# ORIGINS OF THE GROUND ICE IN THE ICE-FREE LANDS OF THE NORTHERN FOOTHILLS (NORTHERN VICTORIA LAND, ANTARCTICA)

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#### Abstract

This paper shows the main results of chemical and isotopic analyses of samples of ground ice collected from two debris-covered glaciers named respectively Boulder Clay Glacier and Amorphous Glacier and from two debris cones, located in these two areas not far from the Italian Station of Terra Nova Bay. The massive ground ice of Boulder Clay Glacier was probably produced near a fossil grounding line by the freezing of water derived in variable proportions from glacial meltwater and seawater or meltwater from marine ice. The ice collected from Amorphous debris-covered glacier is clearly continental ice.

The ground ice collected from the two debris cones seems to result from melting and refreezing of these two different kinds of massive ground ice with an input of fresh water. This fresh water is produced by snow melting, which suggests a periglacial origin for these landforms.

#### Introduction

In a coastal permafrost area, it is possible to find ice of various origins, including massive marine, glacial and segregated ice, as well as interstitial ice (French and Harry, 1990). The identification of these different types of ground ice is useful for a better understanding of the paleoenvironmental evolution of the Antarctic ice sheet. Little is known about the distribution of ground ice in the permafrost areas of Antarctica. Previous works generally concern geophysical investigations of periglacial landforms (e.g., Barsch et al., 1985; Hassinger and Mayewsky, 1983; Guglielmin et al., 1997; Guglielmin, 1997). Knowledge of the nature of ground ice is still more limited and generally concerns only the geochemistry of the active layer or ice-wedges (Kato et al., 1990; Wang et al., 1993).

# Geomorphological and geophysical settings

The study area is located in the interior of Northern Victoria Land, between Nansen Ice sheet to the south and Mount Melbourne (2732 m a.s.l.) to the northeast (Figure 1). In this part of Northern Victoria Land, the larger ice-free areas are concentrated in the Northern Foothills. Some periglacial landforms, such as rock glaciers, have been described in previous publications (Baroni, 1989; Chinn et al., 1989; Meneghel et al., 1994). The sites for the present investigation were chosen on the basis of this previous research and of new geomorphological surveys. Figure 1 shows the sites of vertical electric soundings (diamonds) and trenches dug to sample the ground ice (triangles).

The two sites chosen (Boulder Clay Glacier and Amorphous Glacier, Figure 1) are two debris-covered glaciers related to the Terra Nova I Drift (Orombelli et al., 1991). According to Denton et al. (1975), these deposits can be correlated to the Ross Sea I glaciation. The surficial morphology of these both ice-free areas is characterized by lateral and shear moraine ridges, large nets and patterned grounds and, above all, by many debris cones located near frozen lakes.

The first step after the geomorphological survey was to undertake vertical electric soundings (V.E.S.) to define the thickness of drift and of the buried ground ice and to know whether this area showed different kinds of ground ice.

The soundings suggested a thin layer of drift, completely frozen (30-130 thick cm), overlying a massive



Figure 1. Study area map showing location of sampling sites and geophysical investigations.

ground ice layer whose thickness is always greater than 60 m. The resistivity values of the ground ice appear noticeably different between the two sites. While at Amorphous Glacier, these values are clearly interpretable as linked to continental ice (values > 7,000 k $\Omega$ m), at Boulder Clay the interpretation is more difficult (1,000-2,000 k $\Omega$ m) because these values can indicate permafrost with a high ice content or continental ice with a higher salt content.

For comparison, some electrical soundings were carried out on a frozen lake named Enigma Lake and located at the northern edge of Boulder Clay Glacier. These soundings showed that the resistivity values of the lake ice can be very variable and range from 20 to  $1,500 \text{ k}\Omega\text{m}$ .

The second step consisted of digging some trenches in the glacial drift of the two debris-covered glaciers (AM1 and BC2) and two debris cones located in the same area (AM2 and BC1). All the excavated sections (except the BC1) are characterized by a thin active layer (10-25 cm) overlying frozen ground with an ice-poor layer (20-50 cm). These sections also show massive ground ice in their lower parts. This ground ice was bubbly, clean and not stratified in BC1 and AM2 sections, while in the AM1, there is an upper layer 10 cm thick of clean and bubbly ice and a underlying layer of dirty ice including a very steeply dipping debris layer. The section dug at the BC2 site showed 75 cm of till with salt concretions in the upper part. This till was frozen only in the lower 10 cm and overlay foliated ground ice with a vertical dip.

# **Analytical methods**

Oxygen isotope analysis was carried out according to the Epstein and Mayeda (1953) technique of isotopic equilibration of  $CO_2$  with water. The measurement of the hydrogen isotopic composition was carried out by means of the zinc reduction technique (Coleman et al., 1982), using zinc reagent supplied by the Biogeochemical Laboratories of Indiana University. The

	Table 1.	Chemical	and isotopic	data of Amorphous	and Boulder Clay	Glaciers ground	ice samples
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SAMPLE	CI	NO3	S04	Na	К	Mg	Са	δ18Ο	δD	d
	µEq/L	µEq/L	µEq/L	µEq/L	µEq/L	µEq/L	µEq/L	(V-SMOW)	(V-SMOW)	
Boulder Clay Glacier										
BCI-A	100.0	0.04	110					-20.55	-169.9	-5.5
BC1-B	196.6	2.31	418	389	14.9	19.4	194.4	-17.39	-134.1	5.0
BCI-C	311.5	2.95	550	644	31.6	46.7	305.3	-22.25	-175.0	3.0
BC1-D	394.1	4.22	1217	993.1	26.9	37.3	413.1	-17.36	-134.5	4.4
BC1-E	311.6	4.1	1121	1258	18.6	28.8	282.2	-14.07	-108.1	4.5
BC2-A	449.8	2.27	2763	2584	53.9	75.3	422.8	-11.40	-87.0	3.5
BC2-B	461	1.09	5419	5069	52.1	80.2	524.3	-7.82	-63.1	-0.5
BC2-C	940.7	3.9	3275	2294	65.3	233.7	1658	-19.90	-161.5	-23
BC2-D	1217	3.45	3684	3702	86.8	265.8	772.8	-16.44	-132.2	-0.7
AMIT	is Glac	ler						17.00		
AM1 D	110 1	7 50	C1 0	050 4	70 7	1010	005 4	-17.29	-138.5	-0.2
AM1 C	440.1	7.53	64.9	353.4	13.1	124.8	205.4	-18.19	-145.8	-0.3
AM1 D	143.6	2.73	57.3	142.1	4.7	10.1	/6.6	-25.26	-203.6	-1.5
	246	0	35.6	218.5	31.7	66.4	130.2	-24.44	-194.7	0.8
AM1-E	000 1	17.00	747	000 4	00.0			-22.59	-181.8	-1.1
AIVI I-F	280.1	17.38	/4./	283.4	23.9	83	152.9	-24.96	-196.7	3.0
AM2-A	27.3	1.36	11.8	34.7	7.5	4.8	19.1	-28.02	-216.9	7.3
AM2-B	14.3	1.03	2.8	18.3	3.9	3.2	7.2	-28.03	-216.1	8.1
AM2-C	7.9	0.83	2.7	11.4	2	2.7	11.3	-28.86	-223.6	7.3
AM2-D	9.7	1.05	6	21.9	3.2	7.2	9.3	-28.54	-221.8	6.5
	10	0.04	10	110	0.0	~ .	~ ~			
LAKE D	27 5	1.34	1.9	14.9	2.9	2.4	9.8	-24.03	-187.6	4.6
LAKE-B	37.5	1.1/	2.1	33.3	2.9	1.9	6	-24.29	-184.0	10.3
311011	65.7	1.57	10.3	61.9	1.4	5.8	8	-22.66	-172.5	8.8

 $H_2$  and  $CO_2$  samples were measured with a Finnigan Delta S mass spectrometer. The results are reported as  $\delta$  units per mil (‰) where :

 $\delta = [(Rsample - Rstandard) / Rstandard] \times 1000 [1]$ 

R being the <sup>18</sup>O/<sup>16</sup>O or D/H ratio. The <sup>18</sup>O and dD values are reported versus V-SMOW isotopic standard (Gonfinatini, 1978). The standard deviations of oxygen and hydrogen measurements are on average  $\pm$  0.07 % (1 $\sigma$ ) and  $\pm$  1 % (1 $\sigma$ ), respectively. The analyses of Na, K, Mg, Ca, Cl, NO<sub>3</sub> and SO<sub>4</sub> were performed by ion chromatography (Dionex 2020i for cations and Dionex 500 for anions). The separations were obtained by means of a Dionex AS11 column (NaOH 60 mM eluent) and Dionex CS12 (methane sulfonic acid 20mM eluent) for anions and cations respectively.

### **Results and discussion**

STABLE ISOTOPES

Direct temperature measurements in the ground (Guglielmin, 1997) and morphological observations

conducted in the study area suggest that seasonal melting-refreezing processes may occur to depths of 30-90 cm. Stable isotope analyses were carried out in order to understand the origin of the different ground ice samples. A combined  $\delta^{18}$ O and  $\delta$ D study proved to be necessary in order to detect possible melting-refreezing processes. Jouzel and Souchez (1982) and Souchez and Jouzel (1984) have shown that after melting and refreezing, basal ice samples lie on a straight line on a  $\delta^{18}$ O/ $\delta$ D diagram, with a slope lower than that of the meteoric water line ( $\delta$ D =  $8\delta^{18}$ O + 10 : Craig, 1961).

The <sup>18</sup>O and  $\delta D$  values obtained from the analyses of the buried ice samples collected in the Terra Nova Bay area are reported in Table 1 along with the chemical data. A snow/firn sample and two lake samples collected in the same area are also reported for comparison. The deuterium excess values ( $\delta = \delta D - 8\delta^{18}O$ ) were calculated for all the samples and are reported in Table 1. The deuterium excess value  $\delta$  is related to the physical conditions (humidity, sea surface temperature and wind speed) prevailing in the source regions of condensing vapor (Jouzel et al., 1982). All the samples presented in Figure 2 do not show any refreezing slope but they lie on or near the meteoric water line (MWL). This fact suggests two possibilities: (1) these ground ice samples did not undergo any melting-refreezing processes or (2) they underwent these processes but in an open system with an input of more negative isotopic water than the initial reservoir. The latter situation has already been reported by Souchez and De Groote (1985). Another possibility could be a incorrect sampling procedure leading to too large sample size for detecting any variation.

The value obtained from the collected snow sample ( $\delta^{18}O = -22.66 \ \%$  and  $\delta D = -172.5 \ \%$ ) is in the range of values already reported for Northern Victoria Land coastal area at low elevation (Caprioli et al., 1997; Gragnani et al., in press) and lies on the MWL (Figure 2) like the two lake ice samples.

In spite of the difficulties quoted above, a clear distinction can be made among the isotopic values obtained from the different geomorphological units. The ground ice sampled in BC1 and BC2 sites is completely different from the one in AM1 and AM2 sites. As regards the Boulder Clay deposits, the values obtained from the BC2 site range from -7.82 to -19.90% for  $\delta^{18}O$ and from -63.1 to -161.5‰ for  $\delta D$ . These isotopic values are intermediate between those of local precipitation and local seawater ( $\delta^{18}O = -0.69$  ‰ and  $\delta D$  = -3.23 ‰; Souchez et al., 1995) suggesting that the ice was probably produced near a fossil grounding line by the freezing of water resulting from the mixing in variable proportions of glacial meltwater and seawater or meltwater from marine ice. A similar process has already been proposed by Souchez et al. (1995) in this area for outcropping basal ice containing debris ice layers. Moreover, positive (+2‰) and very negative (-35‰)  $\delta^{18}$ O values, together with the presence of fossil shell fragments, were also found at Adelie Cove in ground ice contained in Terra Nova I Drift which mantles the eastern flank of the Northern Foothills between Cape Russel and the Campbell Glacier Tongue (Orombelli et al., 1990).

As regards the ice samples collected at the BC1 site, their  $\delta^{18}$ O and  $\delta$ D values (see Table 1) are more similar to modern precipitation, even if the less negative values ( $\delta^{18}$ O = -14.07‰ and  $\delta$ D = -108.1‰) found at depth could suggest either a refreezing front proceeding from below with an input of more negative water or a similar origin to that of the BC2 site.

Apart from the two less negative values of the AM1 site (AM1-A and AM1-B), probably related to the active



Figure 2.  $(^{18}O/(D \ diagram \ for \ all \ samples; \ full \ square \ for \ BC1. \ open \ square \ for \ BC2. \ open \ circle \ AM1. \ full \ circle \ AM2. \ open \ diamond \ for \ lake \ ice \ and \ open \ triangle \ for \ snow. \ The \ meteoric \ water \ line \ is \ also \ drawn.$ 

layer or to a summer snowfall, the  $\delta^{18}O$  and  $\delta D$ obtained (see Table 1) are in the range of values found in the coastal area precipitations (about 0-400 m), suggesting for this ground ice an origin related to the local glacier. More negative values, around -28.4‰  $\delta^{18}$ O) and -220% ( $\delta$ D) were found in the ice of the debris cone AM2. These samples could be influenced by glacial meltwater with more negative values related to glacier ice formed in a colder environment with respect to the present one or to glacier ice formed at higher elevation. In fact, in the area of Terra Nova Bay a value of -28.4% may be found in the precipitation falling at an elevation of about 1000-1100 m (Gragnani et al., in press). In Figure 2, these samples lie on the MWL and their deuterium excess ( $\delta$ ) values (see Table 1) are similar to those found in the snow sample, as well as in the local precipitation. This fact could also suggest a possible preservation of the original isotopic values of these ground ice samples.

#### CHEMICAL DATA

The results of chemical analyses are reported in Table 1. The higher salt concentration was found in BC2 samples whereas the lower concentration was found in AM2 and ice from lake samples. These differences are shown in Figure 3 which displays the concentration of Cl as an example. Generally speaking, the K/Cl, Ca/Cl,  $SO_4/Cl$ ,  $NO_3/Cl$  ratios were much higher than the bulk sea water ratios whereas the Mg/Cl ratio was close to the sea water Mg/Cl ratio. These results were in keeping with results obtained in the study of chemical composition of the Antarctic glacier ice (Legrand et al., 1988). The higher Na/Cl ratio distinguishes the studied samples from glacier ice. Moreover these results differ from those obtained in marine ice (Cragin et al., 1986; Tison et al., 1993) in which, excluding some variations in the K/Mg ratio, the ratios between the major constituents are very close to bulk sea water.



Figure 3. Bar diagram with Cl concentrations of Boulder Clay and Amorphous Glacier ground ice samples.

The "not sea salt" (nss) elements are very useful to determine the origin of the ground ice. In particular, the SO4/nss Na correlation (nss $SO_4=SO_4 - 0.103$  Cl and nss Na=Na - 0.852 Cl, where all species are in  $\mu$ Eq/L) was highly significant (nss Na=-37+0.78 nssSO<sub>4</sub>; r=0.98) confirming that a large part of these ions are in Na<sub>2</sub>SO<sub>4</sub> form. The highly significant (nss SO<sub>4</sub>-nss Na)/nss Ca correlation suggests that a large part of nss Ca is in the CaSO<sub>4</sub> form. Figure 4 is a bar diagram of the concentration of nss Na and nss Ca. In Antarctica, NaSO<sub>4</sub> can be formed in the atmosphere by fractionation of the reaction product between NaCl and H<sub>2</sub>SO<sub>4</sub> (Legrand and Delmas, 1988). Na<sub>2</sub>SO<sub>4</sub> can be precipitated under freezing condition both in marine (Richardson, 1976) and lacustrine (Schmidt et al., 1991) environments. This process can involve a brine formation. Generally, the concentration of Na<sub>2</sub>SO<sub>4</sub> is very low in glacier ice and



Figure 4. Bar diagram with nss concentrations of Boulder Clay and Amorphous Glacier ground ice samples.

only in coastal areas, after salt storms, were high concentrations of  $Na_2SO_4$  found (Gragnani et al., in press) joined with sea salt. In marine ice,  $Na_2SO_4$  enrichment has not been found.

As regards the samples from Boulder Clay, their chemical composition suggests that the ice is probably produced from the freezing of water resulting from mixing between melt water from glacier ice and sea water or melt water from marine ice. The K/Cl, Ca/Cl, and NO<sub>3</sub>/Cl ratios that are higher than bulk sea water suggest a continental input, whereas the high concentration of Na<sub>2</sub>SO<sub>4</sub> could be due to a marine origin. The significant correlation between (<sup>18</sup>O and nss Na in BC samples (r = 0.78, n = 8) can prove that Na<sub>2</sub>SO<sub>4</sub> has a sea origin and that it could be involved in brine migration.

A continental glacial origin is suggested by the results obtained to date about the low concentrations of chemical species of the AM1. Moreover, the similar ionic concentrations in AM2 and in the lake ice samples might suggest a link between the two sites.

# Conclusion

The massive ground ice found in the trenches dug in debris-covered glaciers of Boulder Clay Glacier and Amorphous Glacier (BC2 and AM1) are completely different both from the isotopic and from the chemical point of view. Nevertheless, they show similar textural characteristics (foliations with debris layers characterized by a steep or vertical dip) that indicate different ice formation environment successively involved in the same deformation processes that have also created similar landforms (debris-covered glaciers).

The ice found in BC2 sites can be considered as a relict of the ice formed near the fossil grounding line of Ross Ice Shelf, while the ice of AM1 is a continental Holocene ice. The different altitudes of sampling (360 m a.s.l. for AM1 and 160 m a.s.l. for BC2) suggest that the relict grounding line of Ross Ice Shelf reached a maximum elevation of 200-250 m a.s.l.

This is an important point as the chemical, isotopic and textural characteristics of massive ground ice found in both debris cones are completely different from those of massive ground ice found in their respective debriscovered glaciers.

The ground ice of BC1 and AM2 shows strongly reduced cation concentrations compared to the values found in the massive ground ice of the debris-covered glaciers. In the particular case of AM2, the measured concentrations were very similar to the lake ice. These characteristics and the textural characteristics of the ice (that is not foliated) suggest that this ice could be segregation ice probably supplied by the water that is stored below the lake ice and by snow melt and, hence, that these debris cones would be of periglacial origin.

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