

CHEMICAL AND ISOTOPIC CHARACTERISTICS OF ICE FROM AN ICE-WEDGE IN SEYMOUR ISLAND (ISLA VCOM. MARAMBIO), ANTARCTIC PENINSULA REGION (I)

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Abstract: In Seymour Island free of ice cover were found many ice-wedges and ice-wedge casts. In order to clarify chemical characteristics of ice in ice-wedges, chemical analyses were done on ice samples from an ice-wedge. The concentrations and compositions of chemical species in the ice body vary in an unexpectedly wide range and are greatly different between the upper and lower parts, even from the same ice-wedge ice body. Its lower part shows very high concentrations of Na^+ and SC_4^{2-} , whereas its upper part shows high Ca^{2+} and SO_4^{2-} concentrations. Vertical profiles of the concentrations and compositions of chemical species are also very specific, especially in their tracing zigzag courses. These facts indicate the existence of unexpected but very interesting formation processes of the ice-wedge ice body.

1. Introduction

Even in Antarctica exist a few regions free of ice cover such as the well-known Dry Valleys, McMurdo region. In these regions are seen the permafrost and distinctive ground features such as the polygons and ice-wedges. Nevertheless, the chemical characteristics of ice bodies, which form the polygons and ice-wedges, have not yet been clarified. However, they may provide useful information about the origins of these ice bodies and the processes and environments of formation of the distinctive ground features.

Seymour Island (Isla Vcom. Marambio) is one of ice-free places in Antarctica. The island is located at 64°15'S and 56°45'W, and is a part of the James Ross Group of Islands off the northeastern coast of the Antarctic Peninsula, as shown Fig. 1. The outcrops of upper Cretaceous and lower Tertiary rocks containing abundant fossils are seen (RINALDI *et al.*, 1978). The active layer does not exceed 50 cm deep.

During the research program of December 1987, many ice-wedges and ice-wedge casts were found (FUKUDA and CORTE, 1989; KOIZUMI and FUKUDA, 1989). As shown in Fig. 2, the ice-wedge has a very small width in comparison with its depth, and has grown into the Tertiary bedrock instead of soft Quaternary sediments in the Arctic region, where ice-wedges are larger than in Seymour Island.

Ice structure with oriented air bubbles is clearly visible in the ice-wedges in the island. Formation of new frost cracks was monitored by measuring the change in the

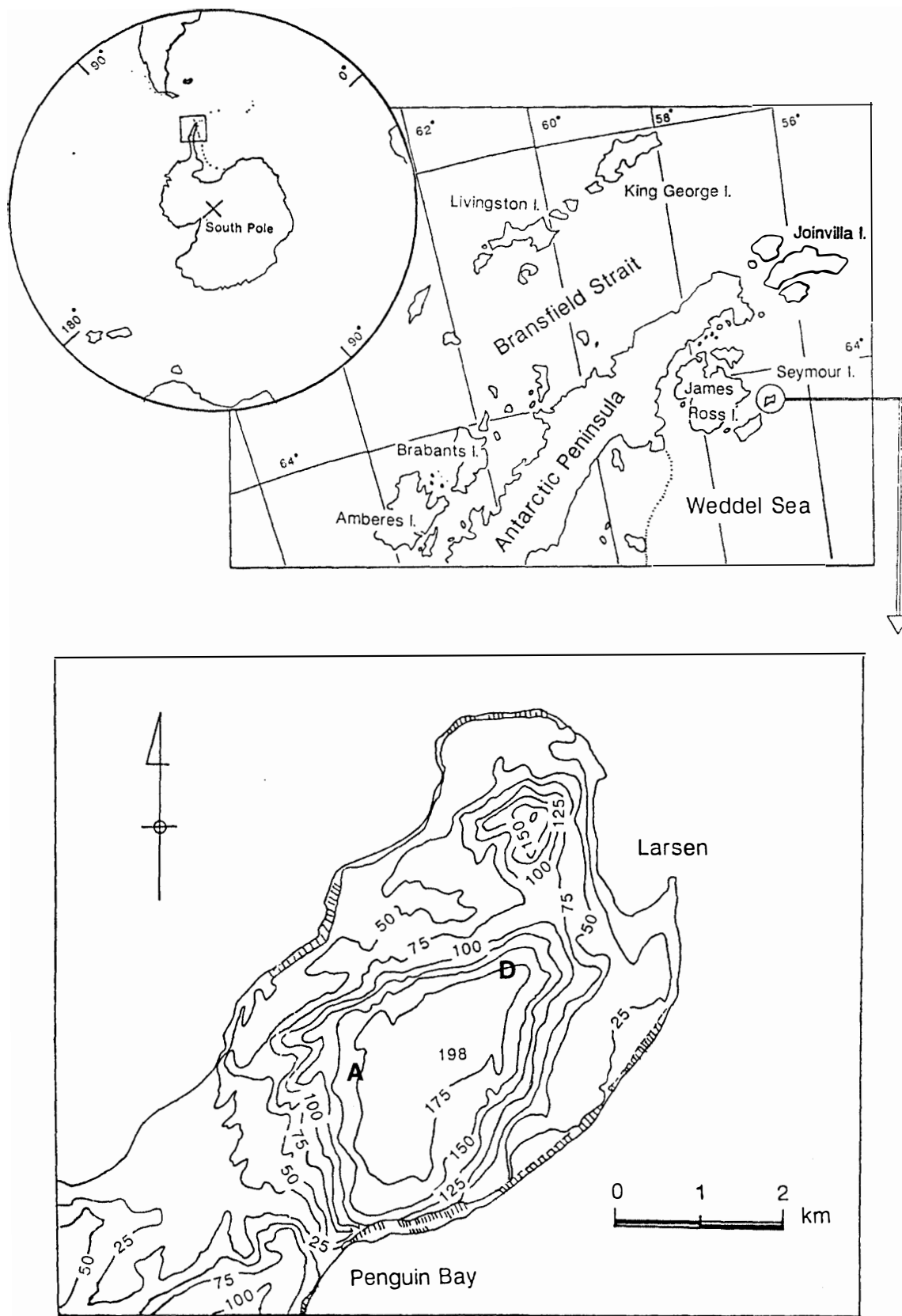


Fig. 1. Locality maps of Seymour Island, the Antarctic Peninsula region, and of the sampling sites.



Fig. 2. Ice-wedge found in Seymour Island.

distance between two poles over the ice-wedge head (KOIZUMI and FUKUDA, 1989).

As the first step of our research program, to clarify the chemical characteristics of ice from an ice-wedge, we determined the concentrations and compositions of chemical species not only in the ice-wedge ice but also in an ice-body on the ground surface and in fallen snows in this island.

2. Experimental

2.1. Samples

The ice samples were taken from an ice-wedge ice body at Site A shown in Fig. 1 (sampling date: 5 December 1987). This ice-wedge is 180 cm deep and 40 cm wide at its top, as shown in Fig. 3. In the lower part of this ice-wedge, some salts were found along the walls of the Tertiary bedrock. After thawed material on the ground

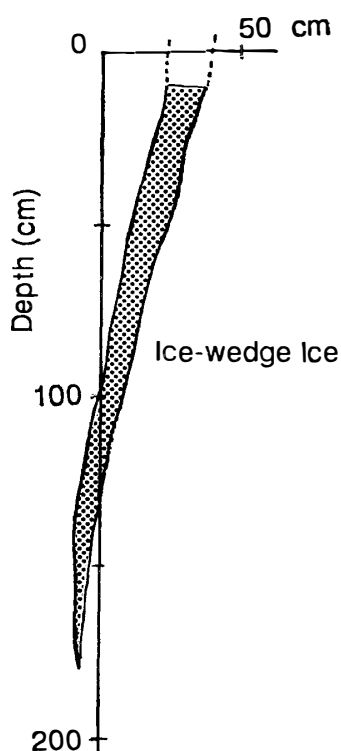


Fig. 3. Cross section of the ice-wedge shown in Fig. 2.

surface adjacent to the site of excavated ice-wedge was scraped off by a bulldozer, the ice samples from the ice-wedge were collected from various depths.

For the comparison of the chemical features of the ice-wedge ice with those of ice-body on the ground surface and also those of fallen snows in Seymour Island, ice samples were taken from an ice-body on the ground surface at Site D (sampling date: 2 December 1987) and two new-snow samples were collected at Site A (sampling date: 3 December 1987), whose localities are shown in Fig. 1.

In order to compare the chemical features of the ices and snows from Seymour Island with those from the Antarctic ice sheet, the concentrations of chemical species in drifting-snow samples collected at Mizuho Station and ice samples from an ice-core at Site S15 on the Sôya Coast were determined. Mizuho Station is located at 70°42'S and 44°20'E with the surface elevation of 2220 m, and Site S15 at 69°01'S and 40°02'E with that of 510 m.

2.2. Chemical analyses

After ice and snow samples were melted, they were filtered by the Millipore HA. Dionex Model 10 ion chromatograph and Dionex ion chromatograph QIC were used for the determinations of Na^+ , K^+ and NH_4^+ , and F^- , Cl^- , NO_3^- and SO_4^{2-} , respectively. Ca^{2+} and Mg^{2+} were determined by Perkin-Elmer Model 503 atomic absorption spectrometer.

3. Analytical Results

3.1. Concentrations of chemical species in ice-wedge ice

Table 1 gives concentrations of chemical species in ice samples from an ice-wedge at Site A in Seymour Island. From this table it is seen that the chemical features of the ice body are different between the depth above 50 cm (the upper part) and the depth below 70 cm (the lower part), even in the same ice-wedge.

The following three interesting facts are also seen from this table: (1) The concentration of determined chemical species, except for NH_4^+ , are unexpectedly high, especially in the lower part of this ice-wedge ice body, for this ice-body was expected to be the source of snow melt. (2) The concentrations of Na^+ , Ca^{2+} and SO_4^{2-} vary greatly with depth. (3) The vertical profiles of the chemical species are very specific, especially in their tracing zigzag courses.

In order to compare the concentrations of chemical species in the ice-wedge ice body with those in fallen snows and in ice body on the ground surface in Seymour Island, those in new-snow samples and ice samples from an ice-body on the ground surface were determined.

Table 1. Ion concentrations in ice melt samples from an ice-wedge at Site A in Seymour Island.

Depth (cm)	Na^+	K^+	NH_4^+	Ca^{2+}	Mg^{2+} (mg/l)	F^-	Cl^-	NO_3^-	SO_4^{2-}
10-20	21	7	—	390	8.2	0.1	4.0	—	480
30-40	93	18	—	150	47	0.2	18	—	300
40-50	84	13	—	110	38	1.3	15	2.3	220
60-70	210	5	—	35	25	0.6	17	2.2	210
70-80	3000	34	—	25	38	4.1	64	3.9	4100
80-90	1600	24	—	81	42	4.2	80	2.0	3600
90-110	5000	35	—	97	55	4.4	73	3.0	7200
120-140	1100	19	—	80	43	7.8	60	2.6	2400
150-170	5800	17	—	81	53	2.1	72	2.5	9100

—; <0.01 for NH_4^+ and <0.05 for NO_3^- , respectively.

Table 2. Concentrations of ions in new-snow melt samples at Site A and ice melt samples from an ice-body on the ground surface at Site D in Seymour Island.

Depth (cm)	Na^+	K^+	NH_4^+	Ca^{2+}	Mg^{2+} (mg/l)	F^-	Cl^-	NO_3^-	SO_4^{2-}
New-snow									
	3.4	0.56	—	7.9	2.7	—	5.9	—	18
	4.5	0.58	—	10	3.1	—	6.3	—	15
Ice-body									
0-20	3.4	0.7	0.39	0.9	0.4	—	1.2	0.8	10
30-40	3.5	0.6	—	2.0	0.9	—	1.8	—	15
40-50	7.3	0.7	0.12	2.1	2.2	—	2.1	—	15
55-65	12	1.7	0.45	3.0	2.6	—	16	—	20

—; <0.01 for NH_4^+ and <0.05 for F^- and NO_3^- , respectively.

The results given in Table 2 show that the concentrations of chemical species, except for NH_4^+ , in the new-snows and the ice-body are lower than those in the ice-wedge ice body. The NH_4^+ concentrations >0.01 mg/l found only in the ice-body on the ground surface may be caused by biological activities before its freezing.

Next, for the comparison of the concentrations of chemical species in snow and ice from Seymour Island with those from the Antarctic ice sheet, those in drifting-

Table 3. Concentrations of ions in drifting-snow melt samples and ice melt samples from ice-cores, Antarctica.

Sample	Na^+	K^+	Ca^{2+}	Mg^{2+} (mg/l)	Cl^-	NO_3^-	SO_4^{2-}
Drifting-snow (collected at Mizuho Station)							
15 July 1982	0.11	—	—	—	0.15	—	0.05
15 November 1982	0.44	—	—	0.04	0.35	0.12	0.59
5 January 1983	0.68	0.05	0.10	0.05	0.57	0.13	1.2
Ice-core from S15							
	0.19	—	0.04	0.01	0.24	—	0.12
	0.82	0.05	0.14	0.07	1.1	—	0.27
	0.68	0.04	0.06	0.05	0.99	—	0.13
	0.21	—	0.17	0.01	0.24	—	0.15

Concentrations of NH_4^+ and F^- in the all samples were <0.005 mg/l.

—; <0.01 for K^+ , Ca^{2+} , Mg^{2+} and NO_3^- .

Table 4. Ratios of the major ions in ice melt samples from the ice-wedge given in Table 1, and in new-snow melt samples and ice melt samples from the ice-body given in Table 2.

Sample	Na^+/Cl^-	$\text{Ca}^{2+}/\text{Cl}^-$	$\text{Mg}^{2+}/\text{Cl}^-$	$\text{SO}_4^{2-}/\text{Cl}^-$	Na^+/K^+
Ice-wedge ice					
Depth (cm)					
10–20	5.3	98	2.1	120	3.0
30–40	5.2	8.3	2.6	16	5.4
40–50	5.6	7.3	2.5	14	6.5
60–70	12	2.1	1.5	12	40
70–80	47	0.4	0.59	64	88
80–90	20	1.0	0.53	45	66
90–110	68	1.3	0.75	99	143
120–140	18	1.3	0.72	40	58
150–170	81	1.1	0.74	126	341
New-snow					
	0.58	1.3	0.54	3.1	5.7
	0.71	1.6	0.49	2.4	7.5
Ice-body					
Depth (cm)					
0–20	2.8	0.75	0.33	8.3	4.9
30–40	1.9	1.1	0.50	8.3	5.8
40–50	3.5	1.0	1.0	7.1	10
55–65	1.9	0.49	1.6	3.3	7.1

snow samples and ice-core samples from the ice sheet were determined and are given in Table 3. The snow and ice from the ice sheet show expectedly far lower concentrations than those from Seymour Island.

3.2. Compositions of chemical species in ice-wedge ice

Table 4 gives ratios of the major chemical species in the ice-wedge ice body and those in the new-snows and the ice-body in Seymour Island. Those in the drifting-snows and ice-cores from the Antarctic ice sheet are given in Table 5.

From these tables, the ratios of the major chemical species in the ice-wedge ice in Seymour Island are obviously specific in comparison with those in the new-snows and the ice-body from the ground surface of this island as well as those in the snow and ice from the ice sheet.

Table 5. Ratios of the major ions in drifting-snow melt samples and ice melt samples from the ice-cores given in Table 3.

Sample	Na ⁺ /Cl ⁻	Ca ²⁺ /Cl ⁻	Mg ²⁺ /Cl ⁻	SO ₄ ²⁻ /Cl ⁻	Na ⁺ /K ⁺
Drifting-snow (collected at Mizuho Station)					
15 July 1982	0.73	—	—	0.33	—
15 November 1982	1.3	—	0.11	1.7	—
5 January 1983	1.2	0.18	0.09	2.1	14
Ice-core from S15					
	0.79	0.16	0.04	0.50	—
	0.79	0.13	0.06	0.25	16
	0.69	0.06	0.05	0.13	17
	0.88	0.70	0.04	0.63	—

4. Discussions

The chemical characteristics of the ice-wedge ice body are very specific, as mentioned above. Both the concentrations and compositions of chemical species are different between the depth above 50 cm (the upper part) and the depth below 70 cm (the lower part), even in the same ice-wedge ice body. Their concentrations in the ice body are unexpectedly high, especially in its lower part. Their vertical profiles are also very specific, especially in their tracing zigzag courses. These analytical results may present some questions on the origin and formation process of this ice-wedge ice body.

Ice-wedge patterns were traced by means of conventional plane board mapping, after the thawed material on the ground surface was scraped off by a bulldozer. As shown in Fig. 4, the patterns showed polygonal forms, which are similar in shape and size to tundra polygons in the continuous permafrost areas of the Arctic region. The polygonal patterns are rectangular and the mean length of each rectangle is 10 m. The structures of the ice-wedge ice body was examined by as the naked eye. The uppermost part contained many air bubbles, which are elongate in the vertical direction. In size and shape their patterns clearly resemble those of the Arctic ice-wedges. Based upon these characteristics of polygonal patterns and air bubble distributions, the excavated

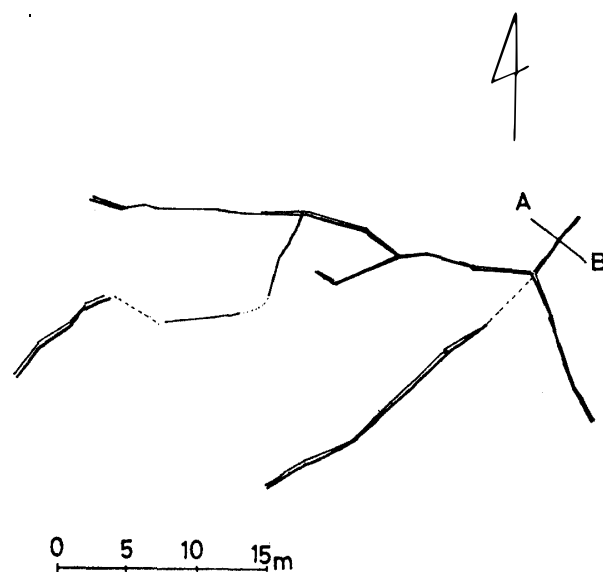


Fig. 4. Ice-wedge patterns in Seymour Island.

ice-wedge ice may be ascribed to frost cracking origin which is the common process of ice-wedge in the Arctic region.

Furthermore, as stated above, formation of another ice-wedge was observed to be active under the present climatic conditions (KOIZUMI and FUKUDA, 1989). This implies that rain- and/or melt-waters are the source of ice, at least, in the upper part of this ice-wedge ice body where the concentrations of chemical species are lower than in the lower part.

Table 6 gives concentrations of major elements in snow samples from a pit in an ice cap covering James Ross Island, east of Seymour Island, shown in Fig. 1 (ARISTARAIN *et al.*, 1982). The concentrations of major chemical species in snows in James Ross Island are rather lower than those in the snows and ices from the ice sheet, which is considered to reflect the difference in the amounts of precipitation. Accordingly, the concentrations of chemical species in the new snows (given in Table 2) from Seymour Island free of ice cover are higher than those in the snows from the ice cap

Table 6. Concentrations and ratios of major elements in snow samples from a pit in an ice cap covering James Ross Island, Antarctica (ARISTARAIN *et al.*, 1982).

Depth (cm of water)	Na	K	Ca	Cl	Na/Cl	Ca/Cl	Na/K
	(mg/l)						
10	0.30	0.010	0.008	0.77	0.39	0.010	30
29	0.50	0.014	0.017	1.31	0.38	0.013	35
48	0.10	0.005	0.008	0.21	0.47	0.035	20
64	0.02	0.005	0.010	0.23	0.87	0.043	4.0
85	0.46	0.015	0.018	0.82	0.56	0.021	31
98	0.02	0.010	0.015	0.18	0.11	0.083	2.0
138	0.30	0.013	0.013	0.62	0.49	0.019	23
191	0.03	0.003	0.004	0.22	0.14	0.018	10

of James Ross Island. This may be caused by the contaminations with salts found on the ground surface of the Syemour Island, which are mainly CaSO_4 , CaCO_3 and MgCO_3 . This is supported by the fact that the new-snows have larger ratios of $\text{Ca}^{2+}/\text{Cl}^-$ and $\text{SO}_4^{2-}/\text{Cl}^-$ than the snows and ices from the ice sheet and the ice cap.

Even the upper part of the ice-wedge ice body shows further higher concentrations of chemical species, except for NH_4^+ , than the new snows and the ice-body on the ground surface. This cannot be explained only by the contaminations of rain-water and/or melt-water with the salts found in this island. This must be caused not only by the dissolution of the found salts into waters but also by concentration of water through evaporation under dry condition. Accordingly, water poured into the crack of the ice-wedge is considered to be supplied as a very small stream. This is supported by the fact that the upper part of the ice-wedge ice body shows further larger ratios of Ca/Cl^- and $\text{SO}_4^{2-}/\text{Cl}^-$ than the new-snows and the ice-body, as seen from Table 4.

On the other hand, in the lower part of this ice-wedge ice body, the concentrations of chemical species are unexpectedly higher than in the upper part. Furthermore, their compositions also greatly differ between the upper and lower parts. Especially, larger ratios of Na^+/Cl^- , $\text{SO}_4^{2-}/\text{Cl}^-$ and Na^+/K^+ are seen in the upper part, whereas the ratios of $\text{Ca}^{2+}/\text{Cl}^-$ and $\text{Ca}^{2+}/\text{Mg}^{2+}$ are larger in the lower part. These facts may indicate that the origin of water and formation process of the ice-wedge are different between the ices forming its upper and lower parts. Therefore, some other causes must be taken into consideration for the interpretations of the specificity in the chemical features of ice in the lower part, and also the great difference between the two parts in the chemical compositions.

One of other causes to be considered is the contamination of water existed in the lower part of ice-wedge with some salts maintained in the high salt layer found by FOURNIER *et al.* (1987). They found the existence of layer of very high salinity in the Tertiary basement rock by using the magnetotelluric sounding. In this case, however, it is necessary that Na_2SO_4 is a major salt among those found in the bedrock and, furthermore in the lower part of the ice-wedge, the concentrations of Na^+ and SO_4^{2-} are much higher in the ice near the bedrock walls than in the central part. If not so, the ice body in certain depth interval of its lower part should have formed the same water body in the past. This means that the origin of water and the formation process are different between the upper and lower parts, even in the same ice-wedge ice body.

If the ice-body of this ice-wedge melted under a warmer condition in the past than at the present, the ice melt should have been able to dissolve the salts in the bedrock and further been concentrated through evaporation. Consequently, as seen from Tables 1 and 2, the concentrations of chemical species in the water in this ice-wedge must have become higher than not only those in the snows and ices in this island but also those in the ice body of its upper part which has never melted. When the climate condition in this island became colder, the water concentrated in this ice-wedge froze. After many times of melting, evaporation and freezing, the concentrations of chemical species in the lower part of this ice-wedge must have become greatly high.

Taking these added causes into consideration, the very specific vertical profiles tracing zigzag courses in the concentrations of chemical species in the ice-wedge ice

may be interpreted as follows: After freezing of the water concentrated in the ice-wedge, some parts of ice-wedge ice melted under the warmer condition. This ice melt was again concentrated through evaporation. After many times of freezing, melting and evaporation, the concentrations of chemical species of the water in the ice-wedge must have become greatly high. When this greatly concentrated water froze, the depositions of salts may have resulted in the change of the chemical compositions of the water concentrated in the ice-wedge, as shown by THOMPSON and NELSON (1956). And also this change must cause the difference in the chemical compositions of ice between the upper and lower parts. The deposited salts may be those found along the walls of the bedrock in the lower part.

Furthermore, because of partial melting of the whole ice-wedge ice body and also because of differences in the degree and the number of times of melting and freezing, the ices in the lower part must show the wide range of variations in the concentrations and compositions of chemical species, and their specific vertical profiles tracing zigzag courses. In this way, melting of the ice-body makes it easy to interpret the specific vertical profiles of the chemical species in this ice-wedge ice body.

However, we are still unable to define completely the specific and minute vertical profiles of the chemical species in the ice-wedge ice body. In order to solve the above-stated problem, determination of the salts found along the walls of the bedrock and isotopic analyses of ice samples from the this ice-wedge ice body may be very important key points. Further investigations should be requisite.

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References

- ARISTARAIN, A. J., DELMAS, R. J. and BRIANT, M. (1982): Snow chemistry on James Ross Island (Antarctic Peninsula). *J. Geophys. Res.*, **87**, 11004–11012.
- FOURNIER, H. G., CORTE, A. E., GASCO, J. C. and MAYANO, C. E. (1987): A very conductive layer below the permafrost of Seymour and Robertson Islands in the eastern Antarctic Peninsula. *Cold Reg. Sci. Tech.*, **14**, 155–161.
- FUKUDA, M. and CORTE, A. E. (1989): A preliminary report on permafrost occurrence in Seymour Island (Marambio Island), Antarctic Peninsula region (abstract). *Proc. NIPR Symp. Antarct. Geosci.*, **3**, 146.
- KOIZUMI, T. and FUKUDA, M. (1989): Ice-wedge formation in Seymour Island (Marambio Island), Antarctic Peninsula region (abstract). *Proc. NIPR Symp. Antarct. Geosci.*, **3**, 147.
- RINALDI, C. A., MESSABIE, A., MORELLI, J., ROSENMAN, H. L. and DEL VALLE, R. (1978): Geologia de la Isla Vicecomodoro Marambio. *Contrib. Inst. Antart. Argent.*, **217**, 44 p.
- THOMPSON, T. G. and NELSON, K. H. (1956): Concentration of brines and deposition of salts from sea water under frigid conditions. *Am. J. Sci.*, **254**, 227–238.

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