

Leaching of ions from the surface of glaciers in western Svalbard

Kumiko GOTO-AZUMA¹, Hiroyuki ENOMOTO², Shuhei TAKAHASHI², Shun'ichi KOBAYASHI³, Takao KAMEDA² and Okitsugu WATANABE⁴

¹ Nagaoka Institute of Snow and Ice Studies, NIED, STA, Suyoshi, Nagaoka 940 Japan

² Kitami Institute of Technology, Kitami 090 Japan

³ Research Institute for Hazards in Snowy Areas, Niigata University, Niigata 950–21 Japan

⁴ National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173 Japan

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Abstract

We collected snow, ice and melt water samples from the surface of glaciers in western Svalbard in the summer of 1991, and analyzed them for NO_3^- , SO_4^{2-} , Cl^- and Na^+ . In addition to the summer samples, we collected snow samples in the subsequent winter from pits dug through the snow cover on Austre Brøggerbreen and analyzed them for major anions and cations. The results showed that the concentration levels in the summer samples were much lower than those in the winter snow, indicating that the ions were flushed out from the surface of these glaciers during the thaw. The vertical re-distribution of ions during the thaw occurred in different manners at different sites. In the later stage of the melt season, ionic concentrations in some of the supra-glacial melt waters were still much higher than those expected from the melt water released in the late thaw.

1. Introduction

On most of the glaciers in Svalbard, surface melting takes place during the summer even in the highest part of the glaciers (Hagen and Liestøl, 1990). Melting causes migration of chemical constituents retained in glacier snow and ice. According to Glen *et al.* (1977), temperate glacier ice is very pure because impurities are flushed out of the glacier by water movement. Evidence of leaching processes in temperate and near-temperate glaciers has been found by previous investigators (Harrison and Raymond, 1976 ; Ricq-de Bouard, 1977 ; Davies *et al.*, 1982 ; Holdsworth *et al.*, 1988). However, detailed chemistry studies of glaciers with heavy melting have not been carried out thus far. Spatial and temporal variations of chemical constituents and chemical processes occurring in such glaciers are not well known. Chemical analyses of snow and ice have so far been focused on glaciers with only a little, if any, melt effects, since long-term atmospheric chemistry records not disturbed by melt effects have been the major concerns of

the investigators. Hence, chemistry data for Svalbard glaciers are sparse, although they are necessary not only for the understanding of the precipitation chemistry and glacier hydrology in Svalbard but also for the studies of the atmospheric chemistry and its spatial and temporal variations in the Arctic.

This study was carried out as a part of an international scientific research "Studies on atmosphere-cryosphere interaction and the variation in Arctic region" (Watanabe *et al.*, 1993; Takahashi *et al.*, 1993). In the present work, we intend to investigate the chemical composition of western Svalbard glaciers and the extent of re-distribution of chemical constituents due to the surface melting. We also intend to clarify the chemical processes occurring on the surface of sub-polar glaciers with heavy surface melting in the summer. For these purposes, we made chemical analyses of samples collected from glaciers near Ny-Ålesund, Svalbard in the summer of 1991 and in the subsequent winter.

2. Sample collection and chemical analyses

2.1. Sample collection

We collected samples from a sub-polar glacier Austre Brøggerbreen (78.9°N, 11.8°E) (Takahashi *et al.*, 1993) between August 6, 1991 and August 14, 1991. The sampling sites during this period are shown by

solid circles in Fig. 1.

The melt season at Austre Brøggerbreen usually begins in June and ends in September (Hagen and Liestøl, 1990). The mean equilibrium line elevation was 417 m a.s.l. during 1967–1988 (Hagen and Liestøl, 1990). The snow line, the border between snow surface and bare ice surface, was located around

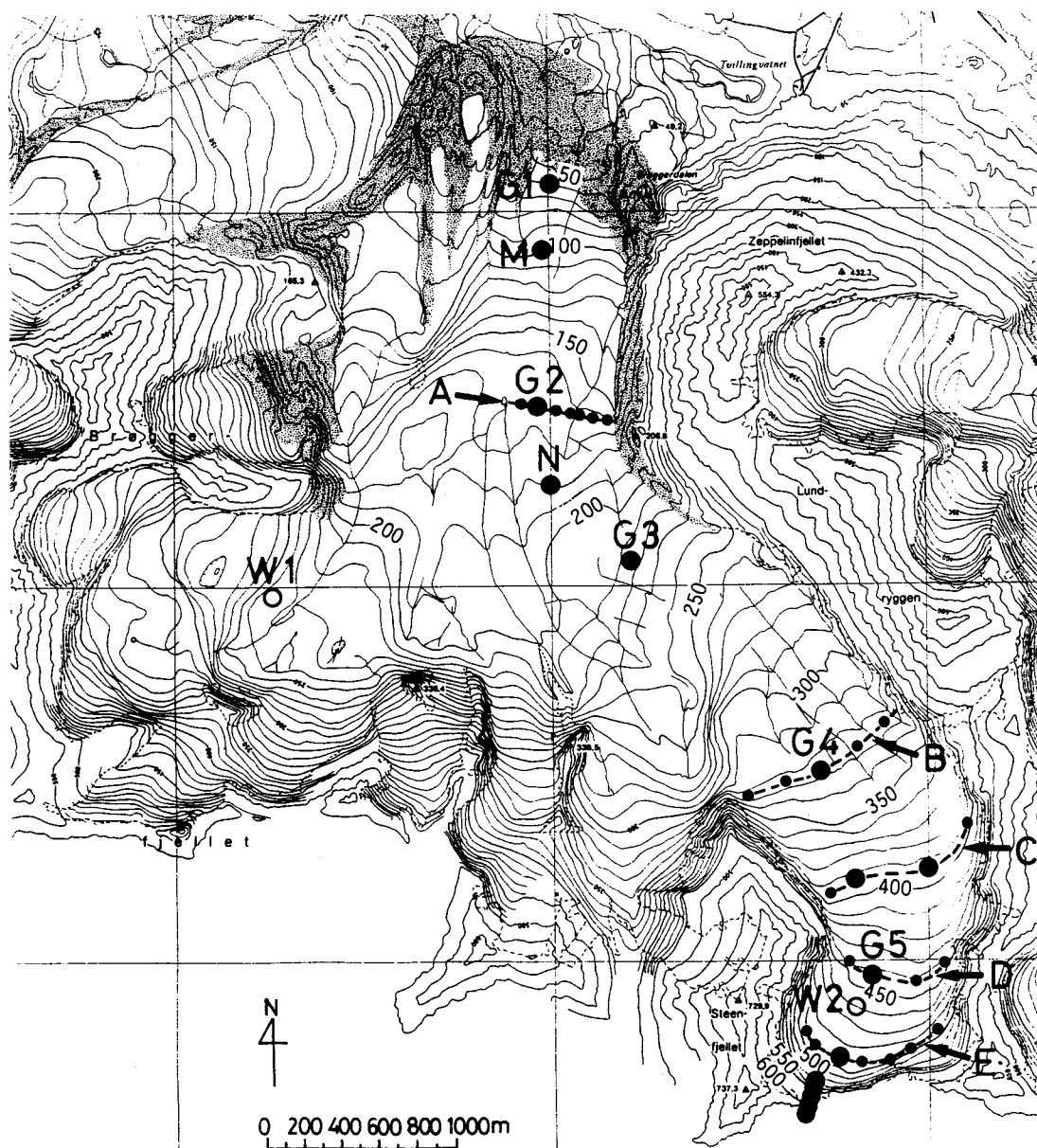


Fig. 1. Sampling sites on Austre Brøggerbreen. Solid circles denote the sampling sites in August, 1991, and open circles (W1 and W2) denote those on February, 1992. Sites G1 to G5 are where automated weather stations were temporarily set up during the 1991 summer field observation (Takahashi *et al.*, 1993).

site G3 on August 6, 1991, and gradually moved upward. It was located around site G4 on August 14, 1991. The glacier surface was more heterogeneous at elevations below the snow line than at elevations above it.

The surface of the glacier in the area around site G1 and site M was bare ice partly covered with brownish red dirt. Supra-glacial melt water was draining through the channels formed with foliation patterns. Sediment was often observed at the bottom of the drainage channels. Some of the channels were covered with beads-like ice grains whose diameter was 2–3 mm.

Around site G2, the glacier surface had similar features to those around sites G1 and M. However, the bare ice exposed at the surface was brittle in this area in contrast with that in the area around sites G1 and M, since inter-connection between individual grains was weak. Cryoconite holes with diameters 5–10 cm and depths 20–30 cm were found in this area. The number of supra-glacial drainages and the dirt-covered area decreased as the elevation increased.

The glacier surface in the area around site G3 and site N was smoother compared to that at lower elevations. It consisted of wet granular snow, slush (*i.e.* a mixture of snow and melt water), blue ice and melt water pools of several meters in size on top of ice. The glacier surface was partly covered with brownish dirt. Although snow cover accumulated in the winter still remained in this area, the area ratio covered with snow gradually decreased during the sampling period and the area ratio of slush, bare ice and melt water pools increased with time.

Upper part of the glacier surface was apparently more homogeneous. The sampling sites at elevations higher than site G4 were all covered with wet granular snow throughout the sampling period. Site G4 was mainly covered with wet granular snow. At around the end of the sampling period, patches of melt water pool and slush were observed at this site.

At sites G2, G3 and G5, we drilled ice cores with a hand auger on August 9, August 8 and August 6, respectively. The ice cores were drilled from the glacier surface down to depths of 1.70 m at G2 and to 0.70 m at site G3. At site G5, we dug a snow pit to the depth of 0.68 m, where we hit super-imposed ice. The density of snow in the pit wall ranged between 470 kg/m³ and 520 kg/m³ on August 6. Melt water was continuously emerging from the bottom of the pit.

We started ice coring from the bottom of this pit and stopped it at a depth of 2.41 m. Snow samples were collected from the pit wall continuously with a pre-cleaned scoop and put into plastic bags which had been assured to be contamination-free regarding with the relevant ions. Ice cores taken at sites G2, G3 and G5 were all cut into 5–10 cm long pieces with a hand saw. After shaving off the surface 0.5–1 cm of each piece with a pre-cleaned knife and disposable plastic gloves, we put each sample into a plastic bag. The core cutting and shaving were done in the field.

In addition to the snow pit and ice core samples, we collected various "surface samples" at sites shown with solid circles in Fig. 1, which include the ice coring sites, during the summer sampling period. "Surface samples" consisted of snow samples from the top 3–5 cm of snow cover deposited in the previous winter, ice samples from the top 3–5 cm of the bare ice, slush samples which are the mixture of snow and melt water, and melt water samples from the glacier surface. The top 1 cm of the glacier surface was removed prior to the sampling to avoid the contamination from our activities on the glacier. The snow, ice, slush and melt water samples were collected in either plastic bags or pre-cleaned polypropylene bottles.

In order to investigate the effects of the surface melting on glacier chemistry at higher elevations where less melting is expected, we extended our summer sampling to a site at 79.1°N, 12.9°E, 850 m a.s.l. on Isachsenfonna which is located about 30 km north east of Austre Brøggerbreen (Takahashi *et al.*, 1993). The snow was wet in the top 2 m layers of Isachsenfonna. We dug a 2.10 m deep snow pit on Isachsenfonna on August 12, 1991 and took 26 samples from the pit wall. The pit samples were collected in pre-cleaned polypropylene bottles.

The winter sampling on Austre Brøggerbreen was carried out on February 20, 1992 to characterize the chemical composition of the winter snow which is little affected by melting. Austre Brøggerbreen was covered with snow which presumably had accumulated since September, 1991. The thickness of the snowpack was 1.10 m at site W1 and 1.15 m at site W2. Pits were dug at both site W1 (235 m a.s.l.) and site W2 (470 m a.s.l.) down to 1.15 m. At both sites, super-imposed ice, which is considered to be the 1991 summer surface, was found beneath the snowcover. The bottom 5 cm of the pit at site W1 was the super-imposed ice, while at site W2 the pit was not dug into the super-imposed ice at all. Samples were taken

from the pit walls with a pre-cleaned scoop and put into plastic bags. 14 and 12 samples were collected continuously at site W1 and at site W2, respectively.

All the samples collected in the field both in the summer and the winter were brought back to Ny-Ålesund to be melted at a room temperature. The samples melted in plastic bags were transferred to pre-cleaned polypropylene bottles after they melted, whereas those collected in bottles were kept in the same bottles. All the summer samples were shipped to Japan in the liquid phase. Immediately after they arrived at Nagaoka Institute of Snow and Ice Studies in early December, 1991, they were refrozen in a cold room and were kept frozen until the chemical analyses were made. The winter samples, which were also in the liquid phase, were brought back to National Institute of Polar Research in Tokyo, Japan within a week from the sampling date. They were analyzed immediately after the arrival in Tokyo.

2.2. Chemical analyses of samples

All the summer samples were analyzed at Nagaoka Institute of Snow and Ice Studies for NO_3^- , SO_4^{2-} and Cl^- with a Dionex Dx-100 ion chromatograph and for Na^+ with a Seiko SAS 7500 atomic absorption spectrophotometer equipped with a flame atomizer. Samples containing visible dirt were filtrated with Nuclepore filters (pore size : 12 μm) prior to the chemical analyses. Measurements on $\delta^{18}\text{O}$ were made at National Institute of Polar Research for samples from Isachsenfonna.

The winter samples were analyzed for NO_3^- , SO_4^{2-} , Cl^- , Na^+ , K^+ , Mg^{2+} and Ca^{2+} with a Dionex 2000i/sp ion chromatograph and for $\delta^{18}\text{O}$ with a Finigan MAT Instrument Inc. δ E mass spectrometer at National Institute of Polar Research.

3. Results

3.1. Ionic concentrations in the summer samples

Vertical concentration profiles of NO_3^- , SO_4^{2-} , Cl^- and Na^+ at sites G2, G3 and G5 are exhibited in Fig. 2 together with the stratigraphy. Vertical profiles of ionic concentrations, $\delta^{18}\text{O}$ and density and the stratigraphy at Isachsenfonna are shown in Fig. 3. As seen from Fig. 2 and Fig. 3, the vertical concentration profile and the concentration level of each ionic species was different from site to site.

Figure 4 and Fig. 5 show the spatial variation in ionic concentrations in the summer surface on Austre

Brøggerbreen.

Concentrations of NO_3^- , SO_4^{2-} , Cl^- and Na^+ in the surface samples collected from the sites along different contour lines A-E (Fig. 1) are plotted in Fig. 4. No systematic variations of concentration levels with distance from the exposed mountain rocks that form the edge of the glacier were observed. As far as the contour lines located above the snow line (*i.e.* contour lines B-E) are concerned, no systematic variations of concentration levels with elevation were observed. The scatter of concentration levels were much greater for contour line A, which was in the ablation zone, than for contour lines B-E.

Figure 5 depicts the concentrations of NO_3^- , SO_4^{2-} , Cl^- and Na^+ in the surface samples collected from the sites near the center flow line of the east branch (the sites are indicated by large solid circles in Fig. 1). We did not observe any trends in concentration levels with time within the sampling period of August 7, 1991 – August 14, 1991. While it drizzled intermittently on August 8, August 10, August 12 and August 13, 1991, we did not see any systematic changes caused by the drizzle. Time-to-time variations in concentration levels were well within the range of sample-to-sample variations. The scatter of concentration levels was greater at sites G2 and G3 than at the other sites.

3.2. Ionic concentrations in the winter samples

Concentrations of NO_3^- , SO_4^{2-} , Cl^- , Na^+ , Mg^{2+} and Ca^{2+} , and $\delta^{18}\text{O}$ in the snowpack along with the visible stratigraphy at sites W1 and W2 are shown in Fig. 6. K^+ concentrations were less than or close to the detection limit (100 ppb) in most of the samples. Almost all Cl^- , Na^+ and Mg^{2+} in the winter snow on Austre Brøggerbreen were the sea salt origin, since the ratios Cl^-/Na^+ and $\text{Mg}^{2+}/\text{Na}^+$ in most of the samples were close to those of the sea water. The $\text{SO}_4^{2-}/\text{Na}^+$ ratio ranged between 0.29 and 0.62, and this indicates that 40–90 % of SO_4^{2-} was the sea salt origin, since the $\text{SO}_4^{2-}/\text{Na}^+$ ratio for the sea water is 0.25. Thus, the sea spray was the major source of ions on a maritime glacier Austre Brøggerbreen.

The stratigraphy, the $\delta^{18}\text{O}$ profile and the concentration level of each ion at site W1 were generally similar to those at site W2. In particular, peaks around 0.3 m and 0.5 m in concentration profiles of SO_4^{2-} , Cl^- , Na^+ , Mg^{2+} and Ca^{2+} at site W1 were found at similar depths also at site W2. The nitrate peak at 0.51–0.53 m at site W2 which were not seen at site W1 was associated with the ice layer at that depth. The

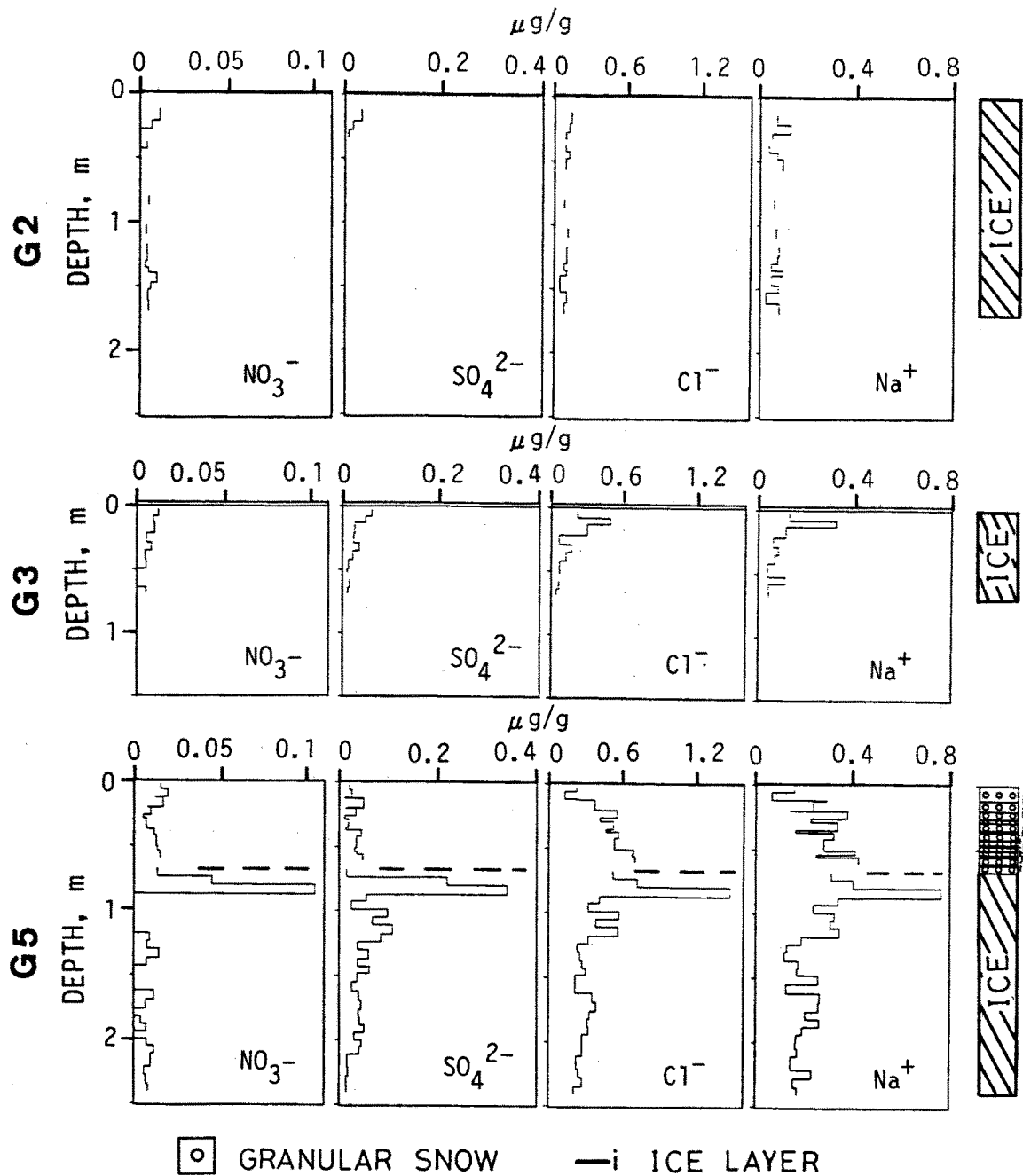


Fig. 2. Vertical profiles of ionic concentrations at sites G2, G3 and G5 on Austre Brøggerbreen in August, 1991 along with the stratigraphy. The snow/ice boundary at site G5 is shown by a broken line.

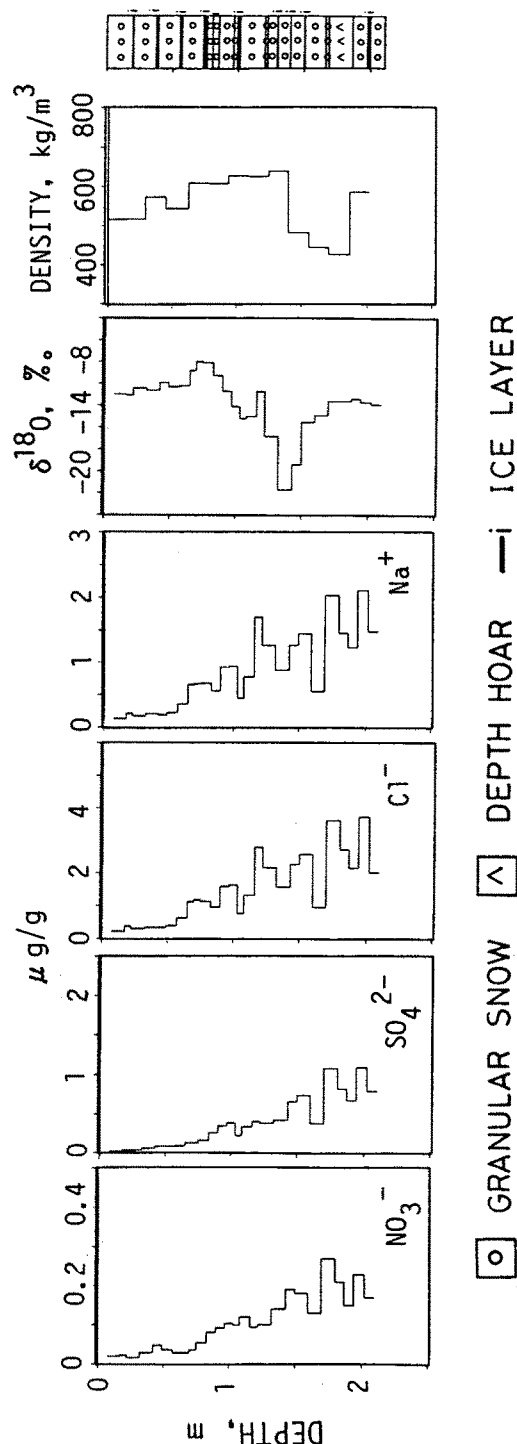


Fig. 3. Vertical profiles of ionic concentrations, $\delta^{18}\text{O}$ and density along with the stratigraphy from the pit dug on August 12, 1991 at Isachsenfonna.

distribution of ions in the glacier surface was more homogenous in the winter than in the summer.

4. Discussion

4.1. Vertical profiles of ionic concentrations created by leaching processes

At site G5, concentration levels of ions in the snow and the super-imposed ice below the snow were much lower than those in the winter snow cover (Fig. 2 and Fig. 6). Moreover, the high peak in concentrations was found just below the boundary between the snow layer and the ice layer. Similar observation was previously made at Folgefonni Ice Cap, Norway by Davies *et al.* (1982), while their data showed the high peak at 12–15 m in depth in contrast with our peak at a much shallower depth. Vertical profiles of ionic concentrations at site G5 indicate that most of the ion input since the 1990 melt season had been released from the snow above the super-imposed ice even at the highest part of Austre Brøggerbreen. The ions released from the snow seem to have moved downward and stopped at the snow/ice boundary. Low ionic concentrations at depths below this boundary suggest that the removal of ions took place also in the previous year(s). The ratio of the peak ionic concentration to the average ionic concentration in the entire depth except for the peak was greater for NO_3^- and SO_4^{2-} than for Cl^- and Na^+ . This may reflect the preferential elution of NO_3^- and SO_4^{2-} to Cl^- and Na^+ from melting snow (*e.g.* Davies *et al.*, 1982, Azuma *et al.*, 1993), although we have to know the initial distribution of each ion in the snow before the melt season to come to a conclusion.

From the analyses of the 60 m core from Folgefonni Ice Cap, Davies *et al.* (1982) suggest that a high peak at the snow/ice boundary exists only temporarily in the melt season and it disappears by the end of the melt season. However, concentration profiles obtained at site W1, Austre Brøggerbreen from the winter sampling (Fig. 6) showed high peaks in what was considered to be the previous summer surface. This presumably indicate that such high peaks occasionally remain after the melt season. A recovery of a deeper ice core is necessary for the further study.

Concentration levels of ions in ice cores from sites G2 and G3 were 1–2 order(s) of magnitude lower than those in the winter snow (Fig. 2 and Fig. 6). Concentration levels in the both cores appear to be even lower than those in samples from site G5 (Fig. 2).

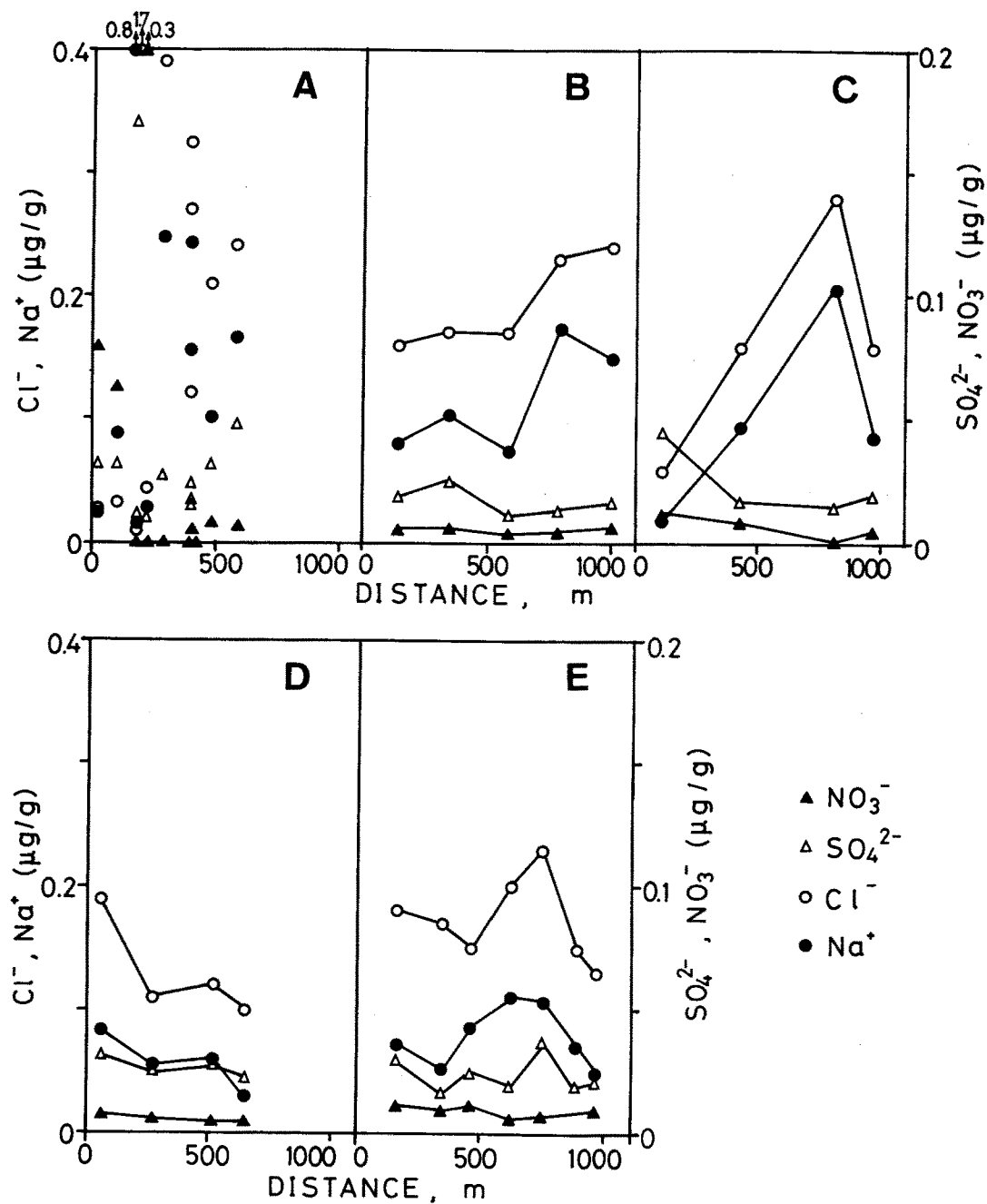


Fig. 4. Concentrations of ions in the surface samples collected from the sites along different contour lines A-E at Austre Brøggerbreen (Fig. 1). The altitudes of the contour lines A-E were 165, 325, 395, 440 and 490 m a.s.l., respectively. Date of the sample collection was August 13, 1991 for contour line A and August 12, 1991 for contour lines B-E. The horizontal axis of each figure denotes the distance on each contour line, where the original point is taken at the east edge of the glacier.

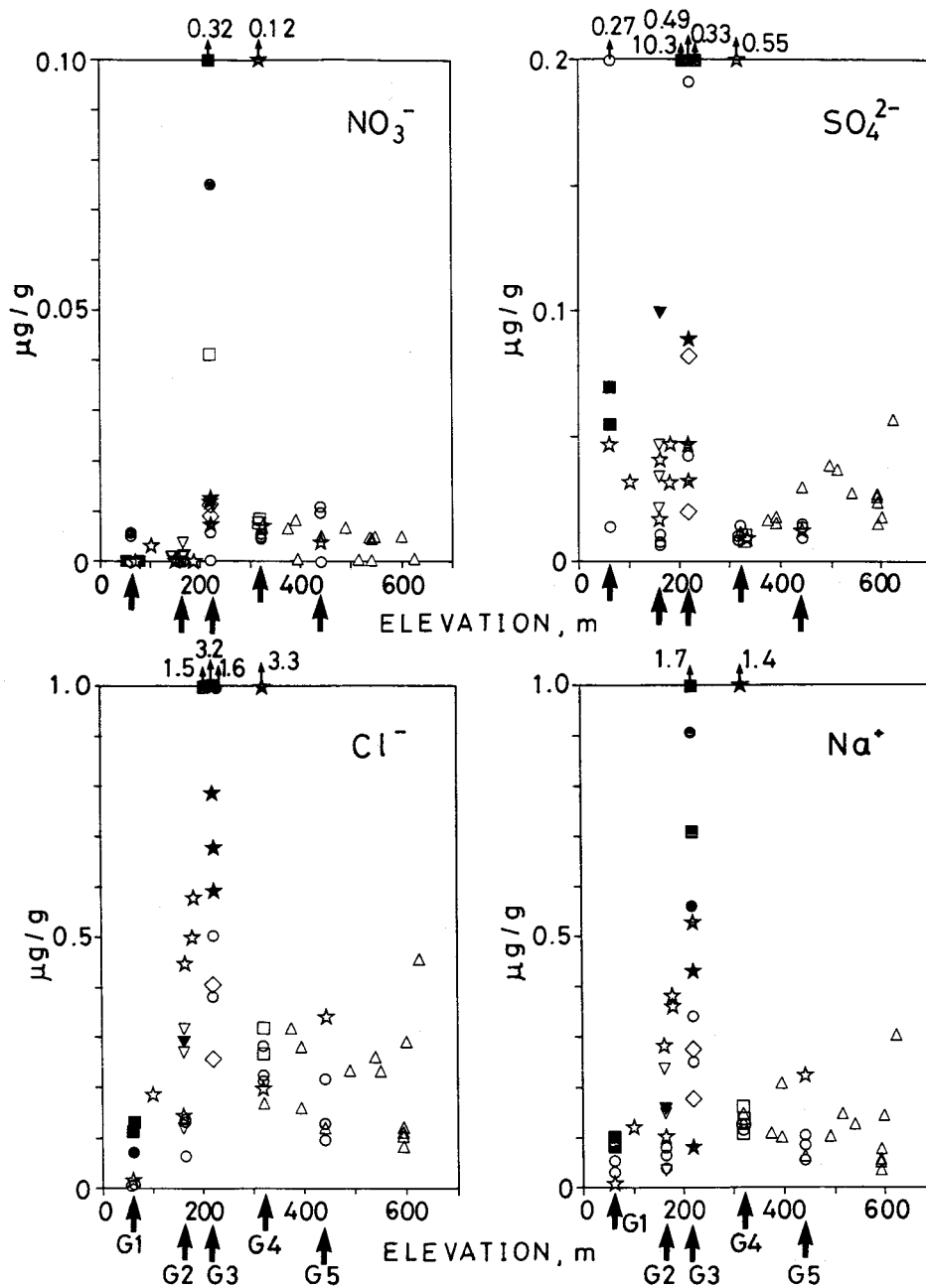


Fig.5. Concentrations of ions in the surface samples collected from Austre Brøggerbreen at the sites indicated by large solid circles (Fig. 1). The horizontal axis represents the elevation of the sampling site. Open symbols denote snow and ice samples. Hatched and solid symbols denote slush samples and melt water samples, respectively. Dates of sample collection are shown by different symbols. Circles : August 7, diamonds : August 8, squares : August 11, triangles : August 12, nablas : August 13, and stars : August 14, 1991.

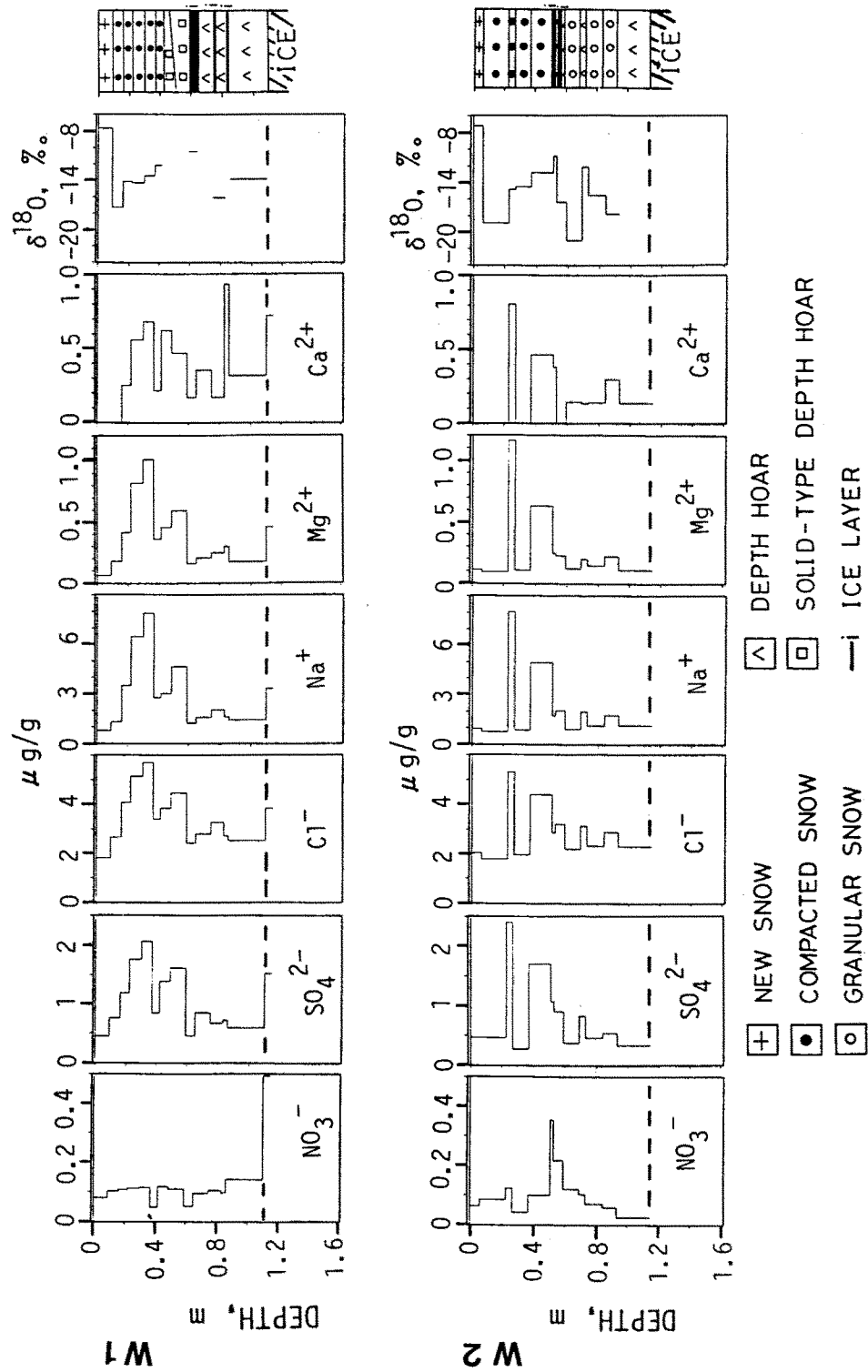


Fig. 6. Ionic concentrations and $\delta^{18}\text{O}$ in the 1991/1992 winter snow pack which were obtained from the pits at site W1 (235 m a.s.l.) and site W2 (470 m a.s.l.). The boundary between the winter snow and the super-imposed ice at each site is shown by a broken line.

Also, the top 0.2–0.3 m of the core from site G3 showed slightly higher concentration levels of Cl^- and Na^+ than in the core from site G2. These facts may reflect the more leaching of ions at lower elevations due to heavier surface melting, while there is another possibility that the concentration levels in the ice presently at the surface of sites G2 and G3 might have been lower than those in present day snow when the ice was originally deposited as snow, for these ice cores were taken from the ablation zone and they might be old ice.

Concentration profiles of different ionic species from the pit samples from Isachsenfonna (Fig. 3) were all similar in contrast with the winter snow pack on Austre Brøggerbreen in which the correlation between concentrations of NO_3^- and those of other ions was weak (Fig. 6). The concentrations showed a general tendency to increase from the surface to the bottom of the pit. These facts indicate that the leaching of ions has occurred at the top 2.1 m of Isachsenfonna. However, the ionic concentrations were close to the winter concentration levels at the bottom of the pit. This suggests that less ions have been escaped from the glacier surface at Isachsenfonna than at Austre Brøggerbreen.

The $\delta^{18}\text{O}$ profile from Isachsenfonna (Fig. 3) did not show any systematic decrease or increase with depth. Since a depth hoar layer is generally formed when cold snow deposited onto the warm summer surface, as can be seen from the one formed on top of the summer surface on Austre Brøggerbreen (Fig. 6), the depth hoar layer with low density at around 1.7 m depth presumably corresponded to the fall layer. Hence, negative peak of $\delta^{18}\text{O}$ seen at around 1.3 m depth may correspond to the winter layer. The variation in the profile probably reflects the seasonal variation of $\delta^{18}\text{O}$ values. The $\delta^{18}\text{O}$ profile for the top 2.1 m of Isachsenfonna appears to have been less modified by melting compared to ionic species.

Leaching of ions by melting is the major process determining the ionic concentrations at Austre Brøggerbreen and at Isachsenfonna. The vertical concentration profiles of ions from sites G2, G3 and G5 at Austre Brøggerbreen (Fig. 2) and those from Isachsenfonna (Fig. 3) are all different, although leaching of ions has taken place at all these sites. Another different profile of ionic concentrations was previously obtained from a crevasse located near the equilibrium line at a temperate glacier (Ricq-de Bouard, 1977). They exhibited the tendency for concentrations to

decrease with depth, which is opposite to the concentration profiles from Isachsenfonna (Fig. 6). The re-distribution of ions by melting seems to occur in a different manner at individual site, possibly depending upon the extent of melting, sub-surface structure, and the vertical temperature distribution.

4.2. *Supra-glacial melt waters with high ionic concentrations*

Levels of ionic concentrations in the surface samples collected on Austre Brøggerbreen in the summer at sites above the snow line and at sites well below the snow line were much lower than those in the winter snowpack (Fig. 2, Fig. 4, Fig. 5 and Fig. 6). One exception is the high SO_4^{2-} level in one sample from site G1 (Fig. 5), which is presumably associated with dirt. On the other hand, some of the samples from the sites around and a little below the snow line contained as much ions as in the winter snowpack. This cannot be attributed to the dirt, since samples containing visible dirt did not necessarily show higher ionic concentrations. Most of the samples with high ion contents were the slush samples and melt water samples.

Previous studies on melting snowpacks (*e.g.* Johannessen *et al.*, 1977 ; Johannessen and Henriksen, 1978 ; Suzuki, 1982) revealed that ions are preferentially released into melt water and that the melt water released at the initial stage of snowmelt is rich in ion contents. Accordingly the melt water released at the later stage becomes poor in ion contents. Hence the low ionic concentrations in the melt water at site G1 indicates that this was the melt water produced at the later stage of melting. On the other hand, samples with high ionic concentrations as found at sites near and a little below the snow line seem to be associated with melt waters with high ionic concentrations. These melt waters cannot be the ones which have just been released from the snow, since most of the ionic load accumulated since the previous melt season had been already escaped from the snow by the time of the sampling, as described so far.

The melt waters which contained high ionic concentrations might have been originated from the melt of the layer with high ionic peak as seen in Fig. 2, since such a layer probably had just been exposed at the surface in the area around and a little below the snow line. The melt waters around site G1 could have been low since such a layer is considered to have been already melted out in the previous summer or in

the early melt season at a lower elevation, or such a layer might not have been formed at site G1. Further studies are necessary to clarify the origin of the melt waters with high ion contents.

Spatial variations in the structure and the ionic concentrations of the glacier surface were much greater in the summer than in the winter (Fig. 2, Fig. 4, Fig. 5 and Fig. 6), since melting of the glacier surface occurred heterogeneously. The greatest spatial variations observed at elevations around and just below the snow line (Fig. 4(A) and Fig. 5) can be attributed to the co-existence of snow and ice containing low ionic concentrations and melt water containing high ionic concentrations at these elevations.

5. Conclusions

Concentrations of NO_3^- , SO_4^{2-} , Cl^- and Na^+ near the surface of Austre Brøggerbreen and Isachsenfonna in western Svalbard were very low in the summer, because most of the ionic inputs were removed from the surface of these glaciers during the thaw. Leaching of ions not only reduced the concentration levels of ions, but also created the characteristic vertical profiles of ions near the glacier surface. The very high peak in concentration profiles was found near the boundary between granular snow and super-imposed ice. We suggest that this high peak may survive the whole melt season in some years.

The high peak in concentration profiles was more pronounced for SO_4^{2-} and NO_3^- than for Cl^- and Na^+ , which was probably due to the preferential elution of the former ions to the latter ions from melting snow and ice as demonstrated by previous studies (*e.g.* Davies *et al.*, 1982; Brimblecombe *et al.*, 1985; Brimblecombe *et al.*, 1987; Azuma *et al.*, 1993).

The surface snow, ice and melt water samples from various sites on Austre Brøggerbreen indicated that the variations of ionic concentrations in these samples were greater in the area around and just below the snow line where supra-glacial melt waters with high ionic concentrations existed. The surface melting seemed to accentuate the heterogeneity of ionic concentrations in the glacier surface.

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