Thermal regime, isotopic and morphological characteristics of ice wedges in northern Victoria Land, Antarctica

R. Raffi,[1] B. Stenni,[2] L. Genoni,[2] O. Flora,[2] and S. Sega[1]

[1]Department of Earth Sciences, Sapienza University, Piazzale Aldo Moro 5, 00185 Roma, I (rossana.raffi@uniroma1.it), (simone_s@yahoo.it)
[2]Department of Geological, Environmental and Marine Sciences, Trieste University, Via E. Weiss 2, 34127 Trieste, I (stenni@univ.trieste.it), (genoni@univ.trieste.it), (flora@univ.trieste.it)

Summary This paper reports the results of a field survey carried out on an ice-wedge polygon site in the Terra Nova Bay area, in northern Victoria Land. Ice wedges were found at depths ranging from 27 cm to 55 cm from the ground surface. The ice wedges had a width at their top of 13 to 55 cm, and a height varying from 50 cm to over 80 cm. Petrofabric analyses were also performed on ice-wedge ice to investigate changes in fabric across wedges, in relation to the growth mechanism. Crystal size increased from the centre outward; *c*-axis directions showed a preferred vertical to sub-vertical orientation, parallel to the axial plane at the wedge centre, and parallel to the foliation at the boundaries of the wedges.

A co-isotopic study was performed by measuring both the oxygen ($\delta_{18}O$) and hydrogen (δD) isotope compositions and the tritium activity. The measurements obtained for $\delta^{18}O$ and δD had extremely negative *d* excess values, showing a strong divergence from the snowfalls expected to occur at the elevation of the site (874 m a.s.l.). Sublimation processes were taken into account to define the origin of the ice-wedge ice. A data logger, using NTC sensors, was installed to record hourly temperatures of the air, of the ground surface, and of the top and bottom of an ice wedge. A complete year of monitoring of the ice-wedge thermal regime (1 February 2004 – 31 January 2005) showed thermal gradients that could trigger ice-wedge cracking.

Citation: Raffi, R., B. Stenni, L. Genoni, O. Flora, and S. Sega (2007), Thermal regime, isotopic and morphological characteristics of ice wedges in northern Victoria Land, Antarctica, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES X, edited by A.K. Cooper and C.R. Raymond et al., USGS Open-File Report 2007–1047, Extended Abstract 204, 4 p.

Introduction

Ice-wedge and sand-wedge polygons are common throughout southern Victoria Land, as studied by different authors (i.e., Péwé, 1959; Black and Berg, 1963; Berg and Black, 1966). In northern Victoria Land, ice-wedge and sand-wedge polygons were widely described by French and Guglielmin (2000). More recently new researches on ice wedges in northern Victoria Land was initiated by the authors, focusing on petrofabric, isotopic and thermometric analyses (Raffi, 2003; Raffi et al., 2004).

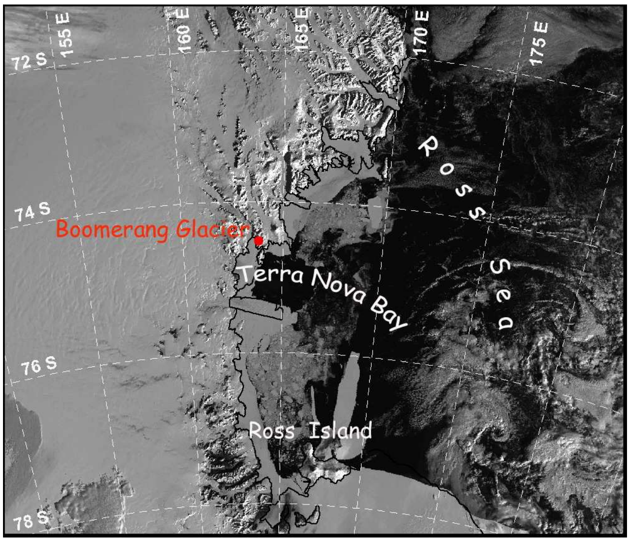

Figure 1. Location of the study site. Satellite image by Italian Antarctic National Research Program.

In northern Victoria Land, polygons are widespread and occur over unconsolidated materials that locally cover ice-free areas. From 1998 to 2006, during four summer field seasons, we excavated numerous polygons, along the coast and in interior areas. Ice wedges were found in 45 sites at depths ranging from 10 cm to 74 cm from the ground surface. Their size ranged from 5 cm to 155 cm in width, and from 20 cm to over 150 cm in height. Three data loggers for monitoring ice-wedge thermal regime were installed at three selected sites: Boomerang Glacier, Baker Rocks and Mount Jackman.

For this study we selected the ice-wedge polygon area, facing Boomerang Glacier and located in the vicinity of Terra Nova Bay, 13 km NNW of the Mario Zucchelli Italian Station (Fig. 1).

Petrofabric and co-isotope analyses ($\delta^{18}O$ and δD) of ice-wedge ice were performed, as well as one year of monitoring of the ice-wedge thermal regime. The purpose of the study was to define the processes which led to the formation of ice wedges and to determine if thermal conditions trigger ice-wedge cracking.

Morphological features of ice wedges and ice crystal petrofabric characteristics

The selected site is placed at 874 m a.s.l., on a slightly sloping bench facing Boomerang Glacier. McMurdo-volcanic regolith, formed by coarse angular clasts, covers the bench. The polygons had a convex surface, 10 to 15 m wide, and were bordered by shallow inter-polygon troughs, 0.20-0.30 m deep and 0.20-0.40 m wide.

We excavated numerous sections across the polygon troughs to a depth of about 1.5 m, including one at the intersection of three polygons. In January 1999, 2001 and 2004, the frost table was 20-25 cm deep. Permafrost was rich in structureless ice cement (French, 2007). Six ice wedges were found at depths varying from 27 cm to 55 cm from the ground surface. The width at the top was between 13 and 55 cm, and their height ranged from 50 cm to over 80 cm. The ice of the wedges was milky white in colour, free of sediments and with visible gas inclusions forming vertical bands. Foliations parallel to the sides were well developed and extended throughout the length of the ice wedges. A vertical crack, 2-3 mm wide, filled with small loose ice grains, was present in the centre of the wedges. In some of the cracks we found hoar frost crystals with a diameter of more than 20 mm. Hoar frost crystals of similar size were also observed during winter and spring seasons by other authors in the ice wedges of the McMurdo area (i.e., Black and Berg, 1963).

Petrofabric analysis of ice-wedge ice may help to infer growth processes and conditions. This is because crystal size and *c*-axis orientation are directly related to the direction of the freezing process (French, 2007).

Thin horizontal sections, normal to the axial plane, and vertical sections, both normal and parallel to the axial plane, were made. In the vertical thin sections, the crystals were predominantly elongated, with an average size of 51-67 mm^2 at the wedge centre, and 114-160 mm^2 at the wedge boundary. These sizes are three to five times larger than those measured by Gell (1978) and by Pollard and Dallimore (1988) in Arctic areas. The *c*-axis directions have a preferred vertical to sub-vertical orientation parallel to the axial plane at the wedge centre and parallel to the foliation at its boundary, thus denoting a rotation of crystals from the centre towards the sides. Moreover, *c*-axes were oriented vertically at the upper end of the wedges, randomly in the middle and, horizontally at the apex, consistent with Shumskii (1964).

Ice-wedge stable isotope composition

$\delta^{18}O$, δD (where $\delta^{18}O$ or $\delta D = \{[(^{18}O\ /^{16}O)_{sample}/(^{18}O/^{16}O)_{V\text{-}SMOW}] -1\} \times 1000$) and tritium activity measurements were performed on two ice wedges and on surface snow samples. Co-isotopic ($\delta^{18}O$ and δD) studies are necessary and widely used to determine whether melting-refreezing processes have affected a ground ice body (Souchez and Jouzel, 1984). Co-isotopic analyses allowed us also to calculate the excess of deuterium ($d = \delta D - 8 * \delta^{18}O$; Dansgaard, 1964), which mainly depends on climatic conditions in the precipitation source regions. Tritium data are widely used to determine whether ice wedges have been active in recent decades (Burn, 1990).

The mean isotopic values obtained from the two ice wedges are -19.28‰ and -22.41‰ for $\delta^{18}O$ and -168.7‰ and -193.8‰ for δD. The first one was re-sampled during a second field season showing similar results (-19.44‰ for $\delta^{18}O$ and -166.6‰ for δD). All the ice wedge samples had negative *d* values ranging from -20.8‰ to -5.6‰. The hoar frost crystals found at the bottom of the ice wedge, showed similar isotopic values. The isotopic composition of the three surface snow samples range from -30.71‰ to -22.07‰ for $\delta^{18}O$ and from -244.6‰ and -171‰ for δD. One of the samples showed negative *d* values (-12.8‰). The tritium activity values range from 0 TU to 6 TU.

The isotopic values of the ice wedges and hoar frost crystals are lying below the meteoric water line, when plotted in a $\delta^{18}O/\delta D$ diagram, and diverge from the snowfall values expected for this elevation (mean annual values of -27‰ and -206‰ for $\delta^{18}O$ and δD respectively; Stenni et al., 2000). The values obtained from the collected snow samples may represent single precipitation events; moreover in one case the isotopic value is hardly preserved and likely affected by wind driven sublimation processes. The *d* values obtained from the ice wedges are all negative, contrary to what is usually observed in Antarctic precipitations (Petit et al., 1991).

Ice-wedge thermal regime

The meteorological and ground temperature conditions, under which frost cracking takes place in ice-wedge polygon areas of the Arctic, have been studied intensively, and are well documented (French, 2007). In Antarctica studies on the hydrothermal regime of patterned ground were provided by Black and Berg (1963).

Monitoring of ice-wedge thermal regime on one of the ice wedges at the Boomerang Glacier site started on 1 February 2004. The data logger (Testor 171/4) utilized NTC sensors (± 0.2°C accuracy) to take hourly temperatures recordings (instantaneous value every hour) of the air at 110 cm, of the ground at a depth of 2, and of the top and bottom of the ice wedge at depths of 38 cm and 83 cm respectively.

The mean annual air temperature (MAAT) during the 1 February 2004 to 31 January 2005 study period was –21.5°C. As evidenced by Burn (1990), it is mainly the winter temperature regime that controls cracking. During the 2004 winter minimum air temperatures were recorded in May and July with lows frequently below than –40°C in the month of July (Fig. 2). The monthly mean air temperatures (MMAT) in May was –29.9°C and in July –33.6°C. Frequent, large temperature fluctuations occurred throughout the season, with either sharp drops or rapid increases in air temperature; variations of 25°C to 30°C were recorded in periods of 1 to 4 days.

The mean annual ground surface temperature (MAGST) at a depth of 2 cm was –20.9°C. During the 2004 winter, May and July were the coldest months with the monthly mean ground surface temperatures (MMGST) of –31.4°C and –34.4°C respectively. The ground surface thermal regime closely follows that of the air, with similar large short-lived fluctuations in temperature. The maximum ground cooling rates (GCR) of 7.4°C/day and 8.4°C/day were reached in June and July respectively, after a sharp temperature drop from –14.0°C to –32.9°C over a 3-days period in June, and after a similar temperature drop in July: from –17.7°C to –40.5°C over a 4-days period.

These values exceed the limit of the 4-days temperature drop rate of 1.8°C/day reported by Mackay (1993), that favored ice-wedge cracking in the western Arctic coast.

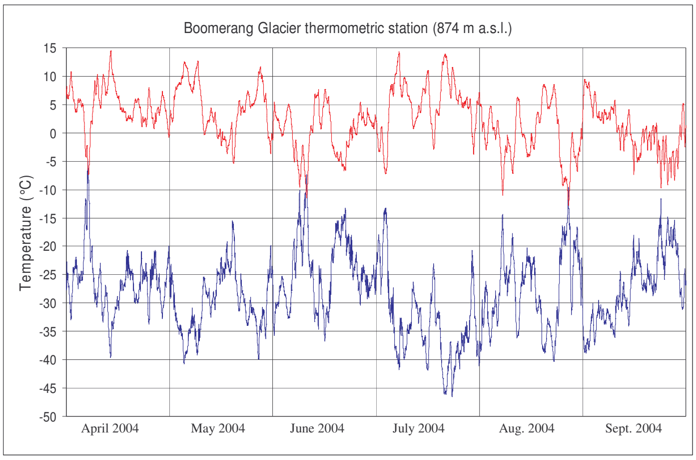

Figure 2. Thermal gradient between the ground surface (-2 cm) and the top of the ice wedge (-38 cm), red line; air temperature, blue line.

The mean annual temperature on the top of the ice wedge at the depth of 38 cm was –20.5°C. Temperatures were below –25°C from May to October, with the exception of two short periods in June and one in July, when temperatures increased slightly. The minimum temperature of –33.4°C was reached at the end of July after a cooling period of 25 days.

According to Mackay (1993), ice-wedge cracking took place both during periods of decreasing or increasing air temperature. At the Boomerang Glacier site frequent inversions of the thermal gradient between the ground surface the and the top of the ice wedge were recorded (Fig. 2). These inversions were caused by cooling and warming of the ground surface. From April to August 40 thermal gradient inversions were recorded. Ten negative inversions of major amplitude occurred in June, July and August: ranging from –2.5°C to –12.6°C, with a mean value of –7.3°C. Eleven major positive inversions occurred in the same period: ranging from +4.7 to +13.9°C, with a mean value of +8.3°C.

Discussion

The morphological features of the ice wedges studied for this paper are similar to those studied in southern Victoria Land (i.e., Berg and Black, 1966). The observed variations in fabrics and textures across the wedges, similar to the Arctic wedges, were the results of recrystallization and grain growth under a lateral stress field and a high temperature gradient (Gell, 1978).

The monitoring of one year of ice-wedge thermal regime at the Boomerang Glacier site highlighted that in winter the temperatures of the air and on the top of the ice wedge fell below –30°C and –20°C respectively. These are the thermal limits at which ice-wedge cracking is known to occur in the Arctic (Lachenbruch, 1966; Fortier and Allard, 2005). Moreover, the high thermal gradients between the ground surface and the ice wedge top, induced in winter by air temperature fluctuations, are by far exceeding the limits recorded at the time of ice-wedge cracking in the western Arctic coast (Mackay, 1993). At present no field data of snow cover are available. However, because the MMGSTs for May and July (-31.4° C and -34.4°C respectively) were lower than the MMATs for the same months (-29.9°C and -33.6°C respectively), we can infer that there was no thick snow cover inside the polygon trough, which would have had an insulating effect. The strong katabatic winds, with gusts often reaching speeds of more than 200 km/h in winter, keep the ground surface bare. Therefore, the ground cools rapidly due to the sharp drops in air temperature, and triggers ice-wedge cracking. Moreover, the presence of open cracks in ice wedges indicates that the growth processes are still active under the present climatic conditions.

The situation found at Boomerang Glacier is similar to, but less extreme than, that observed in northern Victoria Land at higher elevations (Raffi et al., 2004). The stable-isotope analyses suggest that sublimation processes of a porous medium (snow and/or hoar frost) seem to have occurred during the growth of the wedges. However, melting and refreezing processes cannot be excluded *a priori*. A high temperature gradient between low air temperature and higher permafrost temperature, thin or absent snow cover, low humidity and open cracks during winter, are factors which may control the sublimation processes. These factors are consistent with the results of the isotope analyses conducted on ice wedges in northern Siberia (Dereviagin et al., 2002; Meyer et al., 2002).

The sublimation phenomena highlighted in the formation of ice wedges, as well as the monitoring of ice-wedge thermal regime will be studied at other sites in northern Victoria Land.

Summary

The preliminary results of the research carried out on six ice wedges located in the vicinity of Terra Nova Bay, in northern Victoria Land utilized co-isotope analyses to show that sublimation processes contribute to the formation of the ice-wedge ice. Analysis of the thermal regime of one ice wedge over a period of one year shows that extreme gradients between the ground surface and the top of the ice wedge temperatures may trigger ice-wedge cracking.

Acknowledgments. Thanks are due to the co-editor who handled this extended abstract, to Jeffrey R. Watt of the University of Mississippi, and to Mike Muzzio, who reviewed this extended abstract for correct English usage. This research was carried out within the Italian Antarctic

National Research Program. Thanks are also due to Dr. R. Seppi, Pavia University, I, for the active participation in the field investigation; to Ing. R. Bono, CNR-ISSIA of Genova, I, and to U. Gentili, Climate Project, ENEA, Roma, I, for the field maintenance of the thermometric station.

References

Berg, T. E., and R. F. Black (1966), Preliminary measurements of growth of non sorted polygons, Victoria Land, Antarctica, in: Antarctic soils and soil forming processes, edited by J.C.F. Tedrow, American Geophisical Union, Antarctic Research Series, 8, 61-108, Washington, DC.

Black, R. F., and T. E. Berg (1963), Hydrothermal regime of patterned ground, Victoria Land, Antarctica, International Association of Scientific Hydrology, Publ., 61, 121-127.

Burn, C. (1990), Implications for palaeoenvironmental reconstruction of recent ice-wedge development at Mayo, Yukon Territory. Permafrost and Periglacial Processes, 1(1), 3-14.

Dansgaard, W. (1964), Stable isotopes in precipitation, Tellus, 16 (4), 436-468.

Dereviagin, A. Yu., H. Meyer, A. B. Chizov, H.-W. Hubberten, and E. F Simonov (2002), New data on the isotopic composition and evolution of modern ice wedges in the Laptev Sea region. Polarforschung, 70 (1/2), 27-35.

Fortier, D., and M. Allard (2005), Frost-cracking conditions, Bylot Island, Eastern Canadian Arctic Archipelago, Permafrost and Periglacial Processes, 16(2), 145-161.

French, H. M. (2007), The periglacial environment, Third Edition, John Wiley & Sons Ltd, England.

French, H. M., and M. Guglielmin (2000), Frozen ground phenomena in the vicinity of Terra Nova Bay, northern Victoria Land, Antarctica: a preliminary report, Geografiska Annaler, 82 A (4), 513-526.

Gell, W. A. (1978), Ice-wedge ice, Mackenzie Delta-Tuktoyaktuk Peninsula area, N.W.T., Canada, Journal of Glaciology, 20 (84), 555-562.

Lachenbruch, A.H. (1966), Contraction theory of ice-wedge polygons: a qualitative discussion, in: Permafrost, International Conference Proceedings, National Research Council of Canada, publication n. 1287, National Academy of Sciences, Washington, DC, 63-70.

Mackay, J. R. (1993), Air temperature, snow cover, creep of frozen ground, and the time of ice-wedge cracking, western Arctic coast, Canadian Journal of Earth Sciences, 30, 1720-1729.

Meyer, H., A. Dereviagin, C. Siegert, L. Schirrmeister, and H.-W. Hubberten (2002), Palaeoclimate Reconstruction on Big Lyakhovsky Island, North Siberia – Hydrogen and oxygen isotopes in ice wedges, Permafrost and Periglacial Processes, 13 (2), 91-105.

Petit, J.R., J. W. C. White, N. W. Young, J. Jouzel, and Ye. S. Korotkevich (1991), Deuterium excess in recent Antarctic snow, Journal of Geophysical Research, 96 (D3), 5113-5122.

Péwé, T. L. (1959), Sand-wedge polygons (tesselations) in the McMurdo Sound region, Antarctica – A progress report, American Journal of Science, 257, 545-552.

Pollard, W. H., and S. R. Dallimore (1988), Petrographic characteristics of massive ground ice, Yukon Coastal Plain, Canada, in: Permafrost, Fifth International Conference, Trondheim, Norway, 2-6 August 1988, Proceedings, edited by K. Senneset, Tapir Publisher, 1, 224-229.

Raffi, R., (2003), Ice wedges in the Terra Nova Bay region (Northern Victoria Land, Antarctica). Distribution and morphological features, Terra Antartica Reports, 8, 143-148.

Raffi, R., B. Stenni, O. Flora, S. Polesello, and M. Camusso (2004), Growth processes of an inland Antarctic ice wedge (Mesa Range, Northern Victoria Land), Annals of Glaciology, 39, 379-385.

Shumskii, P. A. (1964), Principles of structural glaciology, Dover Publications, New York.

Souchez, R.A., and J. Jouzel (1984), On the isotopic composition in δD and $\delta^{18}O$ of water and ice during freezing, Journal of Glaciology, 30(106), 369-372.

Stenni, B., F. Serra., M. Frezzotti, V. Maggi, R. Traversi, S. Becagli, and R. Udisti (2000), Snow accumulation rates in northern Victoria Land, Antarctica by firn-core analysis, Journal of Glaciology, 46 (155), 541-552.