafrost terrain (Berg and Black, 1966; Bockheim, 2002; Marchant *et al.*, 2002). The ice wedges may reflect, in addition to the presence of (at least a minimum amount of) meltwater, the lack of wind-driven sand particles, which would explain the absence of sand filling in thermal contraction cracks. In fact, recent Antarctic investigations have reported the coexistence of ice (-filled) and ice-free wedges within a small area (*e.g.* Bockheim, 2002).

However, uncertainties still remain regarding Antarctic frost wedges. First, the identification of wedge types is unclear. Although shallow active layers are generally unfavorable for the development of active layer soil wedges, distinction is often difficult between primary sand wedges and ice wedge casts. The second problem is the age and duration of thermal contraction cracking. Few wedge structures have been dated. Also, environmental changes that may have contributed to degradation of ice wedges are rarely evaluated.

High-centered polygons, either dome or flat-top with marginal troughs, occur on moraine fields in the Sør Rondane Mountains, Dronning Maud Land. Matsuoka and Hirakawa (1993) first described the dimensions and internal structure of these polygons. Recent dating using *in situ* produced $^{10}$Be and $^{26}$Al has allowed estimation of the exposure ages of the glaciated mountains (Nishiizumi *et al.*, 1991, 1998; Matsuoka *et al.*, 2006). The purpose of this paper is to compare wedge structures between polygons with different exposure ages and to propose a process of ice wedge formation and degradation. The focus is on the transition from wet to dry permafrost associated with the lowering of the ice sheet. A field measurement of contemporary cracking activity is also reported.

## 2. The study area

### 2.1. *Present periglacial environments*

The Sør Rondane Mountains are ice-free mountains covering an area 200 km wide (22–28°E) and 100 km long (71.5–72.5°S), the center being located about 200 km south of the nearest coast (Fig. 1). The ice-free mountains (the highest at about 3000 m ASL) protrude above the Antarctic ice sheet, the surface elevation of which decreases from about 2500 m at the southern end to about 1000 m at the northern end. The mountains consist of Late Proterozoic to Paleozoic metamorphic and plutonic rocks (*e.g.* Shiraishi *et al.*, 1997).

Meteorological data at Asuka Station (965 m ASL) located at the northern margin of the mountain massif show that the mean annual air temperature (MAAT) is –18.4°C, the summer air temperature approaches but rarely exceeds 0°C, and the winter air temperature falls below −40°C. On north-facing slopes and flat terrain, strong insolation in summer daytime raises the ground surface temperature above 0°C. As a result, thawing occurs frequently on a daily basis, producing an ephemeral active layer shallower than 15 cm in wet soils and 40 cm in dry soils (Matsuoka and Moriwaki, 1992). The active layer depth controls the thickness of debris derived from weathering of the underlying bedrock (Matsuoka, 1995). Deeper deposits result from glacial and, locally, aeolian sedimentation. Whereas younger moraine fields close to the present ice sheet level are underlain by wet (ice-cemented) permafrost, older moraine fields at higher elevations typically display dry (ice-free or partly ice-cemented) permafrost below a dry active layer.

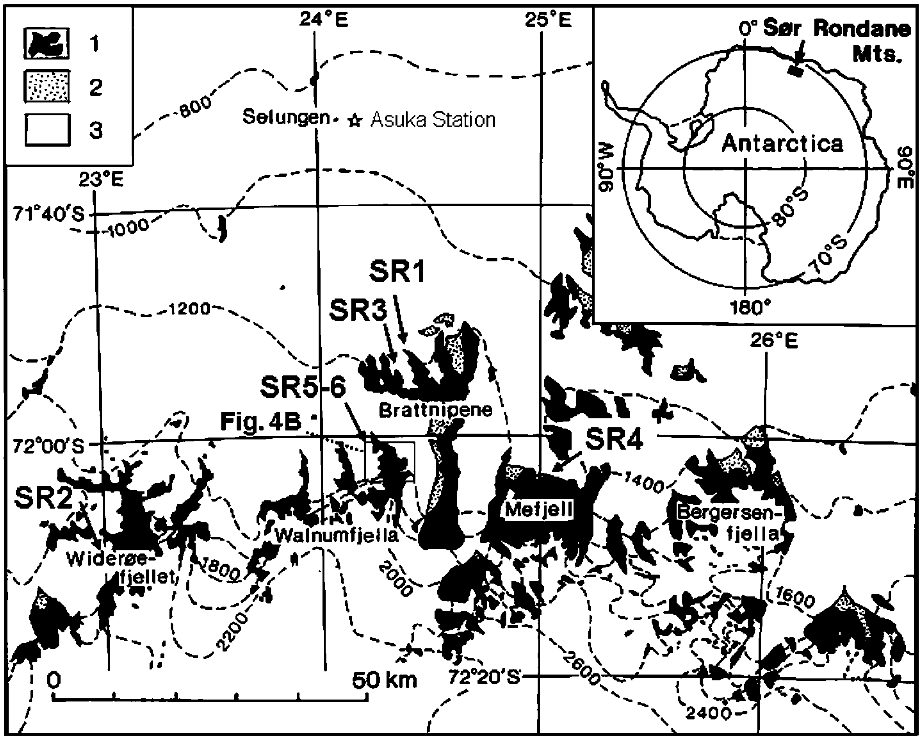

*Fig. 1. The location map of the Sør Rondane Mountains, indicating the excavated polygons (SR1–6). Symbols: 1=Ice-free mountains; 2=Ice-cored moraine fields; 3=Ice sheet.*

Measurable soil displacements (*e.g.* frost heave and creep) occur only on wet slopes having an active layer with a gravimetric water content reaching above 5% (Matsuoka and Moriwaki, 1992). Such wet ground lies exclusively along the ice margin. In other words, cryoturbation rarely contributes to active layer deformation on most of the ground. Polygonal ground is virtually the only periglacial form indicative of permafrost in the study area, because the shallow bedrock, lack of moisture and very cold permafrost generally hamper frost heave, cryoturbation and permafrost creep.

### 2.2. Glacial history

The ice sheet chronology of the Sør Rondane Mountains has been reconstructed by a combination of tills and trimlines at different levels (Hirakawa *et al.*, 1988; Moriwaki *et al.*, 1992), the weathering index (Moriwaki *et al.*, 1991, 1994) and cosmogenic exposure ages (Nishiizumi *et al.*, 1991). These studies identify five glacial stages: the stage number increases with elevation above the present ice level and exposure age. Stage 1 tills mostly constitute thin (<20 cm), supraglacial debris underlain by massive glacier ice and lie within 30 m above the present ice surface. Stage 2 tills, located within 100 m above the ice level, are often thicker than 1 m but in places still ice-cored. The thickness further increases in older tills that have so far shown no evidence of an ice core. Stage 3 tills generally cover an area of 100–300 m above the present ice surface, while Stage 4 covers an area of 200–550 m. The highest ice level (Stage 5) is identified at higher than 600 m above the present level. Since this maximum glaciation the ice level has lowered with minor fluctuations.

A combination of 32 cosmogenic ($^{10}$Be and $^{26}$Al) exposure ages (Nishiizumi *et al.*, 1991, 1998) and the elevations of the sampling sites constrained the minimum ages of the five glacial stages as $<$0.25 Ma (Stage 1), 0.5–1.6 Ma (Stage 2), 1.6–3 Ma (Stage 3), 3–4 Ma (Stage 4) and $>$4 Ma (Stage 5). Recently, corrections have been suggested to the older stages: 0.5–1 Ma (Stage 3), 1–2 Ma (Stage 4) and $>$2 Ma (Stage 5) (Matsuoka *et al.*, 2006), as regards the low atmospheric pressures in Antarctica (Stone, 2000). Accordingly, Stage 2 is considered to be younger than 0.5 Ma, and Stage 1 is also much younger than 0.25 Ma.

## 3. Wedge structures

### 3.1. *General features*

Polygonal ground occurs widely on moraine fields at Stages 1–3 (Moriwaki and Hirakawa, 1992; Matsuoka and Hirakawa, 1993). Polygons with distinct geometry develop mostly on Stage 2–3 moraines composed of gravelly sand commonly thicker than 1 m. In contrast, indistinct or irregular patterns dominate on Stage 1 moraines composed of thin gravelly sand or mud (10–40 cm thick) underlain by massive glacier ice. The latter patterns may be immature or deformed by decaying ice cores.

Polygons are generally small, commonly 3–15 m in diameter (Matsuoka and Hirakawa, 1993), and most of them display high-centered vertical profiles (dome or flat-top with marginal troughs). Troughs delimiting the polygons are commonly about 50 cm wide and 10 cm deep. The troughs are rarely surrounded by a pair of distinct ridges (*i.e.* low-centered) that are common on wet ground in Arctic regions (*e.g.* Mackay, 2000).

Polygons with distinct surface geometry are investigated at six sites in four areas (Fig. 1): northern Brattnipene (SR1, 3), Widerøefjellet (SR2), northern Mefjell (SR4) and northern Walnumfjella (SR5–6). A representative trough at each site was excavated with an engine cutter. The polygonal patterns and wedge structures are summarized in Table 1. Five troughs (SR1–5) are underlain by ice wedges while one (SR6) is accompanied by an ice-free (permafrost soil) wedge.

### 3.2. *Polygons on Stage 2 moraines*

All excavated polygon troughs on Stage 2 moraines (SR1–4) have ice wedges (Table 1). The ice wedges have dimensions of up to 90 cm wide and 80 cm in the vertical dimension and underlie dry ice-free debris 15–30 cm thick (Figs. 2–3). Because the debris thickness only slightly ($<$15 cm) exceeds the active layer thickness at the excavation, these ice wedges are considered to be active or to have not been subjected to a warmer climate since being inactivated. The bottom of the ice wedges lies at 60–120 cm depth from the ground surface (Table 1), the depth being nearly proportional to the diameter of the adjacent polygons (Matsuoka and Hirakawa, 1993). New, open cracks were not observed in the ice wedge troughs.

The active layer and permafrost of the ice wedge polygons contrast in the moisture (water or ice) content. The active layer is very dry, typically having a gravimetric

*Table 1. Wedge structures below excavated polygon troughs.*

| Area | Site | Elevation | Glacial | Excavation | ALT[a] | Permafrost | Polygon | Wedge structure | | | Host |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (m ASL) | stage | date | (cm) | humidity | diameter (m) | Type[b] | Width (cm) | Depth (cm)[c] | material[d] |
| N-Brattnipene | SR1 | 1120 | 2 | 16/01/87 | 15 | Wet | 7.1 | ICW | 75 | >65 | GS (till) |
| Widerøefjellet | SR2 | 1600 | 2 | 17/01/89 | 15 | Wet | 5.2 | ICW | 70 | 120 | GS (till) |
| W-Brattnipene | SR3 | 1260 | 2 | 31/12/90 | 25 | Wet | 5.3 | ICW | 88 | 105 | GS (till) |
| Mefjell | SR4 | 1260 | 2 | 10/01/91 | 30 | Wet | 5.5 | ICW | 45 | 110 | GS (till) |
| N-Walnumfjella | SR5 | 1550 | 3 | 30/01/91 | 20 | Wet | 3.7 | ICW | 6 | 56 | GS (till) |
| N-Walnumfjella | SR6 | 1550 | 3 | 30/01/91 | 20 | Dry/Wet | 11.9 | IFW | (45)[e] | 124 | GS (till) |

[a] ALT: Active layer thickness (at excavation).

[b] ICW: Ice wedge; IFW: Ice-free wedge.

[c] Depth from the ground surface to the bottom of wedge.

[d] GS: Gravelly sand.

[e] Width at the top of permafrost.

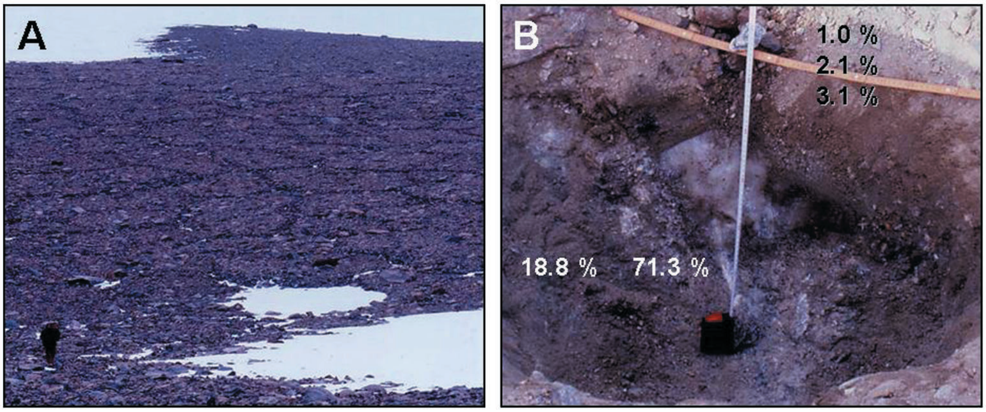

*Fig. 2. Flat-top polygons and an excavated ice wedge on a Stage 2 moraine field at SR1, northern Brattnipene. (A) Polygon diameters are 5–10 m. A man at the left-lower corner gives scale. (B) The vertical scale is 1 m long. The figures indicate the gravimetric water content of the active layer and ice content of the permafrost when excavated.*

water content of $<4\%$ that increases downward, while the uppermost part of permafrost surrounding the ice wedges is considerably wet (*i.e.* ice-cemented) with a gravimetric ice content of $>15\%$ (see Figs. 2B and 3B).

### *3.3. Polygons on Stage 3 moraines*

Two kinds of polygons, of different dimensions and shapes, coexist on a Stage 3 moraine field in an upland dry valley, the up-valley of which ends with a wind gap falling 300 m toward an outlet glacier (Fig. 4B). Small flat-top polygons (SR5) occur along

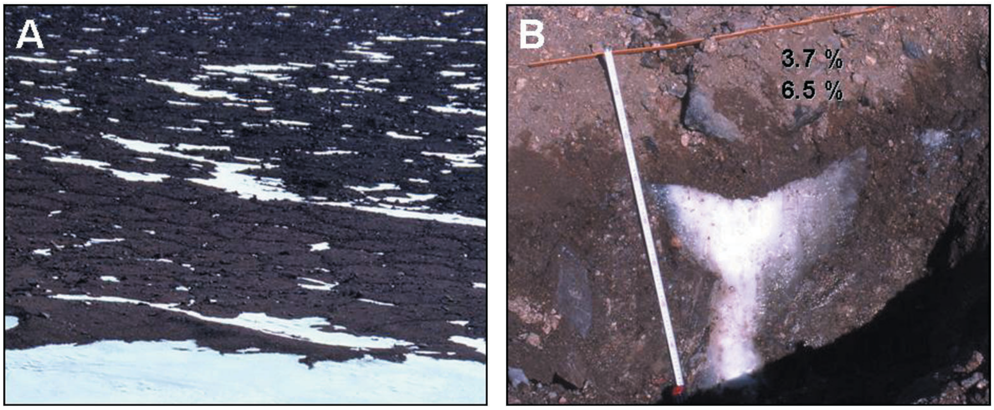

*Fig. 3. Flat-top polygons and an excavated ice wedge on a Stage 2 moraine field at SR4, Mefjell. (A) Polygon diameters are 4–8 m. (B) The vertical scale is 1 m long. The figures indicate the gravimetric water content of the active layer when excavated. Note that the boundary between the light and dark layers indicates the frost table on excavation, which lies 10 cm above the top of the ice wedge.*

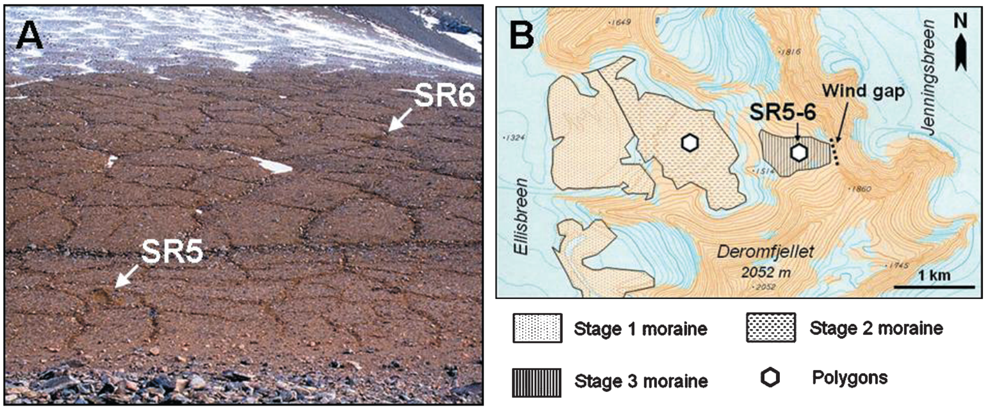

*Fig. 4. (A) Two types of high-centered polygons, flat-top (SR5, 3–5 m in diameter) and dome (SR6, 5–10 m in diameter) on a Stage 3 moraine field, northern Walnumfjella. The arrows indicate the excavated troughs. (B) SR5–6 polygons are located in a dry valley, the upper end of which constitutes a wind gap located 300 m above Jenningsbreen glacier.*

the northern margin of the valley floor, while larger high-centered (domed) polygons with deeper troughs (SR6) occur at the center of the valley floor (Fig. 4A). The former are 3–5 m in diameter and delimited by shallow troughs. Excavation of a trough displays under the dry active layer a miniature ice wedge 6 cm in the top width and 20 cm in the vertical dimension, surrounded by ice-cemented permafrost (Fig. 5). The bottom of the wedge lies at 56 cm depth. Perhaps this is one of the smallest ice wedges ever reported.

The ice-free wedge (SR6) occurs adjacent to the miniature ice wedge (SR5). The

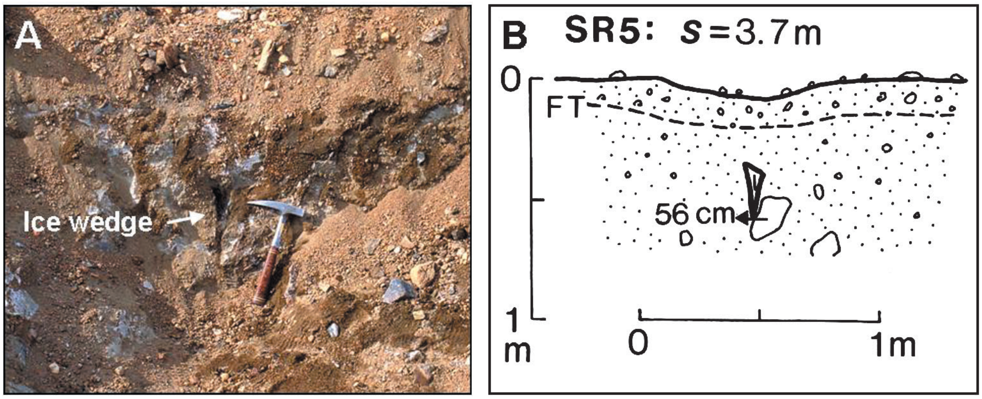

*Fig. 5. A miniature ice wedge at SR5. (A) The hammer is 33 cm long. Note the dark (ice-cemented) permafrost surrounding the wedge. (B) The average diameter of two adjacent polygons S, the depth of the wedge-tip (arrow) and the frost table when excavated (FT) are indicated.*

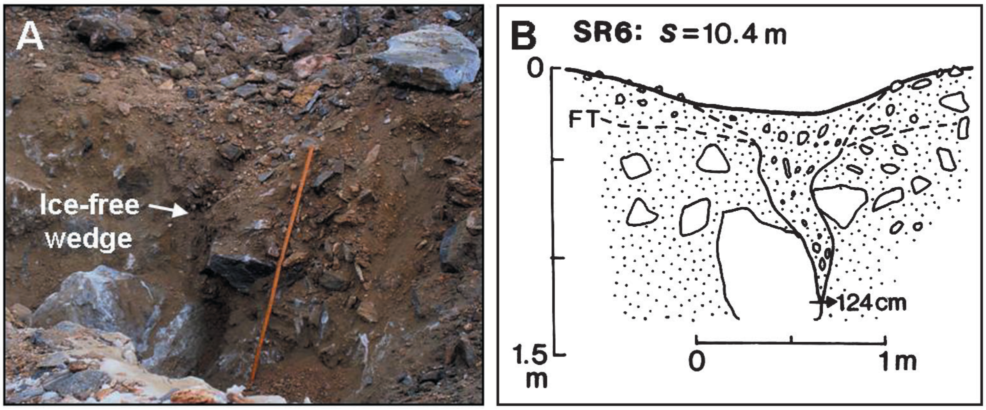

*Fig. 6. An ice-free wedge at SR6. (A) The scale is 1 m long. Note the coarse and loose debris with vertically-oriented clasts in wedge and the surrounding dry debris. (B) The average diameter of two adjacent polygons S, the depth of the wedge-tip (arrow) and the frost table when excavated (FT) are indicated.*

ice-free wedge underlies a trough fringing slightly domed polygons (Fig. 4A). The polygons are nearly the largest (10–15 m in diameter) observed in the study area and their morphology is similar to that of the mature stage (sand wedge) polygons in McMurdo Dry Valleys (Marchant *et al*., 2002; Sletten *et al*., 2003). The bottom of the wedge, lying at 124 cm from the surface, penetrates well into the permafrost. The wedge is composed of poorly sorted gravelly sand dominated by vertically oriented clasts (Fig. 6). The whole wedge filling consists of coarse and loose materials compared to the host material, while a concentration of fine debris indicative of a sand wedge is not observed in the wedge. When excavated, the active layer, wedge and uppermost part of the host permafrost display dry surfaces devoid of any visible ice (Fig. 6A). In contrast, the deeper permafrost partly showed a dark, ice-cemented face. Although snow is occasionally trapped in the marginal troughs when an intensive blizzard has passed, most of the snow seems to sublimate before melting and percolating in the ground.

## 4. Cracking activity

Contemporary cracking activity was evaluated by a simple field measurement of the growth of polygon troughs at two ice wedge sites, SR1 and SR4 (Figs. 2–3). A pair of iron rods, 2 cm in diameter and 20 cm in length, were installed vertically across an ice wedge trough. The distance between the two rods was measured with a steel tape at intervals of 1–4 years. The top 2 cm of the rods was exposed above the ground surface. A small hollow 1 mm in diameter marked on the top surface of the rods ensured the accuracy of the measurement. The bottoms of the rods were not anchored in permafrost, but the dry sandy sediments hamper the movement of the rods by frost heave and/or cryoturbation in the active layer (cf. Matsuoka and Moriwaki, 1992). Accordingly, the technical error and/or disturbance by the active layer deformation is considered, in most cases, to be less than 2 mm. The measurement was undertaken at ice wedge troughs near the excavated troughs using six pairs of rods at SR1 and four pairs at SR4 (Fig. 7).

At both sites, changes in the distance between the two rods were negligible (within the technical error) in the four year period (1987–1991). An exception was a decrease (closing of the trough) of 5 mm recorded at 1E (Table 2), although this value is questionable, because the large distance between the rods (*ca.* 1.2 m) may have significantly lowered the accuracy. Even though the measurement was accurate, the troughs failed to demonstrate significant widening indicative of ice wedge growth. Our measurements imply either present-day inactivity or extremely slow growth of the ice wedges, although at least a few decades of measurements are required to obtain a significant conclusion (*e.g.* Mackay, 1992, 2000).

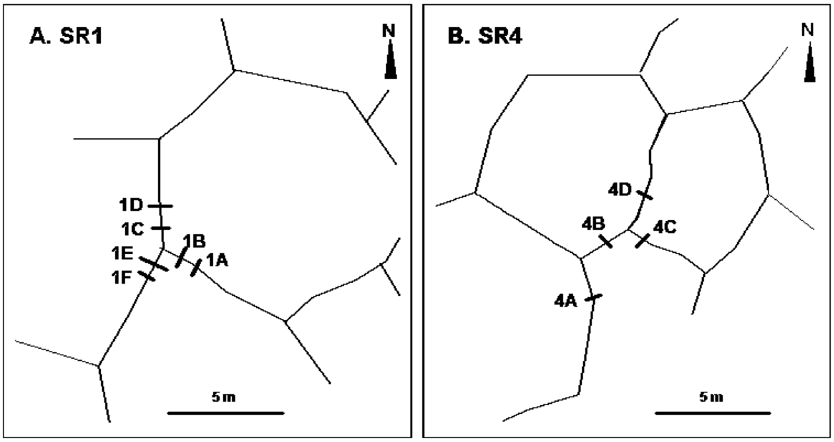

*Fig. 7. Polygonal patterns at SR1 and SR4, indicating the locations of the distance measurement across ice wedge troughs.*

*Table 2. Widening of ice wedge troughs at SR1 and SR4 (in mm).*

| Rods | Initial distance | Incremental distance (datum Jan. 87) | | |
|---|---|---|---|---|
| ID[a] | Jan. 87 | Feb. 88 | Dec. 88/Jan. 89[b] | Jan./Feb. 91 |
| SR1 | | | | |
| 1A | 673.0 | -0.1 | -0.3 | -0.8 |
| 1B | 828.8 | 0.6 | -0.4 | -0.6 |
| 1C | 730.5 | 0.5 | 0.0 | -0.7 |
| 1D | 951.3 | 0.8 | 0.2 | -0.8 |
| 1E | 1194.2 | -1.2 | -1.5 | -5.1 |
| 1F | 769.5 | -0.4 | -0.8 | -1.8 |
| SR4 | | | | |
| 4A | 648.8 | - | - | 0.4 |
| 4B | 479.0 | - | - | 0.8 |
| 4C | 499.8 | - | - | -0.9 |
| 4D | 604.6 | - | - | 0.8 |

[a] See Fig. 7 for locations.

[b] Averages of two measurements.

## 5. Discussion and conclusions

### 5.1. Polygon geometry and wedge structure

One of the characteristics of the polygonal ground in the Sør Rondane Mountains is the small diameters (3–15 m), which are minimum of the typical polygons (5–30 m) in both Arctic regions (*e.g.* Black, 1974) and Antarctica (Berg and Black, 1966; Marchant *et al.*, 2002; Pringle *et al.*, 2003). The predominance of small polygons may reflect the material, climate or age. The glacial deposits at Stages 2–3 in the study area are coarse but well consolidated compared with younger and finer soils at typical Arctic ice wedge sites (*e.g.* Mackay, 2000). In the frozen state, the former material probably has larger resistance to thermal stress than the latter. Such resistant frozen ground may produce a shallower crack and narrower stress relief resulting in a smaller polygonal spacing (Lachenbruch, 1962; Pringle *et al.*, 2003). In addition, episodic cold temperature with rapid cooling induces high tensile stress (*e.g.* Lachenbruch, 1962; Matsuoka, 1999) that can generate new cracks and subdivide the polygons (Plug and Werner, 2002). The lack of snow cover, shallow active layer and/or very cold uppermost permafrost in the study area favor such rapid cooling. Furthermore, the long-term exposure for more than 100 ka in the study area, increases the chances for episodic cold winters and thus for subdivision of polygons.

Small polygons with a diameter of less than 5 m usually lack ice wedges but have only active layer soil wedges in most polar regions (*e.g.* Jahn, 1983). This is because such small polygons are usually accompanied by shallow thermal contraction cracks that do not reach the underlying permafrost. Cold summer with a very shallow active layer (~30 cm) in the Sør Rondane Mountains favors ice wedge formation despite the shallow thermal contraction cracks (Matsuoka and Hirakawa, 1993).

### *5.2. Origin of the ice-free wedge*

An ice wedge accompanies all of the excavated polygons developed on Stage 2 moraines. Whereas the active layer is dry (gravimetric water content usually $<4\%$), the uppermost part of the permafrost is ice-cemented (gravimetric ice content $>15\%$). The ice wedges occur in the ice-cemented permafrost. The ice wedge growth was not detectable within four years, which implies contemporary inactivity or very slow growth. These conditions suggest that ice wedges grow when minimum supply of snow and subsequent melting take place following rapid cooling that induces thermal contraction cracking. In contrast, regardless of present-day activity, sublimation has not yet consumed a large part of the ice in the uppermost permafrost including the ice wedge. As a result, ice wedges are preserved in wet permafrost. Stage 2 moraines appear to favor the ice wedge preservation, because of the location close to the moisture source (snow-covered ice sheet), the relatively short exposure age ($<0.5$ Ma), or both.

A Stage 3 moraine has polygons fringed by deep troughs and an underlying ice-free, gravelly wedge with vertically oriented clasts (SR6). Two origins, monogenetic and polygenetic, are suggested for this morphology and structure. In the monogenetic process, a sand wedge develops by repetitive thermal contraction cracking coeval with sublimation of the underlying glacier ice under a long-term arid climate (Marchant *et al.*, 2002), which is regarded as a kind of primary sand wedge (*i.e.* Murton *et al.*, 2000). This process leads to a wedge with primary filling sand in the lower part and loose gravelly debris in the upper part. The polygenetic origin includes ice wedge growth under a relatively wet condition and subsequent ice melting under a warm climate or ice sublimation under a cold-arid climate, thus producing an ice-wedge cast.

At SR6, polygenetic origin is plausible. This is because the whole wedge consists of loose gravelly debris with vertically oriented clasts, which implies the falling of the active layer into the space produced by ice wedge degradation, while clasts, where present, must be concentrated near the tops of sand wedges (Murton *et al.*, 2000). In addition, the wedge structure lacks primary filling fine debris either laminated, or massive and well-sorted (Murton *et al.*, 2000). However, the hypothesis that the ice wedge cast at SR6 has resulted from melting of permafrost is ruled out, because it requires an episodically warm period having produced an active layer deeper than 124 cm during the last few 100 ka. Antarctic nunataks surrounded by the huge ice sheet are unlikely to have experienced such deep melting that requires several months of continuously positive temperatures, although the presence of large gypsum crystals on Stage 2 moraines implies a past warm period that produced at least a salty water reservoir (Moriwaki and Hirakawa, 1992).

A more plausible process of ice consumption is sublimation under a cold-dry climate (*e.g.* Marchant *et al.*, 2002; Bockheim, 2002). When located close to the ice sheet level, the polygons may have developed in wet permafrost that promoted ice wedge formation. The subsequent ice lowering and predominance of colder and drier conditions, possibly aided by the valley morphology susceptible to passage of dry wind, may have gradually induced ice sublimation from both the ice wedge and the host permafrost over the last few 100 ka, which eventually produced the ice-wedge cast surrounded by dry permafrost. The high permeability of the wedge filling debris may promote sublimation around the wedge (*e.g.* Marchant *et al.*, 2002).

The coexistence of the miniature ice wedge (SR5) and ice-wedge cast (SR6) in the same valley is problematic. The two wedges contrast in the dimensions of polygons and wedge structures, wedge types and permafrost humidity. The contrast may indicate that the smaller polygons are much newer features and/or have not experienced significant subsidence due to ice sublimation, possibly because they are situated in a less windy location (a margin of the valley floor).

### 5.3. *Rates of ice wedge formation and degradation*

In the McMurdo Dry Valleys, measurements of widening of polygon troughs for 39 years show that sand wedges have grown at a mean growth rate of 0.6 mm $a^{-1}$ (Sletten *et al*., 2003; measurements initiated by Berg and Black, 1966). Inward tilting of the rods due to uplift of the wedge periphery may lead to slight underestimation of the actual growth rates. Another measurement in the Dry Valleys, automatic monitoring of sand wedge widening for four years, shows a mean growth rate of 1.4 mm $a^{-1}$ (Sletten and Hallet, 2003). On the assumption that ice wedges grow at a rate similar to sand wedges, extrapolation with a conservative rate of 0.6 mm $a^{-1}$ accounts for the width of typical ice wedges in the Sør Rondane Mountains (40–90 cm) by about 1 ka of continuous thermal contraction cracking. This estimation implies that individual ice wedges formed within a short period during a long exposure history (>100 ka).

The growth of ice wedges terminates when the active layer dries up or climate change decreases intensive cooling events. However, polygons and the underlying ice wedges are still preserved until sublimation or melting of permafrost completely consumes the wedge ice. As discussed above, the ice wedge cast at SR6 most likely resulted from sublimation of the uppermost part of the permafrost.

The rate of sublimation of massive ice beneath the glacial drift has been estimated using cosmogenic nuclides of clasts in the drift to be a few meters to several decameters per Ma (Schäfer *et al*., 2000; Marchant *et al*., 2002; Ng *et al*., 2005). This suggests that an ice wedge about 1 m in the vertical dimension would disappear within a few 100 ka by sublimation, although the rate of sublimation of wedge ice surrounded by ice-rich permafrost may slightly differ from that of massive ice. These conditions lead to a conclusion that ice wedges in the Sør Rondane Mountains develop in a short period under a relatively wet and cold environment close to the ice sheet level, and they are preserved under a drier climate until the wedge ice completely sublimates by long-term exposure for more than a few 100 ka and finally turns into ice-wedge casts.

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