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ACADEMIC YEAR 1992

THE DYNAMICS OF A SMALL ANTARCTIC

ICE SHELF AS INDICATED

BY AN ICE COMPOSITION STUDY

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Denyse RONVEAUX Université de Bruxelles Travail présenté pour l'obtention du titre de Docteur en Sciences (Grade légal)

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INTRODUCTION

The accumulation of greenhouse gases in the atmosphere can lead to a significant increase in the temperature of ocean water and air in the coastal regions of Antarctica. This has an effect on the ice shelves which fringe 50% of the Antarctic coastline and cover an area equal to 11% of the continent land area. The ice shelves act as buttresses which control drainage from the ice sheet. Their stability is dependent in part on exchanges at the interface between ice and sea water and on either melting or freezing at their underside.

A distinction must be made between small and large ice shelves because in the case of small shelves, their reduced thickness makes them more sensitive to warm water intrusion.

The behavior of small ice shelves must be studied in relation to global climate changes. Our study deals with a small ice shelf which has unusual characteristics. Because of ablation due to katabatic winds, deep ice layers move upward to the surface, which allows them to be easily studied.

The approach used in this study is based on isotopic composition analyses, crystallographic studies and the cationic content of the ice.

I. THE HELLS GATE ICE SHELF AND ITS REGIONAL ENVIRONMENT

A. Localization

The Hells Gate Ice Shelf is a small ice shelf located in the southern part of Terra Nova Bay.

Terra Nova Bay is a large inlet located in Victoria land, a region in Eastern Antarctica lying north of the Ross Ice Shelf. The region, named for Queen Victoria in 1841, is bounded by the Transantarctic Mountains to the west and by the Ross Sea to the east. Terra Nova Bay's southern boundary is Drygalski Ice Tongue at 75°15'S., while its northern limit is Mt Melbourne (2,732 m) at 74°21'S and 164°42'E (Swithinbank, 1988). It is situated between the meridians of 163°30' and 165°30' east. The mountains fringing the Bay belong to the Transantarctic Mountains. They are divided into different ranges separated from each other by outlet glaciers originating in the East Antarctic Ice Sheet. Fig 1, a NOAA 6 image taken on February 27, 1980, and published in Swithinbank (1988), illustrates the surroundings of Terra Nova Bay.

In the north of the region lie the Southern Cross Mountains. Mt Melbourne, a part of the range is a stratovolcano, almost entirely covered with ice. Many areas of hot steaming ground can be found near the summit. It is thought to have erupted in historic times, as suggested by ash layers exposed in the nearby floating glacier tongues (Nathan and Schulte, 1967).



Figure 1. NOAA 6 image taken on February 27, 1980, and published in Swithinbank (1988).

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Along Mt Melbourne's western slope, Campbell Glacier drains the Southern Cross Mountains.

The Eisenhower Range stretches from Priestley Glacier to Reeves Glacier. Priestley Glacier¹, an outlet of the East Antarctic Ice Sheet, originates in the Priestley Névé. In its downstream part², tributary glaciers which contribute ice to the Hells Gate area, feed into it, such as Corner Glacier south of Black Ridge and Boomerang Glacier flowing into Browning Pass.

South of the Eisenhower Range, Reeves Glacier, flowing NW to SE, is nourished by the Reeves Névé. Hansen Nunatak and Teall Nunatak lie in the lower part of an icefall, just before Reeves and Priestley Glaciers merge to form the Nansen Ice Sheet. This floating ice sheet is approximately 28 km wide between Teall Nunatak in the west and Inexpressible Island in the east. It is 40 km long from Rhodes Head to its southernmost section. Nansen Ice Sheet's extension is about 1,800 km² (Baroni et al, 1991).

¹ Figure 2: The Hells Gate Ice Shelf, looking north-east toward Priestley Glacier Valley. In the foreground, a double line of dirt cones and meltstreams; to the left, in the background, the northern tip of Inexpressible Island. At the far right end, the southern tip of Vegetation Island; in the background, the Beacon Supergroup erosion surface cutting through the Mount Nansen area. Photograph: R. Souchez.

² Figure 3: The upper NW-SE portion of Priestley Glacier looking upglacier. On the left-hand side, the Deep Freeze Range, composed of Wilson Metamorphics and Granite Harbor Intrusives. On the right-hand side, the metamorphic complexes of Wilson Terrane. Photograph: R. Souchez.



Figure 2. Photograph of Hells Gate Ice Shelf.



Figure 3. Photograph of upper NW-SE portion of Priestley Glacier Valley looking up glacier.

Located on Nansen Ice Sheet's eastern edge, Inexpressible Island was named after six members of Scott's Northern Party, led by V. Campbell, spent the 1912 winter in a snow cave near Seaview Bay. On January 25, 1913, when the ship the Terra Nova entered the Bay, Campbell suggested that a food depot should be left on the Hells Gate beach of Inexpressible Island. This large food depot was discovered on January 8, 1983, by members of the New Zealand geological expedition (Antarctic Journal of the U.S., March 1983).

South of Reeves is Larsen Glacier, which also flows NW to SE. The Southern boundary of the region is represented by David Glacier, extending into the Ross Sea for more than 100 km to form Drygalski Ice Tongue. All above mentioned features can be found on figures 4 and 5.

B. Geological and Glaciological Settings

1. Geological Formations of the Terra Nova Bay Area

Antarctica is made up of two structural provinces: East Antarctica is a stable shield separated from the much younger Mesozoic and Cenozoic belt of West Antarctica. The contact zone between these two provinces is the Transantarctic Mountains and the depression separating the Ross Sea and the Weddell Sea.

The region was first studied by members of Scott's



· Outcrops of low-grade metasediments (Priestley Formation) and contact metamorphosed Priestley Formation in the region between David and Mariner Glaciers, North Victoria Land. Outcrops mentioned in this work are shown in

black and are indicated by numbers in circles, as follows: 1. Arrowhead Range; 2. Vulcan Hills; 3. Mt. Jiracek; 4. Burns Glacier; 5. Pinckard Table; 6. Styx Glacier; 7. Tinker Glacier; 8. Ogden Heights; 9. Foolsmate Glacier; 10. Mt. New Zealand; 11. Mt. Borgstrom; 12. O'Kane Canyon and Mt. Baxter; 13. Tourmaline Plateau; 14. Gerlache Inlet; 15. Rhodes Head.

Key to symbols: 1. Mc Murdo Volcanics (late Cenozoic - Quaternary) 2. Beacon Supergroup and Ferrar Supergroup (Permian - Mesozoic) 3. Dessent Metamorphics (? Precambrian), Bowers Terrane (Middle Cambrian - Early Ordovician), Robertson Bay Terrane (Cambrian - Early Ordovician) and Admiralty Intrusives (Devonian - Carboniferous) 4. Granite Harbour Intrusives (Late Cambrian - Ordovician)

5. Metamorphic Complexes of the Wilson Terrane (? Precambrian)

6. Main overthrusts

Figure 4.

Geological setting of Terra Nova Bay.



Figure 5.

Map produced by the Italian Antarctic Research Program at the 1:250,000 scale.

northern party who explored and mapped the Terra Nova Bay area before being forced to spend the winter on Inexpressible Island (Priestley, 1914). Very little research was devoted to the region in the following decades. In 1963, coastal rocks were sampled and analyzed (Ricker, 1964). During the 1969-70 austral summer, Skinner conducted a geologic survey of the igneous and metasedimentary rocks outcropping along the coast of Terra Nova Bay (Skinner, 1983). Whitehouse and Chinn (1985) studied the geomorphology of the Northern Foothills.

This region was explored by the Italian expeditions of 1985, 1986, 1987, and 1988 (Ghezzo et al, 1989) and mapped by the Italian Antarctic Research Program at the 1:250,000 scale. The region contains essentially crystalline rocks that are described below in chronological order.

The Wilson Terrane is the nearest to the East-Antarctic Craton. Probably dating back to the Precambrian, these high grade metamorphics noted PChg form the backbone of the Deep Freeze Range, the northern tip of the Northern Foothills, the eastern part of McCarthy ridge outcropping at Gray Rock and the central and western portions of Inexpressible Island. The Wilson Terrane includes gneiss and migmatite in the Deep Freeze Range, and quartzite, biotite schist, and garnet-biotite paragneiss elsewhere. The Wilson Terrane was intruded by Ordovician granitoids, *i.e.*, the Granite Harbor Intrusives.

The Granite-Harbour Intrusives (Ordovician) are

represented by plutons (Ohm and Ohg). Ohm (Amphibolite and biotite quartzodiorite; diorite and gabbro; ultramafic rocks) is found in the Northern Foothills bordering the eastern section of Hells Gate Ice Shelf, on Vegetation Island and on Inexpressible Island.

The exact separation between Ohm and Ohg is easily seen on figure 6, since Ohm is darker and more resistant than Ohg. The abrasion resistance of Ohm resulted in the formation of a small scarp, north of Cape Russell.

Ohg comprises syenogranite, biotite monzogranite, granodiorite, and a two mica granite. Small outcrops of tonalite (Oht) are also part of Granite Harbour Intrusives: they are found in the southern tip of Black Ridge and throughout Anderson Ridge. Ohg is described in Skinner (1983) as Hells Gate Granite on the northeastern coast of Inexpressible Island, and as Inexpressible granite south of the two faults on Inexpressible Island. Figure 7 is a vertical aerial photograph of Inexpressible Island showing a fault scarp between Ohm (the more resistant) and Ohg.

The Granite Harbour Intrusives are found almost everywhere in the southern section of the Prince Albert Mountains, between David Glacier and Eisenhower Range. To the north, they are still present but intermingled with the Wilson Terrane metamorphics. A regional erosion surface developed that cuts across the metamorphic rocks and the Early Paleozoic





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rocks (Carmignani et al, 1989). It is on this peneplain that the Beacon Supergroup continental sediments were deposited.

The Beacon Supergroup dating from the Permian-Triassic unconformably overlies the early Paleozoic granitoids of the Granite Harbour Intrusives. The Beacon Supergroup is well known for the Beacon sandstones. The erosion-resistant sandstones form a promontory overlooking Priestley Glacier. The variable altitude of the peneplain suggests very active tectonics in Victoria Land.

The Ferrar Supergroup massive tholeiites and dolerites were intruded as sills into the Beacon layers during the Jurassic. The Ferrar Supergroup is found among others in Skinner Ridge, Mount Nansen, the Eisenhower Range, and in the northern section of the Deep Freeze Range at high altitude (Mount Hewson, 3,720 m, Shaker Peak, 3,600 m, Mount Adamson, 3,399 m).

The McMurdo Volcanics, late Cenozoic to quaternary in age, contain alkalibasalt, trachyandesite, phonolite, and volcanoclastics. These terranes are found in two areas: the McMurdo Sound area, which borders Mount Erebus, and the Mount Melbourne region.

Mount Erebus (3,794 m), in the McMurdo region, has erupted intermittently since 1841 when it was discovered by James Ross, but it has shown increased activity since December 1972 when a lava lake formed.
2. The origin of the Antarctic Ice Sheet

About one hundred million years ago, Antarctica, then drifting as part of the Gondwana landmass, arrived in the vicinity of the South Pole. The Antarctic continent separated from Gondwana about 30 million years ago and since has been surrounded by the circumpolar Antarctic Ocean (Dudeney, 1987). This induced the formation of the West Wind Drift that isolated Antarctica from the warm currents transporting heat from the Tropic of Capricorn to high-latitude regions (figure 8¹).



~ 40 Million Years BP

~ 20 Million Years BP

Figure 8.

The separation of the Antarctic continent from Gondwana 30 million years ago induced the formation of the West Wind Drift. After Dudeney, 1987, p.194.

3. Figure 8: Evolution of the ocean currents between about 40 million years B.P. and 20 million years B.P. After Dudeney, 1987, page 194.

Evidence of the origin and age of the Antarctic Ice Sheet is rare. Since only 2 % of the continent is ice-free, the search for fossil evidence is limited to the Transantarctic Mountains, the Antarctic Peninsula and to portions of the coastline. Fortunately, studies of planktonic Foraminifera and Radiolaria in sediment cores can compensate for the scarcity of terrestrial fossils. Indeed, the abundance of these planktonic organisms has been used successfully to discriminate between cold- and warm-water types. This led to estimates of the onset of Antarctic glaciation. Other indicators of the size of the past ice sheet are the fluctuations of δ^{18} O content in calcareous oozes and shells, and the presence of erratics on the ocean floor that supposedly are of ice-rafted origin.

The oxygen isotope record of the Deep Sea Drilling Project sediment cores indicated that the ice cover reached the Ross Sea coast about 25 million years B.P. but then receded (Dudeney, 1987). Figure 9 shows a progressive decrease in bottom water temperature attributed to the gradual extension of the ice sheet. The sharp reduction of the bottom water temperatures observed corresponds to the formation of large ice shelves similar to those observed currently (Doake, 1987).



Figure 9. Bottom water temperature variation as interpreted from the δ^{18} O records. After Dudeney, 1987, page 196.

3. The Ross Sea Ice Sheet

On at least four occasions (Ross Sea IV, III, II and I), the Ross Ice Shelf expanded to form an ice sheet grounded on the floor of the Ross Sea (Denton et al, 1970). All four are younger than 1.2 million years. The oldest glaciation, Ross Sea IV, must be younger than 1.2 million years and the most recent, Ross Sea I, reached its maximum extension during the late Wisconsin glaciation, about 18,000 B.P. (Denton et al, 1970, 1971). See figure 10 for the present-day situation and figure 11 for the late Wisconsin glacial extension.

During these Ross Sea glaciations, ice sheets in McMurdo Sound attained thicknesses of more than 1,000 m. Their outlet glaciers pushed westward into the mouths of ice-free valleys on McMurdo Sound's west coast and dammed large lakes (see figure 12 for the Ross Sea I ice sheet extension and figure 13 for the present-day configuration).

The end of Ross Sea I must have coincided with a rapid rise of sea level synchronous with the massive recession observed in South America (Denton and Hughes, 1986). This recession began about 13,000 years B.P. when a warm oscillation reinforced Milankovitch high summer insolation. Algae resting on Ross Sea I drift provide a minimum date of 9,490 years B.P. for the initial stages of withdrawal of the Ross Sea Ice Sheet (Denton et al, 1971).

Thomas and Bentley (1978) estimated that the retreat of the Ross Ice Sheet, from the edge of the continental shelf to its present position several hundred kilometers away, occurred at a rate of a few kilometers per year. Shriver et al (1981) suggested that the Ross Sea Ice Sheet thinned and lifted off the bottom to become an ice shelf.

The post-glacial rise in sea level caused a retreat of the grounding line to a new set of pinning points (Ross Island and Roosevelt Island). These islands are situated approximately 500 km south of the western and 1,000 km south of the eastern outer shelf banks (see figure 11).

The grounding line reached Black Island by 6,600 ¹⁴C years B.P. (Kellogg et al, 1977).





Figure 11.

Late Wisconsin glacial extension of the Ross Sea I Ice Sheet and the Antarctic Ice Sheet. After Denton and Hughes, 1986, p.8.



Figure 12.

. McMurdo Sound, southern Victoria Land, Antarctica (south is at the top). Upper: Index map; only a few pertinent alpine glaciers are shown in the Transantarctic Mountains. Lower: The extent of the Ross Sea I ice sheet in McMurdo Sound. In places this ice sheet exceeded 1000 meters in thickness. The outer limits of Ross Sea II, III, and IV ice sheets projected short distances beyond the borders of the Ross Sea I ice sheet. The present-day configuration is shown for the ice sheet in East Antarctica.

Extent of the Ross Sea I Ice Sheet in the McMurdo area.

After Denton et al, 1971, p.277.



Figure 13.

Present-day configuration in the McMurdo area. After Denton et al, 1971, p.277.

4. The formation of Hells Gate Ice Shelf

At the time of the maximum extension of the Ross Sea Ice Sheet, all the outlet glaciers of the East Antarctic Ice Sheet, located along Terra Nova Bay, were forced to flow northward along the western edge of the Ross Sea Ice Sheet. The orientation of large and deep oceanic trenches (Drewry, 1986) and glacial striations preserved locally, suggest ice flows from SSW to NNE. At the same time, the damming of the outlet glaciers increased the ice thicknesses in Terra Nova Bay by at least 400 m (Orombelli, 1990). Hells Gate Ice Shelf could not possibly have existed in such conditions.

As mentioned above, deglaciation began around 13,000 B.P. (Denton et al, 1989) but was interrupted at times by colder periods when glaciers readvanced, as witnessed by the Anderson Ridge moraine (Orombelli, 1990). This is to say that from 13,000 B.P., when the Ross Sea Ice Sheet began to retreat, to about 6,600 B.P., when the Ross Sea Ice Shelf reached Black Island, the Terra Nova Bay was progressively freed of ice. Assuming that the rate of retreat was slow at first and increased rapidly as soon as the Ross Ice Sheet lifted off the bottom, the southward retreat of the grounding line, over a distance exceeding 1,000 km, could have taken 2,890 years to 6,400 years (after Denton's minimum age obtained on algae resting on the Ross Sea drift I, 1971).

The withdrawal of the ice sheet was followed by a glacioisostatic uplift of the continent. The isostatic uplift took place at the rate of about 10 mm per year following deglaciation to about 2 to 5 mm per year during the last three thousand years (Baroni and Orombelli, 1991). Everywhere in Terra Nova Bay, no glacial drift can be found at an elevation lower than 30 meters along the coastline (Baroni and Orombelli, 1989). This altitude of 30 meters above the present sea level corresponds to the upper limit of the relative sea level.

The oldest and therefore the highest raised beaches date to about 7,000 B.P., based on ¹⁴C datations of penguins remains (Orombelli, 1990). This dating was made possible as a result of a study of nesting zones of Adelie penguins. Taking advantage of ice melting, isostatic uplift and eustatic movement, the Adelie penguins moved to different locations. Their presence in these locations was used to calculate the minimum age of deglaciation of those sites. In fact sediments must be completely out of water and out of reach of waves (at least one to two meters below the nesting sites) in order for the birds to establish themselves in that location (Baroni and Orombelli, 1991, see figure 14).

Baroni and Orombelli argue that the uplifted beaches situated along the southwest coast of Inexpressible Island have been partially covered by an extension of the Nansen Ice Sheet and Hells Gate Ice Shelf. This suggests that the

glacier advanced approximately 8 km along the coast during the Holocene.



Profiles of raised beaches at Terra Nova Bay. A: Inexpressible Island, southern margin of Seaview Bay. P1, P2, and P3: Soil profiles from abandoned penguin nesting sites (depth in cm) with ¹⁴C ages obtained from organic horizons. Arrow (right) shows the high tide level. I: Surficial pebbly horizon accumulated by penguins. 2: Organic horizon (guano). 3: Sandy gravel with guano. 4: Sandy gravel and boulders. B: Evans Cove (western coast of the Cape Russell peninsula). 1: ¹⁴C ages of mixture of shells collected at the surface of the raised beaches. 2: ¹⁴C ages of Cirripedia plates collected at the surface of the raised beaches. 3: ¹⁴C ages of pelecypods collected in situ. 4: ¹⁴C ages of Adamussium colbecki collected in situ. 5: ¹⁴C ages of Laternula elliptica collected in situ.

Figure 14: Inexpressible Island and Evans cove topographic and soil profiles showing the uncorrected ¹⁴C ages obtained from organic horizons located on raised beaches. After Baroni and Orombelli, 1991.

5. Present-day glacial characteristics

5.1. Introduction

The East Antarctic Ice Sheet forms an ice dome dominating the western portion of the Terra Nova Bay region. Nearly half of the coastline of Antarctica is fringed by floating ice sheets called ice shelves. Ice shelves are the seaward extensions of the continental ice sheet. The two largest ice shelves, Ross (536,160 km²) and Ronne-Filchner (532,200 km²), together represent 67 % of the total area of Antarctic ice shelves.

When the outlet glaciers draining the Antarctic ice sheet reach the sea, they begin floating. Thomas (1979) demonstrated that they float under their own weight and become thinner at their seaward edge. For the largest ice shelves, thickness of the ice varies from 1,300 near the grounding line to 200 m at the front. Figure 15 represents the major ice shelves.



Figure 15: Map of Antarctica showing the major ice shelves. After Thomas, 1979.

Ice shelves gain mass in three different ways. Accumulated snow on their surface can be transformed into ice. The freezing of seawater directly to the bottom of ice shelves, such as the Ross Ice Shelf, also contributes to the ice shelf thickness (Zotikov et al, 1980). However, no ice shelf would exist without the supply of ice coming from the inland ice sheet (Thomas, 1979).

On the other hand, ice shelves lose mass in five ways: by the calving of icebergs, by the melting of ice in contact with the sea, by snow blowing off the edge of ice shelves, by enhanced sublimation of ice, and by superficial melting (Thomas, 1979). Since surface melting in Antarctica is negligible (Jenkins and Doake, 1991), and since wind ablation is limited in general, nearly all mass loss is the result of either iceberg calving at the seaward margin or bottom melting of ice in contact with the sea.

5.2. Terra Nova Bay

In the area of Victoria Land, studied in this work, there is little melting and little accumulation. Glaciers exhibiting a negligible ablation and an equilibrium line at low altitude or near sea level extend into the sea (Sugden, 1982).

David Glacier, located south of Hells Gate, is a very good example. It drains an area of 224,000 km² (McIntyre,

1989) with a discharge of 14 km³ per year and an ice thickness locally exceeding 2,500 m. It coincides with a subglacial trench (Steed and Drewry, 1982) that transects the Prince Albert Range and extends inland for over 300 km (Swithinbank, 1988).

Drygalski Ice Tongue is the seaward extension of David Glacier. This ice tongue is of special importance in the study of Hells Gate Ice Shelf. Indeed, Drygalski Ice Tongue acts as a barrier to prevent the northward drifting ice pack from closing the Terra Nova Bay polynya.

5.3. The Hells Gate Ice Shelf

By Antarctic standards, Hells Gate is a very small ice shelf. Its north-south extension, from the northern end of Vegetation Island to the ice front, is about 10 km. From Vegetation Island's southern tip to the ice cliff, the distance is around 7.5 km. The east-west width of the ice shelf, as measured at the latitude of Cape Confusion, is 9.9 km. An estimate of Hells Gate's area has been obtained using the dot grid technique described later in this chapter. Hells Gate has an estimated area of 70 km².

Besides being small, Hells Gate shows extensive ablation areas due to the steady katabatic winds. Three ablation areas, characterized by dark blue colors, are clearly observable on figure 16 taken from Swithinbank (1988). They



Figure 16. Ablation areas on Priestley Glacier, Reeves Glacier, Nansen Ice Sheet, and Hells Gate. correspond to the lower portions of the Priestley Glacier and Reeves Glacier merging into the Nansen Ice Sheet and to Hells Gate Ice Shelf north of Inexpressible Island. Even though surface melting is not the principal cause of the mass loss of Hells Gate Ice Shelf, numerous meltwater lakes have been observed on its surface, east of Inexpressible Island and near the ice front. Figure 17, an aerial photograph, illustrates this fact. A great number of meltwater lakes are also present on Nansen Ice Sheet, downstream of Reeves Glacier and southeast of Inexpressible Island. Over fifty frozen lakes are reported on the 1:250,000 map of Mount Melbourne sheet (U.S.G.S.), figure 18.

The Hells Gate Ice shelf can be partitioned into three sectors separated from each other by two double ridges of debris cones².

Figure 21 is an oblique photograph of the ice shelf delineating the western (red), the central (orange), and eastern sectors (green).

The two double ridges of debris cones have been identified as medial moraines. The western medial moraines originate at Vegetation Island while the eastern stretch of

2. Figure 19: Hells Gate Ice Shelf, looking south; note the the double ridge debris cones. On the left-hand side, the Terra Nova Bay polynya. To the right, Inexpressible Island. In the background, Nansen Ice Sheet.

Figure 20: Hells Gate Ice Shelf, looking north; in the foreground, the debris cones and a melt pond. In the background, Vegetation Island. Photographs: R. Souchez.





Figure 18. Topographic map of Mt Melbourne sheet at the 1:250,000 scale, U.S.G.S.





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Figure 20. Hells Gate Ice Shelf: debris cones and melt ponds.



debris cones forms at Cape Confusion.

Field studies (Baroni et al, 1989) have ascertained the origin of the scattered debris encased in ice in the eastern medial moraines. The pebbles and rock fragments consist of granitic and mafic rocks outcropping at Vegetation Island (Carmignani et al, 1988; Skinner, 1983).

The debris cones increase in height toward the ice cliff, reaching a maximum of 24 m above sea level at site A.



Figure 22: Sketch cross section of the eastern portion of Hells Gate. 1: Elevation (m) above sea level measured with telemeter and clinometer (February 6, 1988). 2: Sea. 3: Sea ice. 4: Snow. 5: Ice. 6: Supra-glacial debris. 7: Uncalibrated ¹⁴C ages (plates of Cirripedia). hs: main height of the Hells Gate Ice Shelf surface near the moraine of Hells Gate East (after Baroni, 1989, page 238).

Figure 22 shows a cross section of the eastern portion of Hells Gate including the altitudes, the ice types and the ages of marine specimens collected in A, D, and E.

The maximum altitude of a dirt cone in the western

section is 31.12 m. The closest cone to the ice cliff' in the western margin reaches 23.65 m. Figure 25, taken from Baroni (1989), was drawn after a detailed topographic survey, made on the 21st and 23rd of January 1988. For a detailed description of the debris cone sites, see Baroni (1989).

Numerous marine organisms have been found scattered over the Hells Gate Ice Shelf. The bulk of invertebrate remains was located in the rock debris and at the base of the debris cones. Some shells found far from the cones had evidently been reworked by the wind (Baroni, 1989) while most organisms were discovered frozen into the ice. The remains found on the surface were comprised of plates of Cirripeds, Pelecypods, Serpulid worm tubes and penguin bones⁴.

Cirripeds (known also as barnacles) were idendified as Bathyslasma corolliforme; they have mean calibrated ages

3. Figure 23: The Hells Gate ice front. In the foreground, annual sea-ice. In the background, the two ridges of supraglacial debris. On the right-hand side, frozen meltwater streams.

Figure 24: Close-up view of the left part of figure 23, showing blocks of various sizes in a probable shear zone and the height of the ice cliff.

Photographs: R. Souchez

4. Figure 26: Serpulid worm tubes found at the surface of Hells Gate Ice Shelf, in such an accumulation that they seem to have been reworked by the wind.

Figure 27: Sponges found frozen into the Hells Gate marine ice.

Photographs: R. Souchez.



Figure 23. Photograph of the Hells Gate Ice Front.





- Geomorphologic Sketch map of Hells Gate West (figs. 1 and 8) drawn on the basis of a detailed topographic survey made on the 21th and 23th of January, 1988. 1: boundary of dirt cones. 2: supraglacial debris. 3: snowdrift. 4: sea-ice. 5: meltwater pond. 6: meltwater rill. 7: ice cliff. 8: sea. 9: cross section (real and exaggerated heigths). 10: heigth above the sea ice located about 40 cm a.s.l. (10 a.m., Jan. 23, 1988). 11-

14: uncal ¹⁴C ages obtained from samples of mixture of shells (11), Cirripedia (12), Serpulid worm tubes (13) and penguin bones (14).

Figure 25.

Sketch of Hells Gate debris cones sites after a detailed topographic survey. After Baroni, 1989, p.241.



Figure 26. Serpulid worm tubes.



Figure 27. Sponges found frozen into the Hells Gate marine ice.

varying from 1050 to 1541 B.P., Pelecypods (or bivalves) have been identified as Adamussium colbecki, Laternula elliptica, Thracia meridionalis, and Limopsis marionensis: their mean calibrated ages range between 1050 and 1148 B.P. (Baroni et al, 1991).

As early as 1920, Debenham postulated that the marine organisms found on the ablation surface of the Koettlitz Ice Shelf had been incorporated by freeze-on processes at the bottom of the ice shelf as it touched the sea floor. These organisms were later exposed by surface ablation.

The uplift of fauna resulted from ice formation at the underside of the ice shelf followed by ablation of its surface. Swithinbank et al, 1961, supported this idea for the Koettlitz Ice Shelf. Other authors proposed different explanations such as anchor ice formation (Dayton et al, 1969) or incorporation into a fossiliferous moraine (Gow et al, 1965). In the latter case, the fossils were likely to be crushed while the former would bring up more intact remains. Kellogg and Kellogg (1987) maintained that the biogenic material preserved in the McMurdo Ice Shelf is the result of basal adfreezing at its underside.

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The effectiveness of anchor ice for raising debris from the sea floor was demonstrated when scuba divers observed portions of the substratum weighing as much as 25 kg being lifted up from the sea bed (Dayton et al, 1969).

The finding of whole or decapitated fish on the Koettlitz

Ice Shelf near the Dailey Islands seems to be related to another mode of formation. These fish were probably abandoned by the Weddell seals near the top of a tide crack (see figure 29; photograph A. Gow). Neither fish nor tide cracks were found on Hells Gate Ice Shelf. Serpulid worm tubes, sponges and shells were discovered on both ice shelves. If one compares the serpulid worm tubes found on Hells Gate Ice Shelf to the ones photographed by A.Gow (figure 28, reproduced here by permission of the author), it becomes evident that the numerous broken tubes packed together have been reworked after their incorporation. Serpulid worms do not live in colonies but are scattered on the sea floor (Gow, personal communication).

Baroni's conclusion of the study of the marine specimens present at the ice shelf surface is that rock debris and fossiliferous sediments probably originated at the grounding line. They were incorporated by bottom freezing and migrated upwards to the surface as a result of surface ablation.

Similar accretion has been observed in numerous other ice shelves, and has been studied by Debenham (1920), Swithinbank et al (1961), Gow et al (1965) and Kellogg & Kellogg (1987, 1988).

¹⁴C ages based on these remains increase from Vegetation Island to the ice cliff. However, the most recent serpulid was collected north of S₃ and was dated 1550 \pm 175 years (GX -14084) and S₃ is not located at the ice cliff.



Figure 28. Invertebrate fossils found in moraine near the easternmost Dailey Island; Taylor Formation.

- (a) and (b) gastropods,(c) and (d) pelecypods,
- (e) plates of Hexelasma antarct-(f) icum, a barnacle, (f) serpulid worm tubes,
- (g) terebratulid brachiopod,
- (h) fragments of polyzoa,
- (i) pecten, Adamussium colbecki,
- (j) glass sponge.

One-half natural size.

*



Figure 29. Fish remains near a tide crack.

Surface ablation has been estimated to be about 10 cm per year. However, differential ablation is demonstrated by the increasing size of the dirt cones. Protected by their rock cover, they offer a better resistance to eolian erosion and sublimation than the surrounding areas, which appear depressed.

Baroni (1989) estimated the thickness of the ice shelf by applying the formula

$$D_i H = D_w (H - h)$$

A

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proposed by Shabtaie and Bentley (1982) for an ice shelf in hydrostatic equilibrium. D_i is the ice density, D_w is the density of sea water, H stands for the ice thickness, and h represents the elevation above sea level. The ice density was estimated to be 890 kg m⁻³, and sea water density as 1,027.55 kg m⁻³.

Table 1 summarizes Baroni's computations concerning the ice thickness and the velocity of Hells Gate Ice Shelf.

LOCATION	THICKNESS (m)	MEAN HEIGHT ABOVE SEA LEVEL (m)	VELOCITY (m/year)
WESTERN MARGIN			min 7.4
Near the ice cliff	34.5	4.6	avg 10.4
3 km inland	82.0	11.0	max 17.4
EASTERN MARGIN	C		min 3.0
Near the ice cliff	63.5	8.5	max 3.7

Table 1 : Computed Data Relative to HGIS

(From Baroni, 1989, page 249)

These velocities are very low in comparison with velocities measured on large ice shelves.

Such low velocities have been observed on small ice shelves, as pointed out by Swithinbank (1970) and Kellogg & Kellogg (1987) for the McMurdo Ice Shelf.

Ross Ice Shelf	875 m/year	(Swithinbank, 1988)
Filchner Ice Shelf	1,240 m/year	(Crabtree, Doake, 1980)
Amery Ice Shelf	> 1,200 m/year	(Swithinbank, 1988)
Koettlitz Glacier	5 - 10 m/year	(Gow, 1973)

Radio-echo sounding cross sections of Hells Gate show a striking contrast between the western and the central sectors

(Souchez et al, 1991). See figure 30 for the thickness of Hells Gate Ice Shelf as indicated by the radio-echo sounding. In the western sector, a principal reflector is observed at 60 m depth, suggesting an interface between ice and sea water, or glacial ice underlain by sea ice. The reflector disappears under the dirt cone ridge separating the western from the central sector of Hells Gate. The central sector of the ice shelf displays an undulating interface at a depth between 25 and 50 m, though it is occasionally more shallow than 20 m. Figure 31 shows two echo-sounding profiles obtained along cross-sections A and B. Figure 32 is the echo-sounding profile obtained along cross-sections C.

Figure 33 is an aerial photograph representing the position of the reflectors as obtained by the radio-echo sounding of Hells Gate.





PROFILE A



Figure 31. Profiles obtained by radio-echo sounding along cross-sections A and B. After Tabaccol and Lozej.

PROFILE B







1-063 11-6-85 TERRA NOVA BAY H2 8000 FL 152.27 TMA-2851-V



C. Climatology of the region

1. Availability of data

Up to 1984, the only climatological data in the vicinity of Hells Gate had been recorded by Raymond E. Priestley, who lived in a snow cave on Inexpressible Island during the winter of 1912 (Priestley, 1914). Priestley, along with the other members of Scott's Northern Party, kept journals containing extensive meteorological data. Their day to day estimation of the velocity of the katabatic winds served as the only database for over 70 years.

Estimates of air temperature, precipitation, atmospheric pressure and wind could be obtained by interpolating the meteorological data of two automatic weather stations: Hallett (N.Z.) located at 72°18'S and McMurdo (U.S.) at 77°51' S, approximately 3° north and south, respectively, of Hells Gate.

Bromwich and Kurtz (1982, 1984) examined R. E. Priestley's database. They concluded that the katabatic winds at Inexpressible Island and Hells Gate are "of similar strength and persistence to those at Cape Denison and Port Martin," which are the best documented areas in Antarctic for katabatic winds (Parish, 1981, 1982, 1984; Parish & Bromwich, 1986, 1987, see figures 34 and 35).



Figure 34.

Location and topographic map indicating the sastrugi and prevailing wind directions.

* Bromwich, D.H. et Kurtz, D.D., 1984:Katabatic Wind Forcing of the Terra Nova Bay Polynya, Journal of Geophysical Research, 89, C(3), p. 3561-3572.



Figure 23b. Streamlines of the time-averaged surface airflow (adapted from Parish, 1982) in Bromwich and Kurtz, 1984, p.3564.
The need for *in situ* data led to the installation of an <u>A</u>utomatic <u>Weather S</u>tation (AWS) by Stearns on February 4, 1984 (Stearns, 1986). Named Manuela, this AWS was set up on the southern tip of Inexpressible Island. Due to a combination of electronic and mechanical difficulties, the AWS has operated intermittently from 1984 to 1987. "The major problem comes from the anemometers' inability to withstand the intense mechanical stress exerted by the turbulent, high momentum airstream." (Bromwich, 1989). Indeed, on April 29, 1987, the propeller of the Belfort model 123 anemometer blew off in winds of around 155 km/hour (43 m s⁻¹).

The basic AWS units measure air temperature, wind speed, and wind direction, all at 3 m above the surface. Air pressure is recorded at a height of 1 m. The AWS is monitored by a microcomputer which updates the data every 10 minutes (Stearns & Wendler, 1988). Every 200 seconds, the AWS broadcasts three to five data points for each sensor. The message is received by ARGOS equipped NOAA polar orbiting meteorological satellites. When two satellites are in orbit, the data points collected in a 24 hour period range from 100 to 144. Each satellite stores the data, which are transmitted to the Goddard Space Flight Center, Maryland.

The data collected are not always continuous as the AWS sometimes stop, and their repair or replacement has to wait until the next field season (Stearns et al, 1990).

The National Science Foundation, Division of Polar Programs, decided to support a research program devoted to katabatic winds. Three locations were chosen: the first, from Dome C to the Adelie Coast near the French station of Dumont d'Urville; the second, on the Ross Ice shelf; and the third, the region subject to the wind flow down the Reeves Glacier to Terra Nova Bay.

Figure 36 from Stearns et al (1991) shows the location of the AWS units for 1991.

Figure 37 is a large-scale map showing the AWS units that have been deployed in the Reeves Glacier area.

Table 2 provides the precision of the meteorological sensors used in each of the AWS and table 3 gives the AWS locations for the Reeves Glacier area.

Table 2: Precision of the Meteorological Sensors of the AWS

Variable	Sensor	Resolution
Air pressure	Parascientific Model 215	0.05 mb
Air temperature	Platinum resistance thermometer	0.125°C
Wind speed	Belfort aerovane model 123	0.25 m/s
Wind direction	Belfort aerovane model 123	2°



Figure 36. Map of the locations of the AWS units for 1991.



Table 3: AWS locations from 1984 to 1991 for Reeves Glacier Area

Site	Argos II	<u>Lat</u>	Long	Alt	Date	W.M.O.
		(degr.)	(degr.)	(m)	start	
Manuela	8905	74.92 S	163.60 E	80	Feb 84	89864
Shristi	8909	74.72 S	161.58 E	1200	Dec 87	89862
Sushila	8921	74.41 S	161.31 E	1441	Jan 88	
Sandra	8923	74.48 S	160.48 E	1525	Jan 88	89861
Lynn	8901	74.21 S	160.39 E	1772	Jan 88	89860
Pat	8931	74.90 S	163.10 E	30	Jan 89	

Manuela, the AWS unit located at the southern end of Inexpressible Island, has functioned almost continuously since 1989.

Pat was installed on the 163rd E meridian, in the center of Nansen Ice Sheet. This central position was chosen to determine the frequency of possible katabatic flow down Priestley Glacier, and to compare its relative occurrence to the flow down Reeves Glacier.

The 1,200 m altitude chosen for the Shristi AWS is the altitude where the ice terrain drops sharply and produces the velocity increase of the katabatic airstreams (Bromwich, 1989).

The next three AWS's are located on the Reeves Névé. Sandra AWS is upstream from Shristi, near the 1,600 m contour line. Lynn is located north of Sandra. Its site has probably been selected to match the latitude of the Priestley Glacier AWS installed by the Italians (see sequel).

Sushila is located between Lynn and Pat. The data collected from the AWS's deployed as part of the Reeves Glacier network have been used to produce the figures to follow.

2. Reliability of Data

The time span is too short to obtain reliable climatological average values for Manuela on Inexpressible Island. The McMurdo weather station, located approximately 300 km south of Hells Gate at 77°51 S, 166°39 E, has been successfully operated since 1957.

This station has shown a remarkable climatological stability and there is no reason why Hells Gate should behave differently. One should bear in mind that winter refers to the period without sunshine (early May to mid-August); summer, with 24 hours of daylight, extends from the beginning of November to mid-February. Spring and autumn are the transition seasons.

3. Temperatures

Table 4 compares Inexpressible Island average monthly temperatures to McMurdo. The comparison shows that Inexpresssible Island is colder than McMurdo in the winter (March to October) but warmer in the summer (November to February). Bromwich (1989) attributes the difference to "a winter reversal of the normal poleward decrease of air temperature at sea level. McMurdo is about 300 km closer to the South Pole than Terra Nova Bay".

Column C can be used to calculate how much colder Inexpressible Island is, compared to the regional temperature field. The temperature contrast for the year is 1.6° C colder than in the rest of the region. It represents 2° C in the winter and 0.9° C in summer.

Figure 36 is a comparison of the average monthly temperatures for the Reeves Glacier AWS array (1989 data). The shape of the temperature curves reflects mostly the altitude of the weather stations. The lowest, Pat, has the highest temperatures. Lynn, with the highest elevation, presents the lowest temperatures.

Table 5 gives the locations of the Automatic Weather Stations installed by the Italian research program.

Month	Average Monthly Air Temperature At Inexpressible Island (I.I)	Number of Months of Data	A Temperature Contrast (I.IMcMurdo)	B Climatological Temperature Contrast McMurdo`vs Terra Nova Bay Vicinity	C Estimate of Climatological Contrast Between I.I. and Regional Temperature Field (A + B)	
Jan	-1.7	2	-0.1	-1.2	-1.3	
Feb	-10.6	4	+0.7	-2.6	-1.9	
Mar	-18.1	4	-1.3	-4.2	-5.5	
Apr	-23.5	4	-4.2	-1.7	-5.9	
May	-24.0	3	-3.5	-0.7	-4.2	
Jun	-24.0	3	-1.8	-0.2	-2.0	
Jul	-26.6	2	+2.2	. +0.5	+2.7	
Aug	-26.2	2	+1.5	-0.6	+0.9	
Sep	-27.1	2	+0.8	+0.2	+1.0	
Oct	-20.0	2	-2.1	-0.8	-2.9	
Nov	-10.4	2	+0.1	-0.4	-0.3	
Dec	-3.0	2	+1.1	-1.1	0.0	
Annual	-18.0		-0.6	-1.0	-1.6	
Mar-Oct	-23.7		-1.1	-0.9	-2.0	
Nov-Feb	-6.3		+0.4	-1.3	-0.9	

Table 4. Surface Air Temperatures (°C) at Inexpressible Island in Relation to the Regional Temperature Field*

*Extraordinary Wind Katabatic Region at Terra Nova Bay, Antarctica, D. Bromwich, Monthly Weather Review.



Figure 38. Comparison of temperatures: the Reeves Glacier array.



Figure 39. Comparison of temperatures for Nansen Ice Sheet, Cape King, Priestley Glacier and Tethys Bay Camp.

Table	5:	Automatic	Weath	ner S	tation	Data
		Ita	alian	Stat	ions,	1989

Elevation	WMO	Name	Latitude	Longitude
(m)			(degr.)*	(degr.)*
53.0	7350	Nansen Ice Sheet	74. 79 S	163.32 E
183.0	7351	Cape King	73. 59 S	166.63 E
650.0	7352	Priestley Glacier	74. 25 5	163.15 E
87.1	7353	Tethys Bay Camp	74. 69 5	164.11 E

* Note that latitude and longitude are indicated in decimal units.

In order to extend the area of study of the katabatic winds, four automatic weather stations were installed by the National Italian Research Program. This researcher is deeply indebted to Dr. Andrea Pellegrini for providing her with the unpublished data. Of particular importance was the installation of the Nansen Ice Sheet and Priestley Glacier stations. Indeed the site of these two stations was chosen to implement the study of katabatic winds in the Terra Nova Bay region. Priestley Glacier station is located along the glacier where it shows intense surface ablation. This area is dark blue on the satellite photograph (figure 40).



Figure 40. Satellite photograph of Hells Gate, Nansen Ice Sheet, and the confluence of Priestley and Reeves Glaciers. ENEA Digital Imagery

While examining figures 38, 39, 41 and 42 (see sequel), one should be aware of the fact that, although the monthly averages have been computed using all available data, in case of mechanical failure of the Automatic Weather Stations, the reduction of the data can lead to higher or lower monthly averages than normal. To avoid misleading interpretation of the temperature and wind curves, it was decided to eliminate monthly means from the graphs if the available data did not represent at least 60% of the possible data set.

The comparison of temperatures (figure 39) reflects mostly the altitudes of the stations. The lowest temperature is observed at Priestley Glacier located 650 m above sea level. The highest temperatures are observed at Tethys Bay Camp (87 m) and Nansen Ice Sheet (53 m).

4. Winds at Terra Nova Bay

As early as 1912, Priestley, stranded at Inexpressible Island, noted, "In mid-February 1912, a gale sprang up that lasted the entire winter." He also stated, "These winds are responsible for the formation and maintenance of a large polynya." (Priestley, 1923).

Table 6 summarizes the monthly surface winds at Inexpressible Island. The data were obtained at the AWS for

Month(s)	Resultant	Wind $(m s^{-1})$	Mean -1	Directional	Maximum Sustained Speed (m s ⁻¹)	Maximum gust (m s ⁻¹)
Honen (3)	Resultant	mind (m 5)	opeca (m o)	constantoj	opeeu (m 5)	
1984						
4-29 Feb	295*	13.7	14.1	0.97	30	36
Mar	295*	18.1	18.3	0.99	36	41
1-19 Apr	304*	16.6	17.0	0.98	31	35
1985						
Feb	300*	15.9	16.9	0.94:	40	45
Mar	304 *	18.5	18.7	0.99	33	40
Aprt	301.	17.4	17.5	0.99	38	43
1987‡						
15-28 Feb	285*	13.5(14.5)	14.0(15.0)	0.96	29(31)	34
Mar	289*	15.9(17.)	16.3(17.5)	0.98	33 (35)	40
1-29 Apr	292*	15.6(16.7)	15.6(16.7)	0.99	35(38)	43
1984-87††						
Feb	294 *	14.6	15.3	0.95	40	43
Mar	296*	17.8	18.2	0.98	36	41
Apr	299*	16.8	17.1	0.98	38	43
1912†††				•		
Feb-Sep	293*	15.0	~16.7	~0.9	~35	?

 Monthly surface winds measured by AWS at the southern end of Inexpressible Island.

[†]Corrected for 18^{*} clockwise wind direction shift detected in mid April 1985. Probably due to metal fatigue of the AWS tower, was found lying on the ground when the site was again visited in February 1987.

‡Values in brackets are estimated speeds at 3 m height, which are taken to be 1.07 times the measured speeds at 1.5m. #Based upon estimated 3 m wind speeds for 1987.

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tttDerived from noninstrumental historical observations by Bromwich and Kurtz (1982, 1984). These data describe the topography undisturbed airflow near Inexpressible Island.

* From: Bromwich, David H., "An Extraordinary Katabatic Wind Regime at Terra Nova Bay, Antarctica," (Byrd Polar Research Center, The Ohio State Univ., Columbus, OH, 10 June 1988 and 6 October 1988), 1989 American Meteorological Society) the months of February, March and April of 1984 to 1987. Extensive studies by Bromwich, Kurtz and Parish have shown that the katabatic winds at Terra Nova Bay are of the Bora type, and that they form on the Antarctic Plateau, upstream from Reeves Glacier. Sastrugi orientations studied on the Plateau at the head of Reeves Glacier, confirmed that katabatic airstreams originate from an altitude of 1200 m, where the ice terrain drops sharply (Bromwich, 1989). Sastrugi are also developed on the surface of Nansen Ice Sheet, downstream from the Reeves Ice Fall (figure 41¹). The strong airstreams blow all the way down the 50 km long, 20 km wide Reeves Glacier.

Figure 16 (page 26) is a composite satellite photograph of the region taken from Swithinbank (1988). It illustrates the ablation zones (dark blue areas) produced by sublimation of the ice and snow into the dry katabatic wind. Their positions correspond to the deflection observed around the Antarctic continent by Parish (1982), and attributed by Ball (1960) to the Coriolis force. It concentrates the katabatic air flow on the left side (looking downwind) of a broadscale topographic trough.

The strongest winds are observed at Priestley

^{1.} Figure 41: Sastrugi developed at the surface of Nansen Ice Sheet, downstream from the Reeves Ice Fall. The sastrugi orientations shown here clearly indicate that the katabatic wind is deflected around the Teall Nunatak.



Figure 41. Photograph showing Sastrugis on the surface of Nansen Ice Sheet.

Glacier station. There, wind is maximum during the winter months, as observed by the six stations installed about Reeves Glacier. It is stronger than on Reeves Glacier, reaching more than 20 m/sec in September. The slight decrease in wind speed noticeable in May-June 1989 for Priestley Glacier, Nansen Ice Sheet, and Tethys Bay Camp, is also observed for Manuela, Pat and, to a smaller extent, for Sushila.

Figures 40 and 41 compare the wind speeds by the four Italian stations and the six American stations.

5. The use of aerial photographs to supplement the climatic data

A search for the available photographs, including the most recent, was undertaken through the U.S. Geological Survey, National Cartographic Information Center, Reston, Virginia. This government agency provides updated information about the available aerial photographs; the photographs used throughout this work have been obtained thanks to their diligent service. The image interpretation of the aerial photographs pertinent to this work required the knowledge of the absolute scale and of the wind velocity, in the case of wind-induced sea ice drift.



Figure 42.

Comparison of wind speeds for Nansen Ice Sheet, Cape King, Priestley Glacier and Tethys Bay Camp.



Figure 43. Comparison of wind speeds for the Reeves Glacier AWS array.

5.1. Absolute scale

The absolute scale, known also as the representative fraction, is either calculated or measured. It can be calculated from the camera focal length and the altitude of the aircraft above the scene being photographed; indeed, the representative fraction is obtained using equation

$$RF = F/A$$

where F is the focal length and A is the altitude. This absolute scale is accurate if and only if the altitude of the plane exactly corresponds to the height indicated along the frame of each photograph.

With the photographs came a note indicating an approximate scale of 1:24,000 with an average relative error of \pm 5% and possible peaks of 12%. However, subsequent checks indicated that the relative error could be as high as 15% for some of the photos selected in this study.

D'Ann Lear, of the National Mapping Division, USGS Reston, Virginia, stated that important variations of altitude during flights are not unusual, and that the altitude figuring along the frames of the aerial photographs is taken at the beginning of the flight. Therefore, it might not represent the exact altitude of the plane at the time the photograph was taken.

Ms. Lear suggested that a more precise scale be estimated through the use of the 1:250,000 map of Mount Melbourne Sheet in Terra Nova Bay. Therefore, to minimize distortions, this study has chosen two features located near the center of the photograph, and used the map previously mentioned to measure the corresponding distances.

5.2. Wind velocity

Numerous attempts to obtain the velocity of the katabatic winds from the US Navy flight log books were made. Unfortunately, they all failed. After consulting with Lee Fowler and Bob Allan at the Department of the Interior, US Geological Survey, this researcher learned that the wind conditions are examined before take-off and during the flight at various intervals, but are not officially recorded.

Table 7 reports the calculated approximate scales for all vertical aerial photographs used in this work.

Photographs	Date	Estimated Scale
0071	December 3, 1956	1:33,742
0072	December 3, 1956	1:29,412
0073	December 3, 1956	1:28,302
292	December 10, 1956	1:27,885
291	December 10, 1956	1:28,045
199	November 28, 1972	1:987,805
23-022	November 6, 1984	1:46,739
1-063	November 11, 1985	1:47,727

Table 7: Calculated approximated scales of all vertical aerial photographs used.

On the oblique aerial photograph (figure 42) taken on December 9, 1957, long streaks of ice are drifting off the coastline. The winds clearly originate from the Reeves Glacier valley. Inexpressible Island, downwind from Reeves, is oriented almost perpendicular to the direction of the approaching wind. The island's maximum elevation is about



390 m above sea level. The examination of the ice streak directions confirms that the katabatic airstream is being deflected north and south of the point of maximum elevation.

The pronounced drainage katabatic flow is even better illustrated by the December 3, 1956, vertical photograph (figure 45). Sea ice is being advected to the east. Long ice plumes are developing in the Terra Nova Bay Polynya bordering Hells Gate. Dunbar and Weeks (1975) observed such frazil features and gave them the name "tadpoles" because of their broad head and their narrow tail shape. These ice plumes stream off the coast, approximately parallel to the direction of the strong katabatic winds. Some of the larger blocks of ice are being eroded from the fast-ice edge of the ice shelf.

To estimate the yearly variations of the portion of Evans Cove covered with fast ice, two vertical photographs taken respectively on November 11, 1984, and November 6, 1985, were studied. To estimate the ice covered area, a dot grid with 16 dots per square centimeter was used. The grid was placed randomly over the area to be computed. The dots falling on ice were then totalled, counting only every other dot that would fall on the boundary of the computed area. Three random drops of the grid over the studied area were done to achieve greater precision.



Table 8 summarizes the study.

Table 8: Estimation of the Ice Covered Area

Date		Dot counts	Average		Area	2
November	1984	427/427/429	427.7		583.93	Ha
November	1985	723/720/721	721.3	1	026.90	Ha

The result of this study clearly demonstrates the annual variability of the fast-ice covered area. Baroni (1989) recognized a retreat of the Hells Gate Ice Shelf during the last thirty years. His analysis was based on the comparison of aerial photographs (1956, 1957, 1958, 1985), the Priestley map (1923), and Mount Melbourne sheet of the U.S.G.S. at the scale 1:250,000. Baroni (1989) concluded that a large iceberg (about 0.5 km²) calved sometimes between 1958 and 1985, the dates of the U.S. Navy vertical aerial photographs he examined. However, my observations of these photographs indicate that the position of the ice front seems very similar on both photographs (although one can note the absence of a very small portion of the shelf at the ice front).

D. Oceanographic Setting

1. Introduction

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Numerous hydrographic studies have been carried out near the Ross Ice Shelf, but very few data were available before 1986 for the area located between Drygalski Ice Tongue and Campbell Glacier (figure 18, page 29).

Physical oceanographic studies were undertaken under the auspices of the Italian National Program for Antarctic Research. Forty stations, over an area between latitudes $74^{\circ}30'S$ and $75^{\circ}30'S$, and longitudes $164^{\circ}00'E$ and $166^{\circ}00'E$, were spaced approximately 8 kilometers apart in the 80 x 66 kilometer area closest to the coast. Stations are 16 to 32 kilometers apart along a transect extending 194 kilometers from the coast at the latitude of the Italian Terra Nova station (\pm 74°45'S). Each station in figure 46 is represented by a number referred to in tables 9 and 9' [from Boldrin and Stocchino (1990)].

The 1987-88 first expedition used the Polar Queen, a ship flying the Norwegian flag, to study the coastal hydrology, the bathymetry, and the physical, chemical, and biological oceanography of Terra Nova Bay. This researcher is grateful to the head of the Italian Program, Ing. Mario Zucchelli, and to Dr. Artignani for supplying the data of the first and the second expeditions used in this chapter, and to Dr Stanley Jacobs for the data obtained by the American expeditions.



Figure 46. Map showing the location of the physical oceanographic study sites.

Table 9 : Italian Data First Expedition (+ Polar Star 1984 and 1985)

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3 5 7 8	74°38.90 74°42.00 74°44.50 74°43.10	165°36.70 166°04.50 164°48.00	34.785-34.859 33.585-34.797	1.057	0.724	0.500	0 262	0.157	-0.090
5 7 8	74°42.00 74°44.50 74°43.10	166°04.50	33.585-34.797				0.303	0.157	-0.090
7	74°44.50 74°43.10	164°48.00		-0.050	-0.244	0.077	0.044	-0.007	-0.659
8	74°43.10		34.620-34.822	0.939	0.886	0.222	-0.011	-0.212	-0.428
0		164°26.00	34.848-34.878	1.990	1.962	0.851	-0.158	-0.394	-0.501
9	74°43.10	164°13.80	34.833-34.899	2.095	2.048	1.894	1.005	0.294	0.129
10	74°48.10	164°11.10	34.861-34.884	2.022	1.536	1.043	0.641	0.055	-0.610
11	74°48.40	164°29.80	34.898-34.930	1.688	1.339	-0.754	-1.398	-1.680	-1.742
12	74°47.90	164°49.80	34.861-34.860	0.804	0.229	0.166	0.117	-0.235	-0.461
13	74°45.80	165°30.90	34.834-34.849	0.744	0.748	0.547	0.494	0.439	0.140
14	74°47.90	166°08.50	34.258-34.832	0.558	0.566	0.569	0.736	0.904	0.751
16	74°48.20	167°17.30	34.041-34.816	1.022	0.957	-0.332	-1.460	-1.747	-1.819
17	74°48.00	167°57.00	32.448-34.638	0.034	0.352	-0.715	-0.929	-0.859	-1.131
18	74°50.90	164°55.30	34.818-34.821	0.367	0.368	0.347	0.288	0.081	0.000
19	74°50.00	164°30.00	34.838-34.846	0.655	0.346	0.189	0.080	-0.038	-0.175
20	74°53.20	164°12.60	34.863-34.882	-0.342	-0.299	-0.462	-0.557	-0.781	-1.070
21	74°58.10	164°05.60	34.784-34.836	-0.478	-0.510	-0.546	-0.553	-0.748	-1.093
22	74°58.20	164°13.70	34.821-34.883	0.601	0.542	0.336	-1.228	-1.657	-1.768
23	74°58.80	164°59.80	34.796-34.823	0.180	0.182	0.160	-0.010	-0.130	-0.445
24	74°58.00	165°38.00	34.803-34.817	0.491	0.497	0.496	0.489	0.436	0.334
25	74°57.20	166°17.20	33.859-34.798	0.969	0.450	0.136	-1.276	-1.584	-1.734
26	75°02.40	164°15.50	34.783-34.845	0.613	0.599	0.578	0.498	0.152	-0.890
27	75°01.90	163°52.10	34.769-34.875	1.426	1.033	-0.593	-1.158	-1.631	-1.767
28	75°07.20	163°52.20	34.752-34.844	1.649	1.102	-0.648	-0.918	-1.102	-1.429
29	75°08.00	164°24.00	34.772-34.872	1.211	0.535	-0.896	-1.670	-1.782	-1.829
30	75°09.00	165°00.30	34.473-34.874	0.745	0.731	0.544	0.120	-1.072	-1.638
31	75°06.40	165°29.10	34.572-34.839	0.863	0.847	0.810	0.589	0.104	-1.181
32	75°07.00	166°08.40	34.677-34.829	1.075	0.832	0.479	0.223	0.057	-0.186
33	75°11.00	164°37.00	34.829-34.867	1.589	1.461	1.192	0.026	-1.267	-1.587
34	75°12.30	164°16.70	34.769-34.848	1.656	1.483	0.597	-0.857	-1.604	-1.622

35	75°11.50	163°59.80	34.503-34.834	1.706	1.293	0.806	-0.475	-1.120	-1.419
36	75°18.00	164°33.00	34.513-34.850	1.841	1.521	1.309	-0.418	-1.318	-1.636
37	75°16.70	164°51.80	34.281-34.786	0.733	0.494	0.182	0.064	-1.604	-1.740
38	75°17.80	165°26.60	34.117-34.834	0.902	0.832	0.524	-1.021	-1.640	-1.708
39	75°17.60	166°08.80	33.817-34.804	0.493	-0.349	-1.565	-1.784	-1.855	-1.868
46	75°29.00	165°31.80	33.814-34.729	-0.226	-0.701	-1.527	-1.515	-1.498	-1.513
47	75°30.00	166°13.20	33.149-34.723	0.606	0.261	-1.001	-1.278	-1.479	-1.691
48	74°57.20	164°37.20	34.810-34.862	-0.567	-0.610	-0.731	-1.608	-1.810	-1.807
49	74°50.40	169°12.70	32.844-34.592	-0.276	0.441	-0.687	-1.107	-1.232	-1.116
50	74°51.70	170°02.50	32.754-34.588	-0.778	-0.730	-0.131	-0.889	-1.196	-1.200
51	74°51.20	171°29.20	33.016-34.639	1.134	1.180	0.211	-0.996	-1.236	-1.133
80*	75°13.00	165°06.00	33.407-34.755	-0.500	-0.523	-1.223	-1.625	-1.883	-1.876
81*	75°10.00	164°54.00	33.293-34.738	-0.693	-0.763	-0.886	-1.616	-1.866	-1.882
82*	75°09.00	164°35.00	33.690-34.747	-0.220	-0.201	-0.661	-1.323	-1.734	-1.799
83*	75°02.00	164°28.00	33.094-34.743	-0.151	-0.149	-1.047	-1.515	-1.594	-1.735
84*	75°00.00	164°14.00	33.027-34.749	0.020	0.014	-0.559	-1.393	-1.620	-1.672
85*	74°54.00	163°52.00	33.069-34.566	0.139	0.120	-0.525	-0.849	-1.060	-1.307
86*	74°59.00	164°09.00	33.092-34.750	-0.424	-0.421	-1.297	-1.371	-1.498	-1.615
133**	74°57.00	164°26.00	33.790-34.748	0.249	0.379	-0.090	-0.993	-1.812	-1.838
134**	75°02.00	163°54.00	33.070-34.743	-0.337	-1.217	-1.517	-1.729	-1.789	-1.851
135**	75°03.00	164°14.00	32.972-34.729	-0.363	-0.883	-1.389	-1.612	-1.791	-1.831
136**	75°06.00	164°29.00	33.353-34.678	-0.728	-0.823	-1.094	-1.494	-1.661	-1.764
137**	75°04.00	163°54.00	32.900-34.738	-0.626	-0.764	-1.283	-1.670	-1.801	-1.834

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One asterisk denotes Polar Star 1984 American expedition. Two asterisks denote the Polar Star 1985 American expedition.

Table 9' : Italian Data First Expedition

SN	Sal. 100 m	5al. 200 m	Sal. 500 m	Temp. 100 m	Temp. 200 m	Temp. 500 m	Hax. Depth
3	34.899			-1.34			153
5	34.853	34.903	34.955	-1.86	-1.90	-1.91	655
7	34.894	34.906	34.946	-1.62	-1.88	-1.91	501
8	34.885	34.915	34.936	-1.58	-1.88	-1.92	603
9	34.906	34.920		-1.74	-1.88		35;
10	34.906	34.921		-1.85	-1.91		353
11	34.941	34.953		-1.84	-1.90	-1.93	49
12	34.893	34.924	34.958	-1.45	-1.87	-1.92	77:
13	34.875	34.909	34.955	-1.19	-1.92	-1.91	64
14	34.838	34.905	34.940	-1.66	-1.89	-1.91	95
16	34.846	34.899	34.935	-1.83	-1.92	-1.91	65
17	34.741	34.804		-1.84	-1.90	-1.93	49
1.8	34.881	34.898	34.939	-1.80	-1.85	-1.92	70
19	34.901	34.908	34.946	-1.66	-1.88	-1.92	68
20	34.904	34.915		-1.85	-1.97		24
21	34.883	34.895		-1.85	-1.91	C	44
22	34.894	34.907	34.934	-1.86	-1.91	-1.90	75
23	34.865	34.889	34.938	-1.75	-1.87	-1.90	88
24	34.865	34.899	34.916	-1.78	-1.86	-1.86	100
25	34.842	34.895	34.925	-1.90	-1.90	-1.91	100
26	34.876	34.894	34.929	-1.78	-1.86	-1.91	93
27	34.889	34.897	34.933	-1.89	-1.91	-1.92	82
28	34.871	34.898	34.929	-1.84	-1.88	-1.92	70
29	34.886	34.893	34.935	-1.89	-1.91	-1.91	70
30	34.896	34.909	34.949	-1.84	-1.89	-1.92	100
31	34.880	34.897	34.936	-1.82	-1.90	-1.91	100
32	34.852	34.899	34.928	-1.88	-1.91	-1.90	85

Table 9': Italian Data First Expedition (+ Polar Star 1984 and 1985)

SN	5al. 100 m	Sal. 200 m	Sal. 500 m	Temp. 100 m	Temp. 200 m	Temp. 500 m	Hax. Depth
33	34.870	34.868	34.929	-1.87	-1.88	-1.89	993
34	34.867	34.891	34.918	-1.69	-1.87	-1.90	993
35	34.839	34.878	34.924	-1.68	-1.88	-1.90	1005
36	34.864	34.893	34.917	-1.78	-1.88	-1.88	811
37	34.841	34.889	34.926	-1.83	-1.86	-1.90	802
38	34.870	34.910	34.950	-1.85	-1.90	-1.91	702
39	34.831	34.882	34.916	-1.88	-1.87	-1.89	703
46	34.823	34.869	34.919	-1.81	-1.83	-1.89	840
47	34.806	34.842	34.924	-1.89	-1.90	-1.90	653
48	34.874	34.896	34.940	-1.84	-1.92	-1.90	903
49	34.745	34.852		-0.78	-1.88		300
50	34.782	34.864		-1.68	-1.90		296
51	34.761	34.842	34.965	-1.20	-1.88	-1.91	500
80*	34.792	34.824	34.869	-1.86	-1.90	-1.91	961
81*	34.783	34.814	34.869	-1.84	-1.89	-1.91	1097
82*	34.777	34.814	34.862	-1.80	-1.88	-1.91	1170
83*	34.785	34.803	34.849	-1.91	-1.90	-1.95	914
84*	34.785	34.824		-1.80	-1.89		465
85*	34.784	34.800		-1.90	-1.98		473
86*	34.786	34.814	34.857	-1.85	-1.90	-1.91	852
133**	34.803	34.823	34.856	-1.90	-1.94	-2.01	813
134**	34.801	34.839	34.925	-1.90	-1.90	-1.92	539
135**	34.787	34.831	34.916	-1.89	-1.90	-1.92	494
136**	34.792	34.868	34.927	-1.90	-1.91	-1.92	490
137**	34.785	34.830		-1.89	-1.90		493

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One asterisk denotes Polar Star 1984 American expedition. Two asterisks denote the Polar Star 1985 American expedition.

The hydrologic measurements performed during the first Italian expedition were obtained during the 1987-88 austral summer in three distinct periods, extending from January to February 1988. The instruments used for the determination of the physical and chemical characteristics of the waters under investigation were:

 Meerestechnik Mod. KMS multi-parametric profilers
C.T.D. equipped with pressure (P), temperature (T) and conductivity (C) sensors. (See Boldrin and Stocchino for details concerning the methodology of the measurements).

Precision : $P = \pm 0.01 \text{ m}$ (pressures given in decibars can be considered equal to the depth in meters within 1% accuracy).

$$T = \pm 0.02^{\circ} C.$$

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 Niskin-type oceanic bottles used for seawater sampling.

1.1. First Italian Expedition - Data Analysis

Innamorati et al (1990) and Boldrin and Stocchino (1990) show surface temperatures west of 167°E. Both maps show similar isotherm patterns with the warmest temperatures observed at Gerlache Inlet (see figure 47). The coldest waters are found in two regions. The first is located east of Hells Gate Ice Shelf and Nansen Ice Sheet. The second is situated near the extremity of Drygalski Ice Tongue.

Surface salinity generally decreases with distance from the coast (figure 48). The salinity of the stations situated



Figure 47. Temperature distribution at 0 m.



Figure 48. Salinity distribution at 0 m.

west of the 166°E meridian is mostly higher than 34.5, and reaches a minimum of 32.45 near 168°E.

Figure 49 shows the potential temperature distribution at a depth of 100 m, while figure 50 illustrates the salinity distribution at the same depth. The potential temperature (θ) is the temperature that the water mass would have if it were raised to the surface without any exchange of heat. It should be noted that the differences between the potential temperature and the normal temperatures are minor at these depths.

At a depth of 100 m, the potential temperatures are all lower than their surface correspondents ranging from -0.78°C to -1.91°C. The eddylike pattern of the isotherms that were centered on station 21 at 0 m is absent from the 100 m depth map. The highest temperatures are found in the vicinity of Cape Washington and the lowest along the coast, from Penguin Bay in the north to Nansen Ice Sheet to the south, and north Drygalski Ice Tongue around 164°E. The salinity of distribution is illustrated on figure 51. In order to illustrate the possible influence of Drygalski Ice Tongue on the salinity of the surrounding waters, stations 39, 46, and 47, which are in its vicinity, were represented by a different sign on figure 51. Their position on the graph reveals a lower than average salinity similar to that observed for stations located at longitudes east of 167°E, at increasing distances from the coast.


Figure 49. Temperature distribution at 100 m. depth.



Figure 50. Salinity distribution at 100 m. depth.



Figure 51. HYDROLOGICAL CHARACTERISTICS OF TERRA NOVA BAY

Everywhere, a salinity increase is observed, but the maximum is found east of Penguin Bay.

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Water masses can be defined conveniently by their particular relationship of salinity and potential This type of diagram was introduced to temperatures. oceanography by Helland and Hansen in 1916. For the purpose of comparing the surface waters to the waters found at 100 m depth, a plot of potential temperatures against salinity of all data at 0.5 m and 100 m depth was made (figure 51). Different symbols were used to represent the samples east of the 167th meridian and west of it. The surface waters present a wide variety of salinities and temperatures. At 100 m depth, the range of salinities is narrower than at the surface. The potential temperatures follow the same trend so that if the most distant stations 49, 50, and 51 are omitted, the plots are clustered in an area corresponding to a salinity of ± 34.80 and a potential temperature near the surface freezing point.

A detailed examination of vertical profiles of potential temperatures reveals that for stations 10, 11, 12, 22, 48, 27, 28, 33, 34, 39, and 47, the overall trend in the upper 50 m is one of decreasing temperature versus depth, with an approximate gradient of about 0.30° C/100m. The maximum temperature gradient is observed for station 11 with a gradient of about 0.7° C/10 m. The temperature profiles of stations 5, 16, 17, 49, 50, and 51 show a general decrease of

the temperature. Below 200 m, the temperature approaches a value of about -1.9° C.

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The salinity profiles show a rapid increase of salinity with depth. This is generally true for stations 5, 14, 16, 17, 25, 38, 39, 46, 47, 49, 50, and 51, which present low surface salinities. Below 200 m, the salinities are rather uniform. Most of the variation is found in the upper 100 m of the water column.

1.2. Second Italian Expedition. Data Analysis

The biological, chemical and geological sampling took place between January 11th, 1990, and February 4th, 1990. The emphasis of the study was put on coastal areas extending from Campbell Glacier Ice Tongue, following the edge of the fast ice covering Gerlache Inlet (with the exception of station 16 situated in the inlet, at the foot of Mt. Browning) as shown on figure 52.

South of the Italian base, the stations closely follow the coast. The last two sampling stations are particularly interesting for this study because they are the closest to the area studied in this work. Station 11 is located along the Northern Foothills, north of Cape Russell, and station 10 is at the ice front of Hells Gate Ice Shelf. Figure 53 gives the hydrological characteristics of the 1990-1991 expedition in Terra Nova Bay.



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Figure 52. Bathymetric map of the Terra Nova Bay area.



HYDROLOGICAL CHARACTERISTICS OF TERRA NOVA BAY 1990-1991 Expedition Figure 53.

Table 10 summarizes the data obtained at the 19 sampling sites. This table contains, in addition to the geographic coordinates of the stations, the salinity ranges from the surface to 50 m depth, and the potential temperatures at depths ranging from 0 to 50 m, with a 10 m increment.

SN	Lat.	Long.	Date	Salinity Range	T°.	15°m	28°m	a Te	48°n	58°m
2	74041.45	164024.01	15.1.90	32.75-34.65	0.65	0.77	0.35	0.13	-1.23	-1.49
3	74039.06	164014.66	26.1.90	33.43-34.29	0.84	0.70	0.73	0.71	0.66	0.02
38	74039.42	164015.74	27.1.90	33.21-34.55	0.58		0.67	0.00		-1.12
4	74041.34	164004.36	26.1.90	33.68-34.29	0.77	0.74	0.63	0.58	0.80	-0.28
44	74041.44	164003.78	31.1.90	33.81-34.35	0.22	0.08	-0.40	-0.48	-	-0.78
5	74040.61	164008.67	13.1.90	32.98-34.60	0.13	0.35	1.67	0.31	-0.54	-0.83
6	74046.35	163057.70	23.1.90	33.86-34.67	0.91	0.70	0.07	-0.74	-1.27	-1.58
7	74046.59	164003.78	23.1.90	33.62-34.67	1.28	1.16	-0.48	-1.36	-1.44	-1.56
8	74042.70	164008.84	28.1.90	33.80-34.68	0.37	0.38	-0.23		-1.58	-1.61
8.4	74042.82	164008.85	20.1.90	33.61-34.67	1.35	0.29	-0.50		-1.09	-1.36
9	74050.52	164001.45	20.1.90	33.78-34.68	1.18	0.20	-0.39	-0.81	-1.40	-1.58
10	74052.56	163048.36	18.1.90	34.45-34.69	-0.75	-1.42	-1.50	-1.69	-1.78	-1.78
11	74053.26	163057.60	18.1.90	34.29-34.67	0.20	0,16	-1,46	-1.69	-1.75	-1+78
12	74045.26	164006.26	29.1.90	33.90-34.57	0.19	0.17	-0.32	-0.88	-1.05	-1,35
14	74049.04	16407.35	29.1.90	33.79-34.58	0.55	0.31	-0.17	-0.37	-1.12	-1.40
15	74041.50	164012.50	31.1.90	33.44-34.44	-0.66	-0.34	-0.43	-0.62	-0.89	-1.20
16	74038.27	164004.58	31.1.90	33.95-34.40	0.47	-0.05	-0.51	-0.67	-0.77	-0.94
17	740.13	164011.75	2.2.90	33.51-34.52	0.01	-0.12	-0.51	-0.73	-1.03	-1.07
18	74039.72	164024.00	02.2.90	33.50-34.57	-0.09	0.12	-0.15	-0.69	-0.92	-1.23

Table 10 : Hydrological Data Italian Expedition 1990-1991.

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In the second part of the table are the salinities and potential temperatures at 100 m, 200 m, and 500 m depth. The last column gives the maximum depth observed at each sampling site.

SN	Sal. 100 m	5al. 200 m	500 m	Temp. 100 m	Temp. 200 m	Temp. 500 m	Max. Depth
2	34.74	34.77	34.82	-1.83	-1.90	-1.96	541
3	34.69			-1.58			180
38	34.74			-1.67			160
4	34.72	34.78		-1.69	-1.92		233
43	34.78			-1.66			211
5	34.74	34.78		-1.67	-1.91		343
6							75
7	34.72			-1.83			195
8	34.72			-1.82			160
88	34.72			-1.73			140
9	34.74	34.78	34.82	-1.91	-1.94	-2.01	117
10	34.74	34.78	34.82	-1.91	-1.94	-2.01	750
11	34.72	34.77		-1.80	-1.94		256
12							100
14	34.72			-1.82			200
15	34.70	34.76		-1.83	-1.90		430
16	34.71	34.77		-1.59	-1.88		232
17	34.71	34.77	34.81	-1.82	-1.90	-1.99	516
18	34.72			-1.69			183

Table 10. Second part.

The depth at station 10 is particularly worth noting since it is the first precise measurement of bathymetry in the near-vicinity of Hells Gate Ice Shelf. This depth exceeds that indicated on the 1960 U.S.G.S. topographic map of Mt Melbourne; the newly measured bathymetry shows that the continental shelf along the Hells Gate Ice Shelf is much deeper than previously thought.

The salinities encountered at the surface for most stations show a rather uniform distribution. Salinities are mostly between 33.2 and 33.95, with station 2 lower than average (32.75), and stations 10 and 11 higher than average (34.45 - 34.29).

Table II ; hydrological baca 1970 - Scalley bacos	Table	11 :	Hydr	ological	Data	1978	-	Stanley	Jacob
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SN	Lat.	Long.	Date	Salinity Range	7°.	.°51	28 ⁰ m	38°m	48°m
166	74025.90	169014.40	06.2.78	34.042-34.494	-1.012	-1.023	-1.113	-1.797	-1.709
168	74057.80	165 ⁰ 33.60	07.2.78	34.604-34.628	-1.473	-1.475	-1.483	-1.469	-1.464

SN	Sal. 50 m	Sal. 100 m	Sal. 200 m	Sal. 500 m	Temp. 50 m	Temp. 100 m	Темр. 200 м	Temp. 500 m	Max. Depth
166	34.568	34.743	34.804	34.873	-1.649	-1.839	-1.927	-1.913	736
168	34.631	34.751	34.797	34.829	-1.468	-1.847	-1.888	-1,902	1120

2. Discussion

2.1. Change in the salinity

Salinity varies with time, due to atmospheric forcing and ocean currents. Indeed, the air temperature influences sea ice production. Depending on wind intensity and direction, existing ice will be pushed away from the coast allowing more ice to form.

Large salinity changes have been observed on the Antarctic continental shelf over the past two decades. These changes cannot be attributed to ice melting as demonstrated by Dunbar et al, (1985). Jacobs proved that there is large seasonal variation in the depths at which freezing temperatures occur. Conditions are different between the Ross Ice Shelf and Hells Gate Ice Shelf, because ocean depths are much greater closer to the Ross Ice Shelf.

2.2. Water Circulation Under Ice Shelves

Water circulation must be inferred from a variety of indirect data. Summer oceanographic observations are made near the edge of the ice. In the case of Hells Gate, the data are too scarce to definitely establish circulation under the ice. However, the first Italian expedition proved that the continental shelf was at a greater depth beneath the ice shelf than previously thought. Numerical models created for the circulation beneath larger ice shelves such as Filchner-Ronne (Hellmer *et al*, 1991), Ross Ice Shelf,..., have not been applied to small ice shelves such as Hells Gate. With the purpose of identifying the water masses, a T-S plot was drawn for station 21 (see figure 54). This diagram shows a strong linear relationship. The correlation coefficient is 0.992. This linear correspondence is in agreement with fresh water ice melting in sea water.

2.3. The Terra Nova Bay Polynya

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The word polynya derives from Russian (meaning open, empty) and was used for the first time in the early 1880s. (The Random House Dictionary, 1987). This is not surprising since polynyas were first known and studied in the Arctic by Russian Scientists. A polynya is a non-linear area of unfrozen sea water surrounded by sea ice.



Figure 54.

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In Antarctica, numerous polynyas have been observed during the austral summer since the early days of exploration, but the members of Scott's Northern party were the first to report the presence of open water during the wintertime in Terra Nova Bay. They attributed the ice-free area to the action of the wind (Priestley, 1914).

Observation of polynyas during the wintertime began when Knapp (1972) used thermal infrared satellite imagery. Knapp hypothesized that the Terra Nova Bay polynya represented a class of polynyas formed by the strong winds associated with passing cyclones.

In 1974, Szekielda attributed the Terra Nova Bay polynya to the presence of submarine volcanic activity or to the upwelling of warm water. In 1981, Wong and Christoffel found no evidence of submarine volcanism when they analyzed the seismic activity across the Drygalski Basin. Anderson and Kurtz (1980) ruled out this possibility when they studied sediments samples and sonar data during Deep Freeze 80.

Subsequent water sampling data (Jacobs and Haines, 1982) denied the presence of exceptionally warm deep water that could provide enough heat to maintain the polynya.

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Relying on the study of infrared images from two polarorbiting satellites taken in April 1979, May 1978, July and August 1979, Bromwich and Kurtz (1989) observed the behavior of the 25,000 km² region surrounding the Terra Nova Bay polynya. They calculated that the mean area of the ice-free

section was 1,300 km². The ice-free area varies from near zero ("a nucleus of open water offshore from Inexpressible Island and the outlet of Reeves Glacier") to 5,000 km². At its maximum extent, the polynya's seaward boundary reached the eastern tip of Drygalski Ice Tongue.

The extent of sea ice has been accurately established since satellite observations became possible. In the case of the Terra Nova Bay polynya, Kurtz and Bromwich established its extent at about 1,000 km². The NOAA satellite photograph, figure 55, reveals the extent of the polynya and the ocean covered by sea ice.

Another method of deducing under ice water circulation is to study biological productivity in surface waters. Biological productivity depends upon the level of illumination, the area of open water during the austral summer, and surface warming. Due to the presence of the polynya in Terra Nova Bay, one would expect a high level of productivity, as demonstrated by Dunbar *et al* (1985). However, high productivity is not found under the polynya, but east of it.

3. Conclusion

The Italian data appear to show (perhaps best from the vertical profiles of T/D and S/D) that Terra Nova Bay is mostly High Salinity Shelf Water overlain by Antarctic Surface



Water. The latter layer, more shallow than 100 m, is generally warmer, fresher and more variable. During the brief summer, this is the water that will interact with the front and underside of Hells Gate.

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The deeper High Salinity Shelf Water will interact with Hells Gate for the rest or for most of the year. The important considerations are its temperature relative to the *in situ* freezing point, the degree of upwelling associated with the winter Terra Nova Bay Polynya, and possibly the strength of the circulation beneath the Hells Gate Ice Shelf.

All the data were recorded during a six-week period, in January and February 1988. The observed variability is possibly of very short term. To emphasize the means more than the variability, the data were averaged to produce a composite profile for Terra Nova Bay. The results can be found in table 12 and on figures 56 and 57.

Given the shallow draft of Hells Gate and the high variability of temperatures and salinities in the surface water, it is unlikely that any of the data will be useful to infer the sub-ice circulation. Since the continental shelf is deeper at the front than previously believed, deeper water (i.e., more High Salinity Shelf Water-like) may penetrate beneath the Hells Gate Ice Shelf. The T/S diagram probably does not help in finding this out because the surface freshness could be due to the melting of sea ice, the melting of ice shelf *in situ*, surface run off, or precipitation.

Table 12: Data Used to Produce a Composite Profile for Terra

T. 0 m	T. 20 m	T. 50 m	T. 100 m	Sal. 0 m	Sal. 20 m	Sal. 50 m	Sal. 100 m
	HELLS GATE	A VICINITY	13-5-				
-0.342	-0.462	-1.07	-1.85	34.863	34.866	34.882	34.904
-0.478	-0.546	-1.093	-1.85	34.784	34.789	34.836	34.883
0.601	0.336	-1.768	-1.86	34.821	34.814	34.883	34.894
-0.75	-1.5	-1.78	-1.94	34.45	34.62	34.69	34.74
0.2	-1.46	-1.78	-1.94	34.29	34.62	34.67	34.72
-0.154	-0.764	-1.498	-1.888	34.642	34.742	34.792	34.828
	DRYGALSKI						100
1.589	1.192	-1.587	-1.87	34.829	34.838	34.867	34.87
1.656	0.597	-1.622	-1.69	34.769	34.789	34.848	34.867
1.706	0.806	-1.419	-1.68	34.503	34.755	34.834	34.839
1.841	1.309	-1.636	-1.78	34.513	34.69	34.85	34.864
0.733	0.182	-1.74	-1.83	34.281	34.49	34.786	34.841
1.505	0.817	-1.601	-1.770	34.579	34.712	34.837	34.856
	POLAR STAR	1984					
-0.5	-1.223	-1.876	-1.86	33.407	34.665	34.755	34.792
-0.693	-0.886	-1.882	-1.84	33.293	34.636	34.738	34.783
-0.22	-0.661	-1.799	-1.8	33.69	34.586	34.747	34.777
-0.151	-1.047	-1.735	-1.91	33.094	34.396	34.743	34.785
0.02	-0.559	-1.672	-1.8	33.027	34.522	34.749	34.785
0.139	-0.525	-1.307	-1.9	33.069	33.785	34.566	34.784
0.424	-1.297	-1.615	-1.85	33.092	34.647	34.75	34.786
-0.140	-0.885	-1.698	-1.851	33.239	34.462	34.721	34.783

Nova Bay



Figure 56. Average water types in the vicinity of Hells Gate Ice Shelf and Drygalski Ice Tongue.



Figure 57.



The Terra Nova Bay Polynya is a winter feature which is persistent but variable in size. Its main significance is that it is likely to be a primary source of High Salinity Shelf Water, possibly also of coastal upwelling, and also of relatively strong ocean currents, as reported by Anderson *et al* (1991). It is not clear how this impacts the summer nearsurface productivity.

There are a few unusual features in the Italian Data, relative to more widely scattered open Ross Sea measurements. One of these features is the high surface salinities of most of the stations, suggesting either a recent upwelling or reduced melting that year.

In order to obtain a clearer picture of the temperatures and salinities, six maps (figures 58a, 58b, 59a, 59b, 60a and 60b) were made of the average bottom water, midwater and nearsurface water (between 10-20 m), combining the data of both years (suggested by S.Jacobs, personal communication, 1991).

3.1. Sedimentation in Terra Nova Bay

In general, marine sedimentation in a high latitude icecovered environment is the result of four factors:

- debris carried into the sea by floating ice tongues and ice shelves,
- material transported by icebergs,
- biogenic sedimentation,

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- subglacial sedimentation.



Figure 58a. Map of the average bottom water temperatures.

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Figure 58b. Map of the average bottom water salinities.



Figure 59a. Map of the average mid-water temperatures.









Figure 60a. Map of the average near-surface water temperatures (between 10 and 20 m).



Figure 60b. Map of the average near-surface water salinities (between 10 and 20 m).

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The first study of sedimentation in the Western Ross Sea was made as part of the Deep Freeze 80 Project. Surface sediment samples from 41 piston cores were retrieved by the United States Coast Guard Icebreaker *Glacier* on its 1980 cruise. Figure 61 shows the Deep Freeze 80 sample locations. Most of these locations are situated within the Terra Nova Bay Polynya. Among these 41 cores, eight were retrieved to the south of Drygalski Ice Tongue and five north of Campbell Ice Tongue.

Anderson and Kurtz (1980) supplemented the previous bathymetric information by compiling the water depths recorded at each sample station of the DF 80 cruise. Figure 61 shows the bathymetry of the Terra Nova Bay area. The bathymetry is characterized by a series of ridges and basins that run subparallel to the coastline. The Crary Bank, one of the ridges, indicated with C on the map, is only 300 m below sea level. Drygalski basin extends from beneath the ice tongue and is oriented southwest-northeast. This 1,100 m deep feature, carved by ice flowing through the area, reflects the grounding of glacier ice during a glacial maximum (Anderson et al, 1980). This glacial maximum is presumed to be the most recent one (Anderson et al, 1984), although absolute ages for the basal tills are not yet available (Anderson et al, 1991).



Figure 61.

Map showing the locations of David Glacier and associated Drygalski Ice Tongue. The bathymetry of the area is also shown (in meters). Note the deep, northeast-southwest oriented trough (Drygalski Trough) that extends from beneath the ice tongue. This feature was formed during several episodes of glacial advance onto the Ross Sea continental shelf. The locations of Deep Freeze 80 piston cores is also shown. Circles are used to designate cores that penetrated basal tills, triangles for cores that penetrated compound glacial-marine sediments, and squares designate cores that penetrated debris flows or turbidites.



Figure 62 - Piston cores collected across a transect (A-A', Fig. 16) are used to illustrate the generalized stratigraphy of the area adjacent to the Drygalski Ice Tongue.

3.2. Sedimentary facies and the Terra Nova Bay Polynya.

Hughes (1986) stated that since the Terra Nova Bay Polynya is more constant than any other Antarctic polynya, it is more likely to influence sedimentary processes and provide information about the past history of the polynya, and about climate and past wind regime in East Antarctica.

The absence of ice on the surface of the sea, pushed seaward by the katabatic winds, should allow more light to penetrate into the water column. The Terra Nova Bay polynya should be a site of elevated levels of organic productivity, since organisms living in the photic zone would receive light for longer periods.

The constant wind stress on the surface of the Western Ross Sea should increase mixing, and mixing should in turn bring nutrient-rich water to the surface. Biologic productivity should be stimulated by the high nutrient content of upwelling zones.

Sedimentation should reflect this by showing a majority of biogenic sediments containing siliceous muds consisting of diatom frustules, sponge spicules. Diatoms are particularly characteristic since diatom population can double in as little as one day (Berger, 1975).

Usually, large amounts of biogenic material, which are produced as a result of the increasing nutrient content of upwelled water, are biogenic opal, organic carbon, fish remains, phosphorite, benthic organisms, and fecal material (pelletal texture). In the studied area, two mechanisms have been suggested to account for the decreased rather than increased biogenic productivity in the polynya. Frequent deep mixing removes phytoplankton from the photic zone before it can bloom (Hughes, 1986) and, speculatively, phytoplankton exclusion because of brine expulsion during ice formation (Dunbar et al, 1985).

These factors, that lead to decreased productivity, override the increased productivity due to enhanced light penetration.

3.3. Sedimentation near Hells Gate Ice Shelf

The studies of Krissek and Hughes contradict the concept of increased productivity in the polynya. Hughes (1986), and Krissek and Hughes (1988) have discussed the different sedimentary facies in Terra Nova Bay and their implications. Figure 63 illustrates the abundance of terrigenous sediment components in core-top samples from Terra Nova Bay. Since terrigenous and biogenous components dominate these sediments, biogenous abundance varies inversely with the pattern shown on figure 63. North of Drygalski Ice Tongue, the abundance of the biogenous component ranges from 25% and 50%, while it is mostly less than 25% within the modern polynya. The stratigraphy of the eight cores retrieved from Drygalski trough show a rapid retreat of the Ross Sea Ice Sheet



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Figure 63. Abundances of terrigenous sediment components in core top samples from Terra Nova Bay.



(diatomaceous mud deposited on basal till - see figure 62). Indeed, if the contact is sharp, it implies a rapid shift from subglacial to marine sedimentation. In the northern part of the trough, the retreat was relatively slower, as shown by the sequences diatomaceous mud, glacial-marine compound overlying basal till (see figure 62, Anderson et al, 1991).

In other words, Krissek and Hughes discovered that terrigenous components account for 75% of the total sediment mass. The outlet glaciers are the principal source of the terrigenous sediments. They present a wide scatter in textural properties. This high percentage confirms the fact that biogenous components are not increased by the presence of the polynya (see figure 64). The sediments found in piston core 117 near Hells Gate were composed of the following:

- unsorted rafted debris
- siliceous biogenic material (mainly diatom frustules)
- calcareous shell debris
- terrigenous silts and clays.

Krissek (1986) studied the sediments found offshore from Hells Gate and discovered the presence of debris of eolian origin mixed with other sediments (see figure 63). The katabatic winds blow over exposed terrigenous debris upwind of the polynya (Whitehouse and Chinn, 1985). These winds are energetic enough to entrain and transport sand and silt-size material into the polynya. Indeed, the most terrigenous-rich



Figure 64. Abundance of the diatom Eucampia Antarctica in the total diatom populations of core top samples from the Terra Nova Bay.

sediments are observed near the coast of Terra Nova Bay (Hughes, 1986).

II. <u>ISOTOPE AND CATIONIC CONTENT OF THE ICE IN AN ANTARCTIC</u> COASTAL ENVIRONMENT

Introduction

Oxygen is the most abundant chemical element in the earth's crust. Oxygen has three stable isotopes with the following abundances (Garlick, 1969):

 ${}^{16}O = 99.763$ % ${}^{17}O = 0.0375$ % and ${}^{18}O = 0.1995$ %.

¹⁷O is usually not considered separately because it is more than 5 times less abundant than ¹⁸O.

Hydrogen has two stable isotopes:

 ${}^{1}H = 99.9852$ % D = ${}^{2}H = 0.0148$ %

²H has acquired the name of deuterium and is often represented in short by D.

D and ¹⁸O have been used in geochemistry since the 1940s (Urey, 1947) to study the hydrological cycle, the motion of water masses in the ocean, and all kinds of natural processes accompanied by fractionation of isotopes.

A. Isotopic Characteristics of Glacier Ice.

1. Isotopic Fractionation

Isotope fractionation results from the fact that thermodynamic properties of molecules depend on the masses of their atoms (Faure, 1986). Table 13 compares the physico-chemical properties of $H_2^{16}O$ and $D_2^{16}O$, $H_2^{18}O$ and $HD^{16}O$.

Table	13:	Characteristic	constants	of	H_O,	H,180,	D.0*,	and	HD16O

Constants	H ₂ ¹⁶ O	H ₂ ¹⁸ O	D ₂ O	HD16O
Density (20°C, in g cm ⁻³)	0.9982	1.1032	1.1050	1.1049
Temperature of greatest density (in °C)	4.0	4.305	11.24	
Mole volume (20°C in cm³/mole)	18.049	18.0724	18.124	18.1290
Melting point (760 Torr in °C)	0.00	0.28	3.82	
Boiling point (760 Torr in °C)	100.00	100.14	101.42	100.738
Vapor pressure (at 100 °C in Torr)	760.00	756.22	736.00 62	
Viscosity (in centipoise at 20°C)	1	1.0564	1.2471	1.1248

* From Hoefs (1980)

In natural waters, the three most abundant isotope water species are $H_2^{18}O$, $HD^{16}O$ and $H_2^{16}O$. Their vapor pressures are inversely proportional to their masses. From the comparison of the vapor pressure data of H_2O and D_2O , it is obvious that
the lighter molecular species enter the vapor phase more readily, while ¹⁸O and D will enrich the liquid phase. Thus, water vapor formed by evaporation of liquid water is enriched in ¹⁶O and ¹H, while the remaining water is enriched in ¹⁸O and D.

The isotopic concentrations of oxygen and hydrogen are measured in terms of relative differences of $^{18}O/^{16}O$ and D/H ratios to a standard. This difference is designated by δ and expressed as follows:

$$\delta_x = \frac{(R_x - R_{STD})}{R_{STD}} \times 10^3$$

where
$$R_x = \left(\frac{D}{H}\right)_x$$
 or $\left(\frac{18O}{18O}\right)_x$

and R_{std} is the corresponding ratio for the standard. The δ -value is expressed in parts per thousand or per mil (%). Positive values show enrichment in the heavy isotopes of the samples, while negative values show depletion in heavy isotopes. This chapter cites the δ -values as $\delta^{18}O$ and δD .

2. Water Standards

Although surface ocean water varies greatly in salinity and isotopic composition, samples of ocean water ranging in depth between 500 and 2,000 m show remarkably homogeneous δD and $\delta^{16}O$ values (Epstein and Mayeda, 1953). The mean ocean water was chosen as the reference standard for natural water since the ocean contains 98 % of the water present on the earth's surface. It has a fairly uniform composition and thus constitutes a logical departure point for describing processes of the water cycle in nature (Gonfiantini, 1981).

2.1. SMOW

Until recently, the standard almost universally adopted to calibrate laboratory measurements was called SMOW for <u>Standard Mean Ocean Water</u> (Gonfiantini, 1981). It corresponded to a hypothetical water having both oxygen and hydrogen isotopic ratios equal to the mean isotopic ratios of ocean water (Gonfiantini, 1981). Craig (1961) prepared a large quantity of such a water for which δD and $\delta^{1*}O$ equal zero by definition. Craig prepared this standard from a large volume of distilled water from the Potomac River; it is distributed by the National Bureau of Standards (Gaithersburg, MD) in the United States (NBS-1) and is related to SMOW by:

D/H (SMOW)	= 1.050 D/H	(NBS-1)
180/160(SMOW)	= 1.008 ¹⁸ 0/ ¹⁶ 0	(NBS-1)

2.2. Vienna SMOW

Another water standard with the same isotopic composition was prepared by H. Craig (1961) for the International Atomic Energy Agency (IAEA) in Vienna, Austria. This new standard is called Vienna-SMOW (V-SMOW) and is distributed by the IAEA (Fritz and Fontes, 1989). The value of R_{v-smow} is given as (¹⁸O/¹⁶O) V.SMOW = (2005.2 ± 0.45) x 10⁻⁶ measured by Baertschi (1976)

and

(D/H) V-SMOW = (155.76 \pm 0.05) x 10⁻⁶ reported by Hagemann et al (1970).

2.3. SMOW Versus V-SMOW

Gonfiantini (1978) calculated the difference between SMOW and V.SMOW for δ^{18} O and obtained -0.07 %.

The hydrologic cycle can be considered as a sequential, dynamic system, in which water moves as a result of processes such as evaporation, condensation, and precipitation (Hoefs, 1980). The water cycle can be compared to a multiple stage distillation column with reflux of the condensate to the reservoir (Epstein and Mayeda, 1953). The oceans represent the reservoir and the snow falling onto the Antarctic ice sheet corresponds to the latest stages of the column (Hoefs, 1980).

The changes in concentration of D or ¹⁸O are produced by a fractionating process taking place along any change of state of the water (Friedman *et al*, 1964). The main factor controlling the fractionation of isotopic species in surface waters is the difference in the saturated vapor between various water molecules: $p H_2$ ¹⁶O > $p H_2$ ¹⁸O > p HDO (Ferronsky and Polyakov, 1982).

3. Fractionation during evaporation of water

This type of isotope fractionation process is governed by an equilibrium fractionation coefficient α defined as:

$$\alpha = \frac{R_B}{R_A}$$

if R_A and R_B are the ratios of the heavy (HDO or $H_2^{18}O$) to the light ($H_2^{16}O$) isotope molecule of water, respectively in phase A and phase B.

Values of the liquid/vapor fractionation factor have been calculated by Craig and Gordon (1965) under equilibrium conditions. At 25°C, they are:

$$\alpha^{18}O = \frac{(.1^{16}O/.1^{16}O)I}{(.1^{16}O/.1^{16}O)V} = 1.0092$$

$$\alpha_{D} = \frac{(D/H)l}{(D/H)v} = 1.074$$

where $(1^{16}O/1^{16}O)$ l is the ratio of liquid water and $(1^{16}O/1^{16}O)v$ is the ratio of water vapor.

These fractionation factors are temperature dependent, which is illustrated in Figure 65¹.



Figure 65. Temperature Variation of Isotope Fractionation Factors for Evaporation of Water

1. Figure 65: Temperature variation of isotope fractionation factors for evaporation of water. The graph illustrates the temperature dependence of these fractionation factors. Plotted from values listed and discussed by Dansgaard (1964). After Faure (1977). The isotopic fractionation coefficient α generally approaches unity at increasing temperatures (Faure, 1986). α^{1*} O and $\alpha_{\rm p}$ increase when temperature decreases.

Epstein (1959) and Dansgaard (1964) have applied the Rayleigh distillation formula to the isotopic fractionation of $H_2^{18}O$ (or HDO) and $H_2^{16}O$ in the meteorological cycle.

In the case of the condensation of water

$$\frac{R}{R_0} = f^{(\alpha-1)}$$

where R is the 10/160 ratio of the remaining vapor.

 R_o is the initial ¹⁸O/¹⁶O ratio of the vapor (before condensation begins). f is the fraction of the vapor remaining. α is the unit isotope fractionation factor (Broecker and Oversby, 1971).

Because most of the world's evaporation takes place over oceans in tropical and temperate climates, an air mass moving toward the poles becomes progressively depleted in heavy isotopes. This is due to a combination of factors.

First, as the temperature of the air mass decreases, the equilibrium fractionation coefficients increase (figure 65). This implies in the subsequent precipitation, the preferential removal of heavy isotopes D and ¹⁸O (due to their vapor

pressures) in the liquid phase causes the enrichment of ¹⁶O and H in the remaining water vapor (Faure, 1986). This preferential removal of D and ¹⁶O explains why a pronounced latitude effect is observed in the isotopic compositions of water and snow collected in the world. This latitude effect reflects the temperatures of condensation in the clouds.

Second, reevaporation of water from rain drops will impoverish the vapor phase in heavy isotopes. Evapo-transpiration of water by plants will have the same effect. Therefore the heavy isotopes will be depleted to a greater extent during any cooling, resulting from either higher altitude or higher latitude.

Figure 66² (after Dansgaard et al, 1973) is a simplified circulation model showing the oxygen isotope fractionation during the evaporation of ocean water under summer (or warm) conditions or winter (or cool) conditions.

2. Figure 66: The upper part (summer or warm climatic conditions) represents a simplified circulation model showing the oxygen isotope fractionation during the evaporation of ocean water (to the left) and the subsequent precipitation, when the air is gradually cooled off by travelling towards higher latitudes or ascending to higher altitudes over an ice sheet (to the right). The lower part (winter or cool climatic conditions): same as above, except that a cooling, increasing with latitude, has changed the isotopic fall-out pattern into lower δ 's at any mid- and high latitude locality (Dansgaard et al, 1973, figure 1).

Figure 66 illustrates the seasonal variations of D and ¹⁸O observed in precipitation: the heavy isotopes are less depleted during the summer and more depleted in winter.



Figure 66: Seasonal variation of D and ^{1*}O observed in precipitation.

4. Meteoric Water Line

In 1961, Craig initiated a worldwide survey of meteoric waters to understand the variations in their isotopic compositions. In Figure 67, the values of δD plotted versus $\delta^{1*}O$ show an excellent linear correlation for precipitation and meteoric waters relative to SMOW. The equation of the regression line, defined by Craig (1961) as the meteoric water line (MWL), is

 $\delta D = 8\delta^{18}O + 10$

The slope of the meteoric water line is close to that of an equilibrium distillation column. It differs slightly because of the fact that the evaporation from the ocean is a non-equilibrium process under natural conditions (Merlivat and Coantic, 1975).



Figure 67: Oxygen 18 and Deuterium Variations in Precipitation and Meteoric Waters Relative to the SMOW Standard *From H. Craig (1961)

Data values of water samples collected in closed basins, where excessive evaporation occurs, fall markedly off the MWL. The equation describing their linear relationship is such that

δD = 5δ180

Because the δD versus $\delta^{1*}O$ relationship for precipitation often differs from the global equation, Dansgaard (1964) has defined the deuterium excess as

$$d = \delta D - 8 \delta^{18}O$$

5. Isotopic Composition of Snow

According to Peel et al (1988), the mean isotopic composition of snow depends upon:

- the distance from the source of water vapor;
- the average temperature at the deposition site. Moser and Stichler (1975) found δD gradients varying from 2 to 6‰/100 m of elevation in fresh snow. Further measurements and calculations showed that it is only possible to establish a relation between δD and the temperature in small regions where the meteorological conditions are rather uniform;
- the relative humidity at the surface of the ocean at the time of the solid precipitation (Jouzel et al, 1982);
- the composition and condensation temperature of the oceanic source;
- the seasonal distribution of the snow accumulation; and
- the snow blown away by the wind, especially for the

case of powder snow, and if slopes are steep. Snow drifts will decrease the values of δD if the snow is carried from higher to lower places.

The distribution of δD and $\delta^{18}O$ in snow depends also on fractionation processes occurring at the phase boundaries liquid water-vapor, ice-liquid and ice-vapor. Table 14 gives the equilibrium isotopic fractionation coefficients relative to phase changes of water.

Table 14 : Equilibrium Isotopic Fractionation Coefficients Relative to Phase Changes of Water (After Gat, 1981)

		α _D	$\alpha_{18}O$
Ice-vapor	(at O°)	1.132	1.0152
	(at -10°)	1.151	1.0166
Liquid-vapor	(at 20°)	1.084	1.0098
	(at 0°)	1.111	1.0117
Ice-liquid	(at 0°)	1.0208	1.0035

6. Isotopic Changes when snow is transformed in ice.

6.1. Evaporation.

The evaporation of the snow surface leads to a linear increase of δD and $\delta^{18}O$ in the rest of the snow (Moser and Stichler, 1975). Figure 68 shows two lines, whose slopes correspond respectively to the meteoric water line (on which is the snow sample before it begins to evaporate; slope = 8) and to the evaporation (slope = 5.75).



Figure 68: $\delta D - \delta^{18}O$ relationship of snow samples; S slope of the evaporation line; the dashed curve corresponds to the precipitation line; x snow originally introduced. After Moser and Stichler, 1975, figure 10.

6.2. Water percolation.

The percolation of water from surface melting induces the enrichment in heavy isotopes (Arnason, 1981).

B. Isotopic Characteristics of Ice Due to Water Freezing

1. $\delta D - \delta^{18}O$ relationship in ice due to water freezing

Since 1955, numerous authors studied the enrichment in δD and $\delta^{18}O$ occurring when water freezes. Table 15 compares the isotopic fractionation factors obtained theoretically and experimentally. For ice formed from SMOW, the deuterium content of the ice should be about \pm 20 % greater than that of the liquid water, while the oxygen 18 content should be about 3 % higher.

The freezing of water involves isotopic fractionation because heavy and light molecules of water freeze at slightly different temperatures.

Jouzel and Souchez (1982), considering a closed system, demonstrated that successive fractions of ice formed during the freezing of water are aligned on a line, whose slope S is called the freezing slope; S equals 6.14 if water is SMOW. If the initial water has negative δD and $\delta^{18}O$, the freezing slope must be lower.

$$S = S_0 \frac{1000 + \delta D}{1000 + \delta_{10}O}$$

In 1984, Souchez and Jouzel established through experimental studies that the freezing slope is not significantly different in an open system (as compared to a closed system) if the input is not markedly different in its isotopic composition.

Authors		Deuterium	180
Weston(1955)	(theor.)	1.0192	-
Posey & Smith (1957)	(exp.)	1.0211	-
Kuhn & Thürkauf (1958)	(theor.)	1.0186	-
	(exp.)	1.0171	-
Merlivat & Nief (1967)	(theor.)	1.0186	-
O'Neil (1968)	(exp.)	1.0187	1.0029
		1.0195	1.0031
Craig & Hom (1968)	(exp.)	1.0203	1.00270
Arnason (1969)	(exp.)	1.0208	-
Lehmann & Siegenthaler	(1991)		
	(exp.)	1.0212	1.00291
Beck & Münnich (1988)	*(exp.)	1.024	-
*in seawater.			

Table 15: Fractionation coefficients in literature'

"The distribution of heavy isotopic species in ice during water freezing is related to the distribution in the liquid immediately adjacent to the freezing front. Since diffusion in ice is slow, the distribution produced in the ice can be obtained from the knowledge of the compositional variations in the liquid at the interface" (Souchez and Lorrain, 1991).

In high latitudes when the surface ocean layer freezes, fractionation of D and ¹⁸O isotopes in the ice-water system

³ Op citu in Kipstuhl, 1991, page 26.

occurs. Variations in the isotopic composition of the surface ocean waters influence the isotopic content of marine ice. They result from various processes, such as

- evaporation and/or precipitation

- mixing of the surface and deep water masses
- inflow of meltwater from continental ice
- melting of marine ice.

2. Isotope fractionation during melting

In 1980, Moser and Stichler established that no fractionation happens when compact ice melts due to the very low diffusion coefficient of HDO and $H_2^{18}O$ molecules

 $(10^{-11} \text{cm}^2/\text{sec})$ in the solid state. The absence of fractionation during melting of ice had been previously suggested by Friedman *et al* (1964). The fresh water discharged into the Antarctic waters comes from the melting of icebergs calving from outlet glaciers and ice shelves, the melting of snow originating from the glaciated continent, and local precipitation. Craig and Gordon (1965) estimated that this meltwater would only account for 2 to 8 % of the freshwater added by marine precipitation. They concluded that Antarctic meltwater would not strongly affect the δ^{18} O content of seawater except immediately adjacent to the Antarctic continent. 3. Isotopic Composition and Salinity relationship for surface ocean water.

A linear relationship between δ^{1*0} or δD and salinity (S) values can be expected, although detailed studies have pointed out that this relationship has a more complicated character (Epstein and Mayeda, 1953).

Slightly negative values of δD and $\delta^{1*}O$ are typical of polar oceans. Craig and Gordon (1965) estimated that because these regions are subjected to much greater precipitation than evaporation, the surface water will be depleted in heavy isotopes.

The freezing of seawater produces ice with a deuterium and oxygen 18 content close to that of SMOW. Inversely, the melting of sea ice reduces the salinity of the surface waters without significantly changing its deuterium or its oxygen 18 content. Meltwater from glacier ice and polar precipitation on the other hand will have very negative isotopic values and salinity values nearly equal to zero. Consequently, in high latitudes, δD or $\delta^{1*}O$ is a good tracer to determine the origin of surface water.

Salinity and variation in D content of polar ocean waters during freezing and melting of sea ice, as well as dilution of these waters with meteoric waters, have been extensively studied by Redfield and Friedmann (1969). By analyzing a great number of water samples, they obtained the following regression equation line:

δD = 6.96 S - 242.8 ‰

The intercept, - 242.8 ‰, is close to the mean δD value of glacier ice samples from Antarctica (-250 ‰).

Figure 69 illustrates the relationship between δ^{1*} O and S for different types of ocean waters. The Antarctic bottom water is the most depleted in heavy isotopes and the least saline of all waters.



Figure 69: Relationship Between δ^{18} O and Salinity for Different Types of Ocean Waters.

Note that in polar regions, salinity variations of the surface waters occur at a quasi constant isotope composition

$$d\delta^{10}O/dS = O.$$

Similarly, Craig and Gordon (1965) had observed in the Weddell sea surface waters an identical relationship between δD and S (see figure 70).



Figure 70: Deuterium and Salinity in Antarctic Waters.

The lowest $\delta^{1*}O$ and δD values are associated with the least saline Antarctic waters.

Isotopic fractionation due to freezing is not very important at the geographic scale, because the differences are small, and because most ice does not move and melts where it was formed (Weston, 1955). The fact that the differences are small is only true if we refer to a large volume of water where good mixing occurs.

Seasonal changes have been observed in the salinity of surface waters. Indeed winter freezing induces an increase in the surface ocean waters' salinity because of selective rejection of salt in the growing solid phase and a slight depletion in δ^{18} O. Summer melting on the other hand reduces the salinity and increases their δ^{18} O content (Jacobs and Haines, 1982).

C. THE ACQUISITION OF THE MARINE ICE CATIONIC CONTENT.

1. Factors determining the chemical content of marine ice.

Three principal factors determine the chemical content of marine ice:

a. - the chemical composition of the parent water

b. - the freezing rate

c. - the type of sea ice formation.

a) Marine ice has a chemical composition mainly conditioned by the seawater from which it formed. Some variations can be expected in the coastal region of Antarctica. These variations have mainly two origins:

- the intrusion of continental melt water beneath the ice shelf can be affected by contacts with sediments or with weathered bedrock; - the melting of marine ice in which the chemical ratios of major cations were different from normal seawater.

b) Freezing tends to concentrate impurities and solutes in the melt (Harisson and Tiller, 1963, page 222, Kvajic *et al*, 1969). If the thermal driving force for ice formation is extremely small, the freezing rate will be slow enough to allow solute to be rejected at the solid-liquid interface (Terwilliger and Dizio, 1970). These solutes build a zone enriched in solutes close to the interface, called the boundary layer. The thickness of the boundary layer is inversely related to the freezing rate (Gross, 1967).

The third factor is related to the type of sea ice formation. For instance, congelation ice formed by the progression of a freezing front in seawater behaves differently in respect to salt incorporation than frazil ice formed by consolidation of small crystals in the water column.

2. Processes involved in the acquisition of the chemical composition of sea ice.

In the analysis of the acquisition of the chemical composition of sea ice, a number of processes have to be considered, including

1. - differential adsorption at the phase boundary
2. - selective incorporation into the ice structure

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 3. - differential diffusion into the liquid away from the phase boundary.

1. Differential adsorption

Differential adsorption of different cations can be considered as the first step of the incorporation of these cations in sea ice and will thus be considered with 2.

2. Selective incorporation

Cations and anions are incorporated into the ice lattice at different rates.

3. Differential diffusion

In 1956, Crank defined diffusion as "the process by which matter is transported from one part of a system to another as a result of random motions". Ions will diffuse following Fick's first law:

$$F_j = -D_j \frac{dC_j}{dx}$$

where F_j is the flux of cation j per unit area per unit time, dC_j/dx is the concentration gradient of cation j along the distance dx,

D_j is the diffusion coefficient of cations in seawater. The "self diffusion" coefficient is the diffusion coefficient of a given ion diffusing in a single salt solution of the same ion.

Self diffusion coefficients at infinite dilution and 0°C are:

-	K	0.99	$10^{-5} \text{ cm}^2/\text{se}$	ec			
-	Na	0.63	10 ⁻⁵ cm ² /se	ec			
-	Ca	0.37	10 ⁻⁵ cm ² /sec	2			
-	Mg	0.36	10-5 cm2/sec	c (Li	and	Gregory,	1974).

Under the electro-neutrality condition, diffusion coefficients D_j^* were obtained by the same authors. They are all greater than their respective self diffusion coefficients.

-	K	2.10	10-5	cm ² /sec
-	Na	1.64	10-5	cm²/sec
-	Ca	0.98	10-5	cm²/sec
-	Mg	0.98	10-	⁵ cm ² /sec

This means that any salinity gradient will provide a mechanism for the change of relative abundance of major ions in seawater. Thus, diffusion will occur if the concentration of an ion in the boundary layer is different from that of seawater. Differential diffusion of different cations depends on their respective diffusion coefficients.

In order to describe the whole phenomenon, a convenient way is to introduce the effective distribution coefficient.

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The effective distribution coefficient is defined as

$$k_{eff} = C_s / C_o$$

where C_s is the concentration of the cations in ice, and C_o is the concentration of the cations in water far away from the interface. The effective distribution coefficient varies from about 10^{-3} (Kvajic and Bryovic, 1971) to almost unity (Terwilliger and Dizio, 1970). It depends in a poorly known way (Terwilliger and Dizio, 1970, page 1332) on the freezing rate, on the concentration and the type of solute, on the temperature in the melt near the interface, on the mechanism of solute and heat transfer and on the crystallographic orientation of the growing ice crystals (Kvajic and Brajovic, 1971).

Few experiments have been performed with seawater to obtain values of effective distribution coefficients for different ions.

In Gross (1965), the distribution curves are given for a solution of different fluorides. The order of decreasing acceptability obtained by Gross is

 $NH_4 > Ca + > Na + > Li > K > H.$

These findings are only valid for the fluorides; in this case Ca is more incorporated into the ice lattice than K.

In the Malo and Baker (1968) experiments, made with

tapwater, Ca is more readily incorporated than Mg, which in turn is more readily incorporated than K in the ice. By considering distribution coefficients only, it is not possible to differentiate whether the dominant process is selective incorporation or selective diffusion.

III. ICE TYPES OF HELLS GATE ICE SHELF

A. Investigation Program

1. Ice Core Sampling

A preliminary study involved the analysis of a satellite photograph of Hells Gate Ice Shelf such as figure 40. Three types of ice can be distinguished, based on their color: glacier ice is whitish-blue; marine ice, greenish; and fast ice, white.

In general, since most Antarctic ice shelves are accumulating snow on their surfaces, their bottom ice layers cannot be reached unless expensive programs are undertaken, e.g., deep ice core drilling. In the case of Hells Gate Ice Shelf, mostly because of the intense surface ablation (see later on) an upward velocity component exists. Marine ice accreted at the bottom of the ice shelf initially is transferred along an inclined surface towards the iceatmosphere interface. In this case, a longitudinal line of shallow ice core drillings could advantageously replace deep core drilling.

Three main directions of sampling sites were decided upon. This is why the first transect of drilling sites was chosen to follow the western ridge of debris cones intersecting the three ice types perpendicularly. From the

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ice cliff toward the northwest, the sampling sites are:

- HG8, HG3, HG2, HG1, HG6 (bottom part) in the marine ice

- HG6 (top portion), HG12, HG13 in the continental ice. Along the second line from the ice cliff were retrieved

- HG4, HG16, HG17, HG18, HG20 in marine ice

- HG5 in continental ice,

- HG14, HG15, HG19, in basal ice.

The third line included

- HG23, HG24, HG25 in marine ice

- HG22, and HG21 in glacier ice.

From the western portion of fast ice located southwest of the ice shelf, two ice cores were retrieved: HG7 and HG9. Then HG10 and HG11 were drilled in the marine section of the shelf. Altogether, twenty-five ice cores, 1 to 1.5 m long, were retrieved from Hells Gate Ice Shelf during the 1989-1990 field season in Terra Nova Bay. The precise location of the drilling sites is indicated on figure 71.

When removing the core from the barrel of the ice corer, if separated pieces were found, each piece was labeled A, B, C,..., from top to bottom, after having discarded the top part in certain cases. Each piece was wrapped in a polyethylene bag, with its top at the closed end of the bag. The samples, placed in 1 m-long core tubes, were shipped frozen to the University of Brussels, Belgium and stored at -30° C until further processing.

The processing of cores for structural analysis began



Figure 71. Location of the drilling sites in Hells Gate Ice Shelf.

with the visual examination and sketching at 1:1 scale of each section of the cores. Any significant features such as the presence of bubbles, the location of sediment, and the variation in the translucence of the ice was carefully reported. The cores were also inspected for layering related to structural banding.

2. Crystallographic Method

Although the cores were not oriented azimuthally during drilling, reference marks were made on the cores to allow proper reorientation of the core sections with regard to the foliation for example. The 7.5 cm-diameter cores were sectioned every 10 cm at the maximum or at coring breaks. Plastic gloves were worn to handle the ice cores without contaminating them.

Contrary to general practice, vertical thin sections were cut for crystallographic investigation instead of the more common horizontal ones.

Vertical one centimeter thick sections were cut off with a band saw in a cold room at -25°C in Brussels. Prior to thinning the high-salinity fast ice and congelation ice, it was necessary to freeze down the edges of the samples with distilled water, to prevent them from slipping off the glass plates. The thick sections frozen onto glass plates were then thinned to approximately 0.4 millimeter with a microtome.

At this thickness, when the section is viewed between crossed polarizers, boundaries of individual crystals are clearly revealed in addition to brine channels and brine pockets.

Each vertical thin section was then photographed at full scale under crossed polarizers with a camera mounted directly above the Rigsby stage, to determine the types of ice present. Each thin section was labeled, wrapped in plastic to prevent sublimation, and stored at -30°C until further use.

Some horizontal thin sections were prepared in selected cases to help confirm the origin of the ice under investigation.

The position of the crystallographic c-axes, measured on the Rigsby stage, is accurate to within 5%.

3. Water Sampling

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Seawater samples were collected by an Italian team on a ship located off the front of Hells Gate Ice Shelf at

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74°52'52"S and 163°48'36"E. They collected the water at depths of 0.1, 10, 25, 50, 100, and 200 m. The water sample obtained at 25 m depth was discarded due to problems that occurred during handling and storing of the sample. The samples are referred to as W_1 , W_2 , W_3 , W_4 , and W_5 in table 15. Water samples were also obtained by R. Souchez near the ice cliffs at depths of 0.1, 10, 20, and 30 m. Data on these samples appear in Table 16 as W_6 , W_7 , W_8 , W_9 for the sampling site located at the edge of the fast ice area. Figure 71 shows the location of the sample sites.

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The samples collected by the Italians arrived in square 100cc polyethylene vials. Upon arrival at Brussels University, the bottles were stored in a refrigerator to await distillation of the samples. Souchez's samples were shipped in 35cc polyethylene bottles with screw-on caps. They were also set aside in a refrigerator, awaiting further analysis. After distillation in Brussels, the samples were sent to the Nuclear Research Center of Saclay in France.

Table 16 contains comprehensive results of stable isotope analyses of the water samples. HDO and $H_2^{18}O$ concentrations are denoted in δ units versus V-SMOW (Vienna Standard Mean Ocean Water), expressed in per mil. Measurement accuracy is 0.5% for δD and 0.1% for $\delta^{18}O$.

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WATER SAMPLES	DEPTH IN M	δD	δ180
Wl	0.1	-3.24	-0.63
W2	10.0	-3.76	-0.55
W3	50.0	-3.75	-0.24
W4	100.0	-4.24	-0.67
W5	200.0	-3.71	-0.38
W6	W6 0.1		-0.60
W7 10.0		-3.33	-0.69
W8 20.0		-4.43	-0.32
W9	30.0	-4.21	-0.58

Table 16: Isotopic Analyses of the Water Samples Collected Near the Hells Gate Ice Front.

4. Cation Content Analysis.

W11

W13

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4.1. The Process of Chemical Sampling

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Two vertical 1 cm-thick slices of ice were cut off each section of the marine ice cores using a band saw (see figure 72a). This was performed at -20°C in the cold room of the Geomorphology Laboratory of the University of Brussels.

-3.55

-3.36

-0.27

-0.81

The first thick section was used to determine the Na and Ca content, while a second was prepared and analyzed for the K and Mg content.

Each thick section was sawed into 0.5 to 0.7 cm slices to provide the samples for Na and Ca analysis (see figure 72b).

Figure 72a.

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Figure 72b.



Slicing of the thick section for chemical analyses.

A thick section procedure.

A precise record of the slicing procedure was kept in order to duplicate the slices as exactly as possible for the Mg and K content on the parallel slice.

Each sample was placed in a test tube, carefully sealed to avoid direct contact of the plastic cap with the ice, and prevent any possible contamination.

The test tubes and caps were rinsed three times with triple-distilled water to eliminate any surface contamination and were then placed in a drying oven. The test tubes containing the frozen samples were stored in a deep freezer until ready for analysis. At that time, they were retrieved and allowed to melt at room temperature.

A Varian Flame Atomic Absorption Spectrometer 300 was used to perform the analyses on all samples. Standard solutions were prepared for the four elements. Lanthanum $(10,000 \ \mu\text{g/ml})$ was added to the samples to eliminate chemical interferences in the air-acetylene flame (see table 17).

4.2. Disregarding the First 30 cm of Each Ice Core

The comparison of Na, K, Ca, and Mg profiles revealed an interesting similarity. All ice cores except HG7 showed an increased cation content deeper than 30 cm. HG7 constitutes an exception in the sense that this ice core is only 30 cm long. This lead to a discussion of the possible elimination of the upper 30 cm of each core.

4.2.1. Factors contributing to the salinity profile

Numerous authors have noticed salinity variation in their ice cores. Several factors are thought to contribute in different degrees to the salinity profile. Weeks and Ackley (1982) have summarized the general opinion. There are five main reasons to explain the salinity distribution in the ice cores:

- a. the initial amount of salt trapped in the ice
- b. the migration of liquid inclusions through the ice crystals
- c. brine expulsion

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- d. brine drainage
- e. flushing of brine

Element	Wave Length nm	Lamp Current mA	Slit Width nm	Acetylen Pressure hPa	e Flame Flow 1 min ⁻¹	A Pressure hPa	ir Flow 1 min ⁻¹
Na	330.2 589.6	10 10	0.2 0.5	63	2.2	350	13
K	766.5	10	1.0	63	2.2	350	13
Ca	422.7	5	0.5	63	2.2	350	12
Mg	285.2 202.6	5 5	0.5 0.5	63	2.2	350	13

Table 17. ATOMIC ABSORPTION SPECTROMETER VARIAN 300

- Precision is $\leq 3\%$ K, Mg, and Ca. For Na, this is only true in the case of $\lambda = 589.6$ nm. In the case of $\lambda = 330.2$ nm, precision is $\leq 6\%$.

- Burner: Varian Mark VI

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- Lamps: Varian Sodium/Potassium (Combined) Varian Calcium/Magnesium (Combined)

Na: Analyzed on $\lambda = 330.2$ nm, the optimum working range is 2-400 ppm

- If lower than 2 ppm, Na was analyzed on $\lambda = 589.6$ nm (optimum working range is 0.01-2 ppm)

- If the value obtained is above 100 ppm, the samples were diluted 5 times*

- Ca: If dilution is performed for Na, concentration for Ca is almost always inferior to 3 ppm which is the upper limit of the optimum working range for Ca (0.01-3 ppm).
- K: For K, concentration is almost always inferior to 1 ppm which is within the optimum working range for K (0.03-2 ppm).

Mg: Concentration for Mg is most of the time below 1 ppm which is the upper limit of the optimum working range for Mg (0.003-1 ppm). If it is not the case this researcher has used $\lambda = 202.6$ nm (optimum working range 0.15-20 ppm).

*If concentration of Na was above 500 ppm, the samples were diluted 10 times. Because of the dilutions performed, concentration of Na in samples never exceeded 100 ppm which implies that the matrix effects can be considered negligible.

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a. The Initial Amount of Salt

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Bennington (in Kingery et al, 1963) noticed that a very low ambient temperature along with the agitation of the sea, causes ice to retain a high salinity. Adams, French and Kingery (1963) noted that the amount of brine entrapped during the solidification of ice is directly related to growth conditions. When the growth rates are high, growth is dendritic and the trapped brine content is also high. After the first ice cover has provided some insulation, the agitation of the sea is very much reduced. The ice crystals formed within the sea water mass have a lower density than sea water. They move upward and float, causing a partial separation of the brine (Adams, French, Kingery, 1963). Indeed, the brine, being heavier, tends to sink, decreasing the salinity of the newly formed ice.

b. Migration of Liquid Inclusions Through the Ice Crystals

As early as 1926, Whitman demonstrated that a temperature gradient induces the formation of a concentration gradient in a brine pocket if phase equilibrium is to be maintained.

During the winter, when the upper saline end of a brine pocket is colder than the lower end, a diffusion of solute will take place from the top to the bottom of the pocket, causing the freezing of the top end. There, salts migrate toward the lower end, causing its melting.

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c. Brine Expulsion

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Bennington (1963) established that when ice is cooled, a pressure buildup occurs in the brine pockets, where the liquid portion of the inclusions has separated from the gas portion.

If pressure becomes sufficiently high, it causes the fracture of the ice surrounding the pocket. This in turn allows the brine to escape and migrate (Untersteiner, 1968), (Cox and Weeks, 1975).

d. Brine Drainage or Gravity Drainage

Kingery and Goodnow (1963), Knight (1962), and Lake and Lewis (1970), have worked on this topic. Brine drains out of the ice sheet under the influence of gravity. Gravity seems to be the most important mechanism for removing salt from natural sea ice into the underlying seawater. Martin and his colleagues (1971, 1974, 1975, and 1979) have shown that the drainage takes place in vertical tubular structures.

e. Flushing of the Brine

In spring and in summer, when the surface of the ice sheet melts, nearly pure freshwater percolates down the permeable ice. According to Untersteiner (1968), it is the most effective process to explain the low salinity of the upper layer of older sea ice.
4.2.2. Cation content as a function of depth

Table 18 contains the Na, K, Ca, and Mg content of each core in meq/1. The cation content was averaged as a function of depth. The left hand side columns represent the values above 30 cm (depth < 30cm); the right hand side columns show the values below 30 cm (depth > 30 cm).

HG17, HG18, HG23 and HG24 do not present any value in the left portion of the table because 30 to 40 cm of ice were discarded prior to shipment. The comparison of the cation content of the ice cores above and below 30 cm shows a systematic rise in salinity when depth increases.

4.2.3. Salinity analysis

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The study of the variation of the cation content required the making of numerous profiles. Each cation was represented separately and the profiles are placed hereafter.

While analyzing the four sets of cation profiles drawn for each core, it soon became apparent that a better way to compare the cores would be to regroup the four profiles on a single graph (see figures 73 to 84). To palliate the difficulties of representing the wide cation content range, a semi-logarithmic scale was used. The cationic content is expressed as the $\log_{10}(x/1000)$, where x is the concentration in ppm. This was done in order to obtain a common scale for all ice cores.

Generally, the examination of the graphs reveals that the

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Ice Cores	Na/K	Na/Ca	Na/Mg	Ca/Mg	Na+K/Ca+Mg	Na/K	Na/Ca	Na/Mg	Ca/Mg	Na+K/Ca+Mg
1	41.43	45.75	10.10	0.33	4.95	57.42	23.13	5.01	0.22	3.79
2	760.00	23.98	8.02	0.40	4.75	56.71	25.03	4.81	0.20	3.81
3	106.00	28.34	7.99	0.30	5.17	66.80	24.47	6.08	0.25	4.58
4	47.71	26.25	15.29	0.70	10.90	48.57	20.90	9.75	0.68	5.'78
6	30.33 449.00	16.55 18.63	3.25 5.04	0.20 0.30	2.80 3.19	58.17 58.94	24.07 24.87	4.92 5.27	0.20 0.22	4.15 4.25
7	72.22	29.96	5.72	0.19	4.81			-		
16	67.14	6.86	0.20	5.84	4.77	51.40	5.93	0.24	4.76	4.03
17						78.33	23.82	6.06	0.26	4.57
18						52.86	45.31	20.82	0.95	5.38
23						67.50	119.44	51.48	1.12	27.04
24						56.00	28.38	4.32	0.16	3.56
25		29.75	30.35	1.19	11.85		30.41	6.92	0.24	4.68

Depth <30 cm

Depth >30 cm

Table 18: Na, K, Ca, Mg content of each ice core as a function of depth in meg/1.

Dep	th	<30	CM
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Depth >30 cm

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Ice Cores	No. of Observations	Na	K	Ca	Mg	Σ4	Na	к	Ca	Mg	Σ4
1 *	32	0.29	0.007	0.01	0.05	0.36	4.02	0.07	0.17	0.91	5.17
2	34	0.76	0.001	0.04	0.12	0.93	3.97	0.07	0.16	0.90	5.13
3	27	3.18	0.03	0.12	0.50	3.83	3.34	0.05	0.14	0.60	4.13
4	35	0.32	0.007	0.01	0.02	0.36	0.34	0.007	0.02	0.04	0.41
6	22 26	1.82 4.49	0.06 0.01	0.11 0.22	0.56 1.19	2.55 5.91	20.94 21.22	0.36	0.87	4.26 4.20	26.43 26.65
7	30	16.61	0.23	0.57	2.93	20.34					
16	31	0.47	0.007	0.02	0.08	0.58	2.57	0.05	0.11	0.54	3.27
17					1		2.35	0.03	0.10	0.42	2.92
18							. 0.37	0.007	0.02	0.05	0.45
23							0.27	0.004	0.00	0.01	0.28
24							1.12	0.02	0.04	0.28	1.46
25	26	0.23	0.007	0.01	0.01	0.26	1.01	0.02	0.04	0.18	1.25

Table 18: Na, K, Ca, Mg content of each ice core as a function of depth in meg/l.



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Figure 73. Cations profiles: ice core 1.



Figure 74. Cations profiles: ice core 2.



Figure 75. Cations profiles: ice core 3.



Figure 76. Cations profiles: ice core 4.



Figure 77. Cations profiles: ice core 6.



Figure 78. Cations profiles: ice core 7.



Figure 79. Cations profiles: ice core 16.



Figure 80. Cations profiles: ice core 17.

Ice Core 18

Salinity Analysis



Figure 81. Cations profiles: ice core 18.



Figure 82. Cations profiles: ice core 23.





Figure 83. Cations profiles: ice core 24.



Figure 84. Cations profiles: ice core 25.



four cation profiles follow parallel trends. Na is the most abundant cation in each Hells Gate profile. The second most abundant cation is Mg for ice cores HG1, HG2, HG3, HG16, HG17, HG24 and HG25. For HG6 and HG7, the situation is different if we consider the concentration in ppm or in meq/l. In the latter case, the second most abundant cation is Ca.

Another group comprises 3 ice cores: HG4, HG18, and HG23. All three present important variations in their cation abundances. These irregularities are best shown by Ca: within a few centimeters, Ca presents the highest and the lowest possible abundance, as compared to cations K and Mg. Apart from this consideration, these cores are the least saline of all cores.

Focussing on the trend of the cation content profiles, HG1, HG2, HG6, HG16, HG25 are characterized by the sharp increase observed around the depth of 30 cm. At deeper levels on the contrary, the cation abundances are remarkably stable.

HG7 is first year very saline sea ice. A slight salinity increase can be observed, but this ice core is too short for us to discuss further its inclusion in this group (HG1, HG2, HG6, HG16, HG25). The cores displaying the sharpest increase are those where the top portion of the core was retained during the field campaign.

The preceding investigation clearly demonstrates that the upper part of the cores is subjected to various phenomena that lead to the elimination of salt. An accurate comparison of the cores has to be limited to the stationary portion of the profiles. This research deals with the selective incorporation of cations by the freezing of seawater, and not with the near-surface phenomena inducing salt removal.

5. Isotopic Sampling

5.1. Preliminary sampling

Each core was cut in half vertically. From one of these half cylinders, several thick sections were cut off using a band saw. The thick section slices were used for crystallographic investigations, for chemical and isotope analyses. The decision as to where to retrieve samples for isotopic analysis was based on the examination of the crystallographic and cation profiles.

Initially, in the cold room at -25° C, a 1.5 cm thick sample was cut from the base of each ice core to be used for isotope analysis. The sample was placed in a Petri dish and stored in the same cold room, awaiting analysis.

Numerous samples were taken in each ice core, either in homogenous crystallographic zones or at the boundary between structurally different zones. The main purpose was to obtain pertinent isotopic information relative to changes of structure and ice type.

5.2. Distillation procedure

The isotopic analysis of seawater and marine ice requires a vacuum distillation. This equipment, devised and perfected in the Laboratoire de Géochimie Isotopique in Saclay, France, was lent by J. Jouzel to R. Souchez and installed at the University of Brussels by J-L. Tison. The distillation itself was performed by J. Haren, laboratory technician in the Département des Sciences de la Terre.

Figure 85 is a sketch of the set-up of the vacuum distillation equipment used for the marine ice and seawater samples. Distillation is performed in a system comprising a vacuum line with six individual distillation devices (fractionating and collecting flasks) as indicated in figure 85. Distillation entailed the following steps:

a. The sample (3 ml) is placed in the fractionating flask which is dipped in liquid nitrogen to freeze it. After freezing, by opening stopcock 4, it is possible to reach a 10⁻² Bar vacuum in the system. After about 15 minutes, the stopcock is closed and the flask, after being removed from liquid nitrogen, is allowed to reach room temperature. In this manner, melting induces degassing of the sample.

b. As soon as melting is completed, the sample is allowed to freeze again. When the sample is completely frozen, the stopcock is opened to exhaust the gases and to restore the 10⁻² Bar vacuum. About 15 minutes later, the stopcock is closed, and the fractionating flask is removed from the liquid



nitrogen. The fractionating flask is then plunged into in lukewarm water to accelerate melting. At the end of this stage, the sample is considered to be fully degassed.

c. The sample is then frozen for the third time. By opening the cock, and with the aid of a mercury diffusion pump, a higher vacuum (10⁻³ Bar) is established and maintained for about half an hour. The cock is then closed and the fractionating flask, after removal from the liquid nitrogen, is allowed to melt at room temperature. The collecting flask is then placed in crushed ice to allow distillation to take place. At the end of this process, the residue is placed in a desiccator at 200°C. In this manner, 100% of the liquid is recovered.

The samples for co-isotopic analyses were brought to the Centre d'Etude Nucléaire de Saclay (Laboratoire de Géochimie Isotopique) in France, which is equipped with twin massspectrometers specially designed to measure deuterium and oxygen 18 concentrations simultaneously on the same liquid drop. The accuracy of the method is \pm 0.5 % on δ D and \pm 0.1 % on δ^{18} O. The complete results are presented in table 19 a and 19 b.

TABLE 19 a: ISOTOPE ANALYSES OF HELLS GATE ICE CORES

SAMPLES	6D%	\$180%	ICE TYPE
HG1c	21.90	3.03	P
HG1d	19.39	2.86	P

HGIf	18.20	2.47	F
HGIP	17.61	3.02	F
HG1k	17.62	1.86	F
HGln	18.03	2.39	F
HGlq	18.15	2.09	F(P)
HG1s	18.10	2.90	F
HClu	18.37	2.41	F
HG2c	22.08	2.36	F
HG2e	19.49	2.48	P
на2ј	18.66	2.31	F(P)
HG2m	14.97	1.64	r
HG2p	18.20	2.11	F
HG2u	18.92	1.99	F
BG2w	18.20	1.95	F
HG22	17.72	2.39	F
HG2aa	17.53	2.38	F
HG2bb	17.56	2.09	P
BG2cc	17.93	3.00	F
RG2hh	16.72	1.86	F
RG2jj	17.06	1.99	F
HG211	17.02	2.31	F
HG2mm	16.41	2.11	F
HG200	17.04	2.13	F
всзь	18.51	2.41	F
BG3c	18.11	2.34	P
HG3e	20.19	3.26	F
BG3g	18.51	2.73	F(P)
BG3h	17.96	2.23	F(P)
вазј	18.35	2.58	F

HG3n	17.72	1.83	F
H03o	18.63	1.90	F(P)
HG3q	17.82	2.40	P
HG3v	17.45	2.15	F
HG3 z	17.06	2.32	F
HG4c	19.23	2.59	F
HG4e	18.24	2.71	P
HG6c	-160.78	-20.79	
HG6d	-18.12	-2.82	
HG6e	-40.06	-5.24	1.1
HG6f	-69.85	-9.57	
RC6g	-100.43	-12.91	
HG6h	-130.56	-16.17	
HG61	-7.38	-1.04	
нсеј	9.76	1.14	c
HG6k	11.17	1.52	c
HG61	14.91	1.64	c
HG6m	16.01	2.02	C(P)
HG6n	23.32	2.08	Р
HG60	19.75	2.13	P(C)
НСбр	16.09	2.51	Р
HG6t	16.57	2.09	
HG7a	11.55	1.74	c
HG7b	10.96	1.57	C(F)
HG7c	11.01	1.14	с
H07d	10.46	1.45	F
HG16g	18.84	2.45	P(F)
HG16n	18.03	2.25	F
HG16g	18.94	2.41	F

HG16r	18.81	2.34	P
HG16s	20.67	2.94	F
HOL6t	19.22	2.71	F(P)
HG16ff	18.10	2.52	P(F)
HG17b	19.08	2.10	F
HG17d	15.78	2.67	
HG17g	20.24	2.58	r
HG17h	18.52	2.88	
HG171	19.26	2.58	P
HG17j	19.07	2.59	P
HG17k	15.51	1.95	F
HG171	17.91	2.99	F
HG17n	19.32	2.17	P
HG170	19.09	2.94	F
HG17q	18.96	2.76	F
HG17r	18.50	2.47	F
HG18(1)al	17.51	3.19	F
HG18(1)a2	18.55	2.73	
BG18(1)c1	19.01	2.46	F
HG18(1)c2	24.26	2.92	1
HG18(2)a	19.11	2.62	F
HG18(2)b	18.28	1.82	
HG21a	-184.72	-23.24	
HG22a	-245.62	-30.55	
HG23a	15.75	2.12	P
HG23b	16.48	2.12	P
HG24a	18.41	2.70	F
HG24b	24.48	2.21	
HG24d	19.02	2.23	r

HG24h	16.56	2.25	F
HG24k	18.03	2.48	F
HG241	17.84	2,62	
HG240	16.04	2+79	F
HG25b	19,89	2.02	F
EG25h	18.74	2,56	P
HG251	18.42	2.48	P
HG25j	18.70	2.14	F
HG25k	18.67	2.57	F
NG25n	19.22	2.67	
HG25r	18.07	2.56	F
HG25s	17.34	2.39	
B025u	18.49	2.13	,

SAMPLES	éD s	5 ¹⁸ O%
HGS	-220.91	-28.21
HG8	19.69	2.28
HG10	18.18	2.45
BG11	17.92	2.15
HG12	-239.77	-31.71
HG13	-214.88	-26.78
HG14	-30.03	-3.07
HG15	-98.90	-12.05
H019	-159.36	-20.72
H020	3.70	-0.33
8621	-150.93	-19.76
BG22	-200.55	-26.25

TABLE 19 b: ISOTOPE ANALYSES OF THE BOTTOM SAMPLES OF HELLS GATE ICE CORES

F : frazil ice;

F(P) : mainly frazil ice containing platelets;

P(F) : mainly platelets ice containing frazil;

C : congelation ice;

C(P) : mainly congelation ice containing platelets;

C(F) : mainly congelation ice containing frazil.

The isotopic analyses were mapped on figure 86. Each rectangle presents the isotopic range observed in each ice core. In certain cases, only one value is shown. It corresponds to the value presented in table 19 b for the



Figure 86. Map of the isotopic analyses of the Hells Gate Ice Cores.

bottom samples of the Hells Gate Ice Cores. The isotopic values reflect the kind of ice that was retrieved in each sampling station. Positive values indicate marine ice and annual sea ice, while negative values are observed in continental ice.

B. Continental Ice

1. Glacier Ice.

1.1. Formation

Glacier ice is formed by the metamorphism of snow and firn. This process involves the gradual elimination of pore space between the individual ice grains, until the pores become sealed off to form individual bubbles. This process occurs in response to steadily increasing overburden pressure, and is accompanied by progressively increasing density. When the pores become completely sealed off, the firn is said to have transformed into bubbly glacial ice. This change occurs at densities of 0.82 - 0.84 10³ kg/m³.

This transformation of snow to ice is also accompanied by significant changes in the size and shapes of the crystals. The time needed to transform snow to ice in polar glacier is much longer than in temperate glaciers, mainly because of the much lower temperature (it rarely reaches the ice melting temperature). In the colder parts of Antarctica, this process can take as long as a thousand years or more to accomplish.

1.2. Structure

The structure of the ice refers to the size and the shape of its crystals. Because Hells Gate glacier ice has been deformed by flow, it shows elongated features, such as tubular bubbles, alignment of small round bubbles and structural discontinuities. The study of the tubular bubbles observed in thin sections could have been used to infer the metamorphic and dynamic history of Hells Gate. Unfortunately, the Hells Gate ice cores could not be oriented in the azimuth during drilling. It was then not possible to determine directly the link between the direction of flow and the variation of the ice fabrics. Instead, the analysis of the aerial photographs provided the researcher with pertinent information concerning ice flow directions and localization of shear zones from a study of the debris cones.

1.3. Crystallographic Properties

The crystalline texture of glacier ice is easily recognized when thin sections are viewed between crossed polarizers. This procedure allows for identification of the sizes and shapes of individual crystals and their relationship to entrapped air bubbles. The crystal diameters generally range from one and two centimeters, but occasionally larger crystals are present. These larger crystals may reflect recrystallization at elevated temperatures. Two examples of the structural characteristics of Hells Gate glacier ice are shown on figures 87 and 88.

Based on the preceding description, five of the twentyfive ice cores examined fall into the glacier ice category: HG5, HG12, HG13, HG21, HG22 and the upper part of HG6. A detailed discussion of the crystal structures of these glacial ice cores and fabric diagrams of selected vertical thin sections is presented in section 1.6. The fabric diagrams were constructed from measurements of c-axes, made on the Rigsby Universal Stage and plotted on the lower hemisphere of the Schmidt equal area net.

1.4. Isotopic Ranges

The isotopic values of the glacier ice samples are reported in Table 20.

Glacier ice is characterized by low δD values due to the depletion in heavy isotopes of the precipitation, from which the glacier ice in Antarctica is derived. The minimum value of δD observed on Hells Gate Ice Shelf is -245 ‰ for HG22. The maximum is -150.93 ‰ for HG21. The δ^{18} 0 values corresponding to the δD range are -19.76 ‰ to -31.71 ‰.





Figure 88. Photograph of HG6A3: glacier ice overlying marine ice.

Ice Cores	δD (in ‰)	δ ¹⁸ O (in ‰)
HG 5	-220.91	-28.21
HG 6	-160.78	-20.79
HG12	-239.77	-31.71
HG13	-214.88	-26.78
HG21	-184.72	-23.24
	-150.93	-19.76*
HG22	-245.62	-30.35
	-200.55	-26.25*

Table 20: δD and $\delta^{18}O$ Values of Glacier Ice

* Bottom of core

An examination of figure 71, the map of the drilling sites, reveals that in the central sector of Hells Gate, two cores of glacier ice were retrieved: HG21 and HG22 downstream from HG21. In the western sector, from north to south, are HG13, HG12, HG6 and HG5. HG6 and HG5 are located at about the same distance from the ice shelf front and are surrounded by marine ice.

Two samples were taken for HG21 and HG22, the first near the top of the core, the second at its base. A significant difference exists between the two isotopic values of each core. This difference could be due to an altitude effect of the source area or a climatic influence. Although no systematic study has been conducted to understand the variation in isotopic composition of Hells Gate glacier ice, an altitude effect, related to different sources of ice, is probably the cause of the difference in isotope values between HG12 and HG13, and HG21 and HG22. Indeed, the latter ice originates from lateral tributaries of Priestley Glacier: Browning Pass and Boomerang glaciers are possible candidates. As can be seen on the aerial photograph, figure 89, the likely source of ice of HG21 and HG22 cores is from the north between Vegetation Island and the Northern Foothills.

The δD values of all the glacier ice samples were plotted versus their $\delta^{18}O$ values with $\delta^{18}O$ as the abscissa and δD the ordinate. The least squares regression line's equation is

 $\delta D = 7.96 (\delta^{18}O) + 4.09.$

The slope of the regression line is 7.96, which can be considered as a precipitation slope. Such a slope is a characteristic of snow and glacier ice that has not been subject to major isotopic changes since its formation (Souchez and Lorrain, 1991). As mentioned previously, the line on which the δD and $\delta^{18}O$ plots are located is the meteoric line. Its equation is $\delta D = 8 \ \delta^{18}O + d$.







Figure 90: $\delta D - \delta^{16} O$ - Glacier Ice Regression Analysis

1.5 Chemistry

The cationic content of the glacier ice samples has not been determined in this study. Only Na has been roughly estimated on the basis of published values. In figure 91, the estimated Na content indicated is less than 1 ppm (part per mil). It is highly probable that this glacier ice contains much less sodium, but this lack of precision does not affect the differentiation among the types of ice present in Hells Gate Ice



Figure 91. Ice types of Hells Gate. δD as a function of Log(Na).
Shelf, as shown in figure 91.

On this figure, δD is the ordinate and $Log_{10}(Na)$ (a proxy for salinity) is the abscissa. The three ice types are clearly separated. Glacier ice has very negative δD values and extremely low salinity. Both congelation and frazil ice have positive δD . Congelation ice has a higher Na content (salinity) than frazil ice. However, the range of values for marine frazil ice is very much larger than for congelation ice. Reasons for this difference are discussed in the marine ice section.

1.6. HG Cores of the Glacial Ice Class (location and crystallographic analysis)

The fabric diagrams of HG5, HG6, HG12, HG13, HG21, and HG 22 are shown in figures 92, 94, 96, 97, 100, 101. The crystallographic profiles of these ice cores are presented in figures 93, 95, 98, 99, 102, and 103.

HG5 is situated in the shear zone separating the western from the central sector of Hells Gate. The ice fabric diagrams of HG5 demonstrate clearly the effects of vertical or nearvertical shearing upon the distribution of c-axes. Almost all c-axes are horizontal and concentrated in one single maximum. HG5B2, HG5(1), HG5(1+2), HG5C(2+3) and HG5B3 are very good examples of the effects of shearing (see figure 92).

When glacial ice is subjected to shearing, the c-axes tend

Figure 92. ICE FABRIC DLAGRAM FOR ICE CORE HG5





Figure 93.

Crystallographic profile of HG5.

Figure 94. Ice fabric diagrams of HG6.



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Figure 96. ICE FABRIC DLAGRAM FOR ICE CORE HG12

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Figure 97. ICE FABRIC DLAGRAM FOR ICE CORE HG13







Figure 99.

Crystallographic profile of HG13.

Figure 100. ICE FABRIC DLAGRAM FOR ICE CORE HG21



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Figure 101. ICE FABRIC DIAGRAM FOR ICE CORE HG22







to become concentrated into a single maximum, as observed in HG5 core fabric diagrams. This relationship was documented in the field by Rigsby (1955). The effects of shearing can be seen with the naked eye in this ice core. Tubular bubbles, alignment of small rounded bubbles and structural breaks constitute the response of the ice to the shearing stress.

Also many of the crystals display undulose extinction between crossed polarizers. This is a typical observation in crystals subjected to large shearing stresses (see for example Rigsby, 1955, and Gow and Williamson, 1976).

Among ice cores not located in the shear zone, HG12 shows a girdle-type orientation of the c-axes. HG13, HG21 and HG22 exhibit a broader concentration of the c-axes than seen in HG5 from the shear zone.

HG6A1 is the vertical thin section of the non-marine ice at the top of HG6, the only core showing the transition from glacial to marine ice. HG6A1 is most certainly glacier ice below which congelation ice was accreted at the bottom of the ice shelf. The incomplete girdle-like fabric diagram shows two slight concentrations in the horizontal plane for the glacial component. No systematic pattern of oriented c-axes was observed in the saline ice.

2. Basal Ice of Continental Origin

2.1. Characteristics

Basal ice is a kind of continental ice that contains debris. The debris embedded in the ice consisted of weathered granitic rock fragments (HG19 and HG15) and sand-sized particles (HG14). All three basal ice cores were obtained in the shear zone.

2.2. Structure and crystallographic properties

The crystalline structure of basal ice is often quite dissimilar from the structure of continental glacier ice. All cores lacked any visible trace of entrapped air bubbles and were generally much coarser-grained than continental glacier ice. The three ice cores in this group contain variable amounts and sizes of debris. HG14 contains the least basal debris and thus was the easiest to work with to obtain the vertical thin sections. For HG15, containing large amounts of medium-sized debris, it was very difficult to calibrate the diamond-wire saw to produce thin sections of the desired thickness. As a result, the photographs of the thin sections HG15A1, HG15C2 and HG15D1 are thinner than the desired 0.4 mm, as witnessed by their poorly contrasted colors when viewed between crossed polarizers.

In the case of HG19, the debris embedded in the ice,

although weathered superficially, was so hard that the diamondwire saw broke while cutting into the bottom part of the core. This bottom section was composed of thin silty ice surrounding a large pebble. A second attempt to cut through the debris caused so much damage to the machinery that it was decided to leave HG19(1) uncut. The fabric diagrams of HG14, HG15, and HG19, are presented in figures 104, 106, and 108. The corresponding crystallographic profiles are shown in figures 105, 107, and 109. The ice fabric of HG19(2)Al shows one localized maximum.

HG15C1 shows numerous small crystals accumulated in a V-shaped wedge contained in much coarser-grained ice. The corresponding ice fabric, HG15 V, has a single maximum, probably confirming the formation of the wedge as a response to shearing. The c-axes of the small crystals of HG15 show a broad single maximum in the horizontal plane while the c-axes of the large crystals are more randomly oriented.

The crystals in ice core HG14 are so large that the fabric diagram is based on three thin sections HG14A(3+4+5) of the same relative orientation. The fact that ice core HG14 was retrieved from the shear zone is clearly indicated by the development of a broad c-axis maximum in the horizontal plane.

Figure 104. ICE FABRIC DIAGRAM FOR ICE CORE HG14



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Figure 106. ICE FABRIC DIAGRAM FOR ICE CORE HG15







Figure 108. ICE FABRIC DLAGRAM FOR ICE CORE HG19





Figure 109. Crystallographic profile of HG19.

2.3. Isotopic values

The isotopic values of the three cores belonging to this category of ice are given in table 21.

Ice Cores	δD (in ‰)	δ ¹⁸ O (in ‰)
HG14	-30.03	-3.07
HG15	-98.90	-12.50
HG19	-159.36	-20.76

Table 21: Isotopic Values of Basal Ice of Continental Origin.

These three samples were plotted on a $(\delta D - \delta^{18}O)$ graph, together with the glacier ice samples. The regression line is $\delta D = 7.96 (\delta^{18}O) + 4.09$. $r^2 = 0.981$, which is identical to the value obtained for glacial ice samples only.

The very high value of the square of the correlation coefficient indicates a strong positive linear dependence between the two variables. Over 98% of the variance of δD is explained by the presence of $\delta^{18}0$.

The variability of deuterium is 7.96 times the variability of δ^{16} 0 less 4.09. This exceptionally strong relationship is illustrated on figure 110: the three samples of basal ice are perfectly aligned on the regression line that includes the



Continental Glacier Ice * Continental Basal Ice

Figure 110: $\delta D - \delta^{10} O$ Continental Ice Regression Analysis

glacial ice samples. The basal ice cannot be distinguished on isotopic grounds from glacier ice. Only their debris content indicates a subglacial origin. The location of the three basal samples in the isotopic meteoric line possibly also demonstrates that the incorporation of debris into this ice was not the result of melting and refreezing. However, the δD and $\delta^{18}O$ values are very much less negative than those of the continental glacier ice. The fact that the basal ice cores are coarsegrained and bubble-free, as well as depleted isotopically, might suggest that this kind of ice was formed by refreezing of waters of mixed origin. The exact origin of this so-called basal ice is difficult to determine without deeper core drilling, preferably to the bottom of the Hells Gate Ice Shelf at continental, basal ice-shear zone, and marine ice locations.

C. Marine Ice

There are two types of marine ice based on differences in texture, congelation ice and frazil ice.

1. Congelation Ice

1.1. Formation

Congelation ice forms by direct freezing of seawater to the underside of an ice sheet. Congelation ice exhibits three characteristics. First, the crystals (= columnar-shaped crystals) are vertically elongated, with cell structure elongations parallel to the direction of the heat flow. Second, congelation ice crystals generally have their c-axes all oriented within a few degrees of the horizontal plane (Weeks and Ackley, 1982). Third, as columnar ice develops, salt, that can neither be rejected from the ice/water interface, nor incorporated within the ice lattice, is segregated as brine pockets in layers located between the characteristic substructure of ice plates composing the elongate columnar crystals (see figure 111).

Ice formed in this fashion shows a spacing of the brine layers that is dependent upon the freezing rate. If the freezing rate slows down, the spacing of the brine increases, reducing the salinity of the ice. Conversely, more rapid growth





HG 9 A(2) VERTICAL SECTION

.HG 9 A(3) VERTICAL SECTION



HG 6

HORIZONTAL SECTION



HG 9 HORIZONTAL SECTION



Figure 111. Examples of congelation ice.

results in narrower plate spacing and higher salinity (Weeks and Ackley, 1982; Gow et al, 1987).

In nature, even small changes in the thermal regime, such as the daily temperature range, can produce important changes in the brine inclusions. As this researcher proceeded with the taking of photographs of congelation ice, the heat of the microscope bulb began to produce changes in the geometry of the brine inclusions. Originally disconnected brine inclusions tended to coalesce into channels. It soon became obvious that, in order to accurately document the ice structure, photographing thin sections of congelation ice under the microscope had to be made at the lowest possible temperature (-30°C). It also had to be performed fast enough to prevent thermally activated redistribution of brine.

Figure 112 is an enlarged photograph of ice platelet/brine layers substructure in congelation ice in core HG9.

Table 22 presents the isotopic values of the congelation ice samples observed in HG6 and HG7.



Figure 112.

 Enlarged photograph of ice platelet and brine layers sub-structure in congelation ce (ice core HG9).

Ice Cores	δD (in ‰)	δ ¹⁸ O (in ‰)
HG6(8)	14.91	1.64
HG6(9)	9.76	1.14
HG6(10)	11.17	1.52
HG6(11)	16.01	2.02
HG7(1)	11.55	1.74
HG7(3)	10.96	1.57

Table 22: Isotopic Values of Congelation Marine Ice.

 δD varies between +9 and +15%. $\delta^{10}O$ ranges between 1 and 2%.

1.2. Chemistry

Congelation ice has a very high content in Na (300-500 ppm). To study the possible relationships between the isotopes, Na content and texture in the marine ice of Hells Gate, two graphs were made. The first, figure 113, plots salinity (estimated from the Na content) versus δ^{18} O. The second, figure 114, plots salinity versus δ D. On both graphs, congelation ice isolates itself by its high salinity accompanied by rather low positive δ values. Frazil and platelet ice plots are intermingled around an average value of 2.4% for δ^{18} O and 18.2 for δ D. Another feature of the plots is the linear





∂Din‰

▲ Congelation

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Platelet

+

◇ Frazil

Table 23. Data used to produce figure 113.

			Platelet	
Na in ppm	2 18 O in ‰	Na in ppm	∂ 18 O in ‰	Na in ppm
5	2,99	65	2,09	70
12	2,17	60	2,31	40
25	2,94	90	2,73	45
75	2,78	55	2,23	150
170	2,47	25	1,90	38
65	3,19	45	2,45	5
215	2,46	3	2,71	40
125	2,62	3	2,52	102
65	2,12	5	1	
20	2,12	10	1	
120	2,70	20		
47	2,23	20	Congelation	
102	2,25	30	2 18 O in ‰	Na in ppm
55	2,48	25	1,64	320
75	2,79	20	2.02	340
130	2,02	6	1,14	468
100	2,56	9	1,52	420
145	2,48	10	1,74	320
103	2.14	25	1.57	440
180	2.57	10	1.14	460
110	2.56	50		
198	2.39	65		
115	2.13	30		
150	1			
30				
200				
75			1.1	
170				
110				
50				
115				
8		-		
7				
80				
40				
45				
62				
42				
27				
115				
95	1			
	Na in ppm 5 12 25 75 170 65 215 125 65 215 125 65 20 125 65 20 125 65 20 125 65 20 120 47 102 55 75 130 100 145 103 100 145 103 100 110 198 1150 30 200 75 110 100 1010 50 115 8 7 80 40 42	Na in ppm ∂ 18 O in ‰ 5 2,99 12 2,17 25 2,94 75 2,78 170 2,47 65 3,19 215 2,62 65 2,12 20 2,12 120 2,70 47 2,23 102 2,70 47 2,23 102 2,70 47 2,23 102 2,25 55 2,48 75 2,79 130 2,02 100 2,56 145 2,48 103 2,14 180 2,57 110 2,56 198 2,39 115 2,13 150 30 200 75 170 110 50 115 8 7 80 40	Na in ppm ∂ 18 O in ‰ Na in ppm 5 2,99 65 12 2,17 60 25 2,94 90 75 2,78 55 170 2,47 25 65 3,19 45 215 2,46 3 125 2,62 3 65 2,12 5 20 2,12 10 120 2,70 20 47 2,23 20 102 2,70 20 47 2,23 20 102 2,79 20 130 2,02 6 100 2,56 9 145 2,48 25 75 2,79 20 130 2,02 6 100 2,56 9 145 2,48 10 103 2,14 25 180 2,57 10	NaNaPlateletNa ∂ 18 O in %Na ∂ 18 O in %52,99652,09122,17602,31252,94902,73752,785552,231702,472251,90653,194552,452152,4632,711252,6232,52652,1251202,121011202,70202472,2320Congelation1022,79202,024772,2330 ∂ 18 O in %552,482551,64752,79202,021302,0261,141002,5691,521452,48101,741032,14251,571802,57101,141102,56501982,39651152,1330200

Table 24. Data used to produce figure 114.

Frazil				Platelet	
∂Din‰	Na in ppm	∂Din‰	Na in ppm	∂ D in ‰	Na in ppm
21,90	5	17,91	65	18,15	70
19,39	12	19,32	60	18,66	40
18,20	25	19,09	. 90	18,51	45
17,61	75	18,96	55	17,96	150
+ 17,62	170	18,50	25	18,63	38
18,03	65	17,51	45	18,84	5
18,15	215	19,01	3	19,22	40
18,37	125	19,11	3	18,10	102
22,08	65	15,75	5		P
19,49	20	16,48	10		
14,97	120	18,41	20		1.1.1.1.1.1.1.
18,20	47	18,64	20	Congelation	
18,92	102	16,56	30	∂ D in ‰	Na in ppm
18,20	55	18,03	25	14,91	320
17,72	75	18,04	20	16,01	340
17,53	130	19,89	6	11,17	420
17,58	100	18,74	9	9,76	468
17,93	145	18,42	10	11,55	320
16,72	103	18,70	25	10,96	440
17,06	180	18,67	10	11.01	460
17.02	110	18.07	50		
16,41	198	17.34	65		
17.04	115	18.49	30		
18.51	150				
18,11	30				
20,19	200				
18.35	75		1	-	
17.72	170	1			
17.82	110				
17 45	50				
17.06	115			-	
19.23	8				
18 24	7	-			
18.03	80				
18 94	40				
18.81	40				
20.67	62			-	-
10.00	42				
20.24	42				
10.24	115				-
19,28	115			-	
15,51	90			-	
	-				
			1	1	

relationship of the stable isotope values to the Na content. Also, Na content of congelation ice is in all cases appreciably more saline (higher Na content) than platelet or frazil ice types. The isotopic values used to plot isotope versus salinity estimated by Na content are reported in tables 22 and 23.

The values of δ^{1*} O observed by Craig and Gordon (1965) in Antarctic Bottom Water are approximately -0.5‰. Jacobs (1970, 1982), studying the Antarctic Surface Waters, found more negative values along the coastline, resulting from the melting of glacier ice.

The waters sampled off Hells Gate ice front are all negative, ranging from -0.24 to -0.81‰ for the most negative water. This leads us to believe that most Hells Gate marine ice samples were formed from a parent water whose δ -values fit within the range of values obtained by Jacobs (see figure 115). Figure 115: Range of Isotopic Values Obtained by Jacobs.



2. Frazil Ice

2.1. Formation

Initial ice formation in the sea occurs at or near the surface of the seawater in the form of small platelets and needles called frazil. Frazil and frazil-like ice crystals can also form at depth in the water column. Weeks and Ackley (1982) have proposed several different mechanisms to explain frazil formation.

2.1.1. Wind and Wave Induced Turbulence

Turbulence in the water column seems to be the most important factor for frazil production in leads, polynyas and marginal ice zones. The wind agitates the surface of the sea. Contact between air below the freezing point and seawater produces a slush-like mass of ice made of tiny crystals that will accumulate at the surface of the sea. This form of turbulence is confined to the upper part of the ocean. This kind of frazil crystals generally exhibits randomly oriented caxes.

Once a continuous ice sheet covers the ocean, windand wave-induced turbulence in the underlying water is significantly reduced (Weeks and Ackley, 1982). Further growth of sea ice occurs by direct freezing of seawater to the underside of sea ice.

2.1.2. Supercooling

The freezing point of water is depressed with increasing pressure. Foldvik and Kvinge (1974) were the first to show the implications of supercooling in ice formation. When ascending water becomes supercooled, it produces nearly pure frazil crystals. Lower in density than the surrounding water, the crystals ascend and accumulate to the underside of existing ice sheets (Weeks and Ackley, 1982). This process is described by Weeks and Ackley (1982) as adiabatic expansion of seawater. By floating upward as crystals or clumps of crystals, frazil aggregate (Gow et al, 1987). Clumps of crystals even as large as several cubic meters can accumulate under an ice shelf as reported by Maykut (1985). Divers have observed accumulations of slush to the underside of congelation ice that are eventually turned into a solid layer by upward loss of heat through conduction. A new layer of congelation ice can form later on below the frozen frazil (Weeks and Ackley, 1982).

2.1.3. Double diffusion

Rejection of salt and drainage of brine from ice covers (Untersteiner, 1968) can result in the formation of cold brine plumes which, as they descend and come in contact with less saline water, can cause nucleation of ice crystals by double diffusion.

This will happen if both water masses, the high salinity
water and the local water, are at their respective freezing points. Weeks and Ackley (1986) observed that freezing occurs due to double diffusion because the transfer of heat (diffusion coefficient on the order of 10^{-2} cm²/sec) takes place at a faster rate than the transfer of salt (diffusion coefficient on the order of 10^{-5} cm²/sec; Terwilliger and Dizio, 1970).

2.2 Isotope and chemistry.

The δD values of frazil ice vary between 22.08% for HG24b and 14.97% for HG2m. The $\delta^{16}O$ values of frazil ice range from 3.19% for HG18(1)al to 1.64% for HG2m. The complete isotope analyses can be found in table 19a. The relationship between the isotopes and Na content is illustrated in figures 113 and 114.

Frazil ice cannot be distinguished from platelet ice because the plots are intermingled. The salinity of the ice samples was inferred from the Na content. This practice is generally accepted since NaCl is usually considered to be chemically conservative. Elemental ratios are then calculated relative to Cl or Na (Duce *et al*, 1972). Furthermore, this can be illustrated by considering the following example. Cragin *et al* (1983) plotted Na concentration versus salinity of samples collected from the McMurdo Ice Shelf. The plots showed a linear relationship with a least squares slope of 0.299 (r=0.972) that agrees well with the expected slope of 0.319 for unfractionated seawater.

The Na content of the frazil ice samples ranges from 215 ppm for our high salinity samples (HG17) to 3 ppm for the least saline of our samples, represented by HG4, HG18, and HG23.

D. Structural analysis of marine ice

The Hells Gate marine ice has been subdivided into two categories according to their structural characteristics:

1. Congelation ice

Congelation ice is separated into two categories: first-year congelation sea ice formed from the freezing of seawater in front of Hells Gate Ice Shelf (as represented in HG7), and congelation ice frozen onto the bottom of Hells Gate Ice Shelf (as observed in HG6).

2. Frazil

Frazil ice crystals occurred in a variety of shapes and sizes; they have been divided texturally into four groups:

* the first group comprises equi-granular frazil ice subdivided on the basis of grain size into

- fine-grained,
- medium-grained,
- coarse-grained.

* the second group includes

- "banded" or "wave-like" crystals1
- rectangular crystals² (see figure

The term "banded" frazil (see figure 117) was used by Gow et al (1987) to describe horizontal plates with vertical

c-axes. "In the water column beneath an existing ice sheet, the plates tend to stay horizontal, a process leading to "banded" frazil or layers exhibiting aggregate vertical c-axes orientation when vertical thin sections are viewed between cross polaroids."

- * the third group is composed of platelet ice (see figure 118); the term was introduced in 1966 by Paige in reference to sub-ice platelets and was used by Gow et al, 1982) to describe large plate-like crystals measuring one centimeter or more across and even wafer-like crystals.
- * the fourth group consists of first-year granular ice. It is rarely observed among the twenty-five ice cores of

¹ known also as wafer-like crystals (Gow et al, 1987)

² known also as tabulate crystals (Gow et al, 1987)

^{116).}





Figure 117. Frazil ice: wave-like or "banded" crystals (HG24(4)).





Hells Gate Ice Shelf. It was only observed in core HG7.

There also exists an undifferentiated frazil type confined to very few ice samples; it represented only 0.6% of Hells Gate marine ice.

3. The overall structural composition

Details of the overall structural composition of the twelve marine ice cores can be found in tables 25, 26 and 27.

Altogether, congelation ice represents 3.9% of the ice cores: 1.6% of first-year congelation ice and 2.3% of congelation ice found in HG6 (see description of the core for details).

Uniform-sized granular ice represents 46.2% of the twelve ice cores, and 47.0% of the marine ice per se (after removing the top part of HG6 composed of glacier ice).

The second group comprised 18.9% of the twelve ice cores (19.2% of marine ice) and 21.6% (22.0% of marine ice) of rectangular frazil. Eventually, when presenting the results of the factor analysis applied to structural characteristics, these two classes will be combined.

Ice core	First year granular	First year congelation	Congelation ice	Fine-grained frazil ice	Medium-grained frazil ice	coarse-grained frazil ice	Wave-like rectangular	Rectangular frazil	Platelet ice	Glacier ice	Indifferentiated	Total
1						20	60					80
2						3	14	67				84
3						32	5	9				46
4				80								80
6			19				5		37	13	4	78
7	21	13										34
16						37	22				_	59
17						7	44					51
18					119							119
23						48						48
24				13	6	5		28			1	53
25						4	3	71				78
Total	21	13	19	93	125	156	153	175	37	13	5	810
Tot. % gl. ice included	2.6	1.6	2.3	11.5	15.4	19.3	18.9	21.6	4.6	1.6	0.6	100%
Tot. % without gl. ice	2.6	1.6	2.4	11.7	15.7	19.6	19.2	22.0	4.6		0.6	100%

Table 25: Overall Composition of Hells Gate Ice Cores

Each figure in the table represents the number of slices of ice corresponding to each category, including slices with missing data.

Ice core	First year granular	First year congelation	Congelation ice	Fine-grained frazil ice	Medium-grained frazil ice	coarse-grained frazil ice	Wave-like rectangular	Rectangular frazil	Platelet ice	Glacier ice	Total	Indifferentiated
1	1					14	31				45	
2						3	13	47			63	
3						25	5	9			39	
4				73							73	1
6			16				2		12	12	42	4
7	2	2									4	
16						32	20				52	
17	-		-		-	6	43				49	
18					113						113	
23	1					39					39	
24				11	5	4		26			46	1
25				-		4	3	64			71	
Total	19	11	16	84	118	127	117	146	12	12	662	6

Table 26: Overall Structural Composition of Hells Gate Ice Cores Absolute Values

Each figure represents the number of slices of ice for which all chemical data were available.

Ice core	First year granular	First year congelation	Congelation ice	Fine-grained frazil ice	Medium-grained frazil ice	coarse-grained frazil ice	Wave-like rectangular	Rectangular frazil	Platelet ice	Glacier ice	Indifferentiated	Total
1						25.0	75.0					100
2			1			3.5	16.7	79.8				100
3						69.6	10.9	19.5				100
4		-		100								100
6			24.4				6.4		47.4	16.7	5,1	100
7	61.7	38.3										100
16						62.7	37.3					100
17						13.7	86.3					100
18					100							100
23						100						100
24				25.0	11.5	7.7		53.9			1.9	100
25						5.1	3.9	91.0				100
Total	2.6	1.6	2.4	11.7	15.7	19.6	19.2	22.0	4.6		0.6	100

Table 27: Overall Structural Composition of Hells Gate Ice Cores Values in Percents

Each ice core has been subdivided according to its structural composition.

The third group, platelet ice, was of limited occurrence representing only 4.5% (or 4.6% of marine ice after removing the glacier ice from the top of core HG6).

The fourth group, first-year granular ice, represented only 2.6%. The rare occurrence of first year granular ice in the twelve ice cores sampled in Hells Gate reflects the fact that HG7 was the only ice core from a fast ice site. A second fast ice core HG9, was studied crystallographically, but was not investigated during the chemical analysis program for two reasons: its obvious resemblance to HG7, and the fact that our investigation focusses on the study of Hells Gate Ice Shelf marine ice.

 Structural and crystallographic description of each ice core

The sketch of the structure of the ice cores showing the various ice types can be found in figures 119, 128 and 129. The ice fabric diagrams of the ice core thin sections are presented, followed by the corresponding crystallographic profiles.

HG 1	HG 2	HG 3	HG 16	HG 17	HG 25
				000000 000000 000000 000000 000000 00000	

Figure 119. Structural description of ice cores HG1, HG2, HG3, HG16, HG17, and HG25.



Glacier ice



Platelet ice







Congelation ice

Rectangular frazil ice

Wave-like rectangular

Fine-grained frazil ice

Medium-grained frazil ice

Coarse-grained frazil ice

First year granular ice First year congelation ice

This ice core consists of 25% of coarse-grained granular ice and 75% of wave-like frazil ice. The internal characteristics of this core illustrating the textures of these two ice types are shown in figure 119. Two thin sections were studied crystallographically (see figure 120).

Their fabric diagrams are presented in figure 121. The caxes appear randomly oriented with localized concentrations of c-axes in the HG1(3+4) thin section.

HG2

This core consisted of 3.5% coarse-grained granular ice, 16.7% wave-like frazil ice and 79.8% rectangular frazil. The core was retrieved from in between HG3 and HG1, which were located 250 m apart. The structural sketch of the core can be found on figure 119. The fabric diagram is shown on figure 122.

One thin section was examined on a Rigsby stage. The caxes are concentrated into a single maximum slightly oblique to the vertical. This angular offset of the platy crystal texture is also evident in the vertical structure photos of this core, at the locations of the c-axis measurements. The crystallographic profile is presented in figure 123.

HG1



Figure 120. Crystallographic profile of HG1.

Figure 121. ICE FABRIC DLAGRAM FOR ICE CORE HG1



Figure 122. ICE FABRIC DLAGRAM FOR ICE CORE HG2





This core was retrieved 10 m from the ice shelf front. It contains on the average coarser crystals than HG1 and HG2 since 69.6% of its crystals are coarse-grained and platy looking; 19.5% are rectangular with the remaining 10.9% consisting of wave-like frazil ice. The structural description is illustrated on figure 119. The vertical thin section profile is given in figure 124.

The fabric diagram is presented in figure 125. The fabric diagram indicates a generally random distribution of c-axes.

HG4

This ice core was retrieved 5 m from the ice front and 70 m from HG3. This core is composed entirely of fine-grained equi-granular ice (see figure 128). The bulk of the c-axes is located in the horizontal plane, which would be consistent with the fact that this ice core was located in the shear zone of Hells Gate Ice Shelf. The fabric diagram is shown in figure 126. Occasional vertically oriented c-axes are also observed in this core. The crystallographic profile is presented in figure 127.

HG3



Figure 125. ICE FABRIC DLAGRAM FOR ICE CORE HG3



Figure 126. ICE FABRIC DLAGRAM FOR ICE CORE HG4





HG 4	HG 18	HG 23		HG 24			
***********	0,0,0,0,0,0,0,0,0,0,0 0,0,0,0,0,0,0,0,0			Olevieviev			
	0,00,00,00,00,00,00,00,00,00,00,00,00,0			Glacier ice			
	00000000000000000000000000000000000000			Platelet ice			
	0,00,00,00,00,00,00,00,00,00,00,00,00,0			Rectangular frazil ice			
	0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,			Wave-like rectangular			
	0,00,00,00,00,00,00 0,00,00,00,00,00,00 0,00,0		***********	Fine-grained frazil ice			
	0,0,0,0,0,0,0,0,0,0 0,0,0,0,0,0,0,0,0,0			Medium-grained frazil ice			
			0000000	Coarse-grained frazil ice			
				Congelation ice			
				First year granular ice			

First year granular ice First year congelation ice

128. Structural description of ice cores HG4, HG18, HG23, and HG24.

HG6 is particularly interesting since the core shows the contact between glacier ice and congelation ice of Hells Gate. This ice core contains 16.7% of glacier ice and 24.4% of congelation ice, with the remainder consisting of 47.4% of platelet ice, 6.4% of wave-like frazil and 5.1% of undifferentiated marine ice.

Continental ice features very depleted heavy isotope contents as shown in 6.1. The contact between congelation and glacier ice is not horizontal (see figure 129). Due to the nature of the sampling, δ -values and cation contents show a mixed signal near the contact and will be omitted in further discussion. Three marine ice fabrics, HG6A5, HG6B2 and HG6GC, are presented in figure 130. C-axis distributions tend towards random patterns or patterns that are difficult to resolve through lack of data points (e.g., HG6GC). The crystallographic profile is shown on figure 131.

HG7

HG7 consists of congelation ice located in first year fast ice close to the ice front. This very short ice core is similar to HG9 (figure 129). In these two cores there is a slight concentration of c-axes in the horizontal plane (figure 132).

251

HG6





Glacier ice







Platelet ice

Rectangular frazil ice Wave-like rectangular

Fine-grained frazil ice Medium-grained frazil ice Coarse-grained frazil ice

Congelation ice

First year granular ice First year congelation ice

Figure 130. ICE FABRIC DLAGRAM FOR ICE CORE HG6



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11/12/16

17/12/18







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17/12/16



Figure 131. Crystallographic profile of HG6.

ICE FABRIC DLAGRAM FOR ICE CORE HG7

Figure 132.



Structurally, the ice consists of 38.3% of columnar crystals in the upper part, followed by more granular ice towards the base of the ice core. Granular ice comprises 61.7% of the total length of the core. This ice core also features abundant brine inclusions and bubbles; it appears from the shapes and distribution of the inclusions that this ice has undergone appreciable brine drainage during the summer. This finding is consistent with the low measured Na contents of this ice core. The crystallographic profile is shown on figure 133.

HG8

This core was obtained in a ridge containing fractured Six vertical thin sections blocks. were examined crystallographically. The fabric diagrams can be found on figure 134. HG8C1 and HG8C3SUP show c-axes oriented merely in a vertical girdle. In the remaining sections, the pattern of caxis orientation is much less obvious. This correlates with the mixed textural make-up of ice in this core. For example the thin section of HG8C3 shows very fine granular ice in sharp contact with sharply inclined columnar ice indicating that this ice has undergone deformation during a ridging event. The crystallographic profiles are presented in figure 135.







Figure 134. ICE FABRIC DIAGRAM FOR ICE CORE HG8

















Figure 135.

Situated 60 m away from Inexpressible Island, HG9 was retrieved from first-year ice near a melt pond and a pressure Structurally, this core consists predominantly of ridge. columnar congelation ice with occasional granular ice intermingled. Of the three thin sections examined crystallographically, only HG9A2 exhibits a horizontal girdlelike pattern of c-axes. In the other two thin sections, c-axes appear to be oriented more randomly (see figure 136 for the fabric diagrams and figure 137 for the crystallographic profile). The girdle-like pattern in the horizontal of HG9A2 is entirely consistent with the typically horizontal nature of distribution of c-axes in columnar sea ice. The lack of azimuthal alignment of c-axes in this ice indicates that the horizontal girdle-like arrangement of c-axes occurred in the absence of any aligned current beneath the growing ice (Weeks and Gow, 1978, 1980).

HG10

Located 260 m from HG9, this ice core was obtained in a pressure ridge. Numerous serpulid worm tubes were found on top of the ice. A photograph of similar tubes, found in HG18, is shown in figure 26. Structurally the ice core at this location

HG9

Figure 136. ICE FABRIC DLAGRAM FOR ICE CORE HG9



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consists of granular ice throughout its entire length. The size of crystals varies from one mm in diameter for very fine grained ice to more than 10 mm in diameter for coarse-grained ice (see figure 138). The two thin sections studied feature a single broad c-axis maximum possibly associated with ice deformation in the pressure ridge. The crystallographic profile is presented in figure 139.

HG11

Retrieved 30 m from HG10, this ice core consists of variable-sized frazil often intermixed, as clearly indicated in the vertical thin section profile (see figure 141). The c-axes observed in fine- grained crystals of HG11C(1+2+3) are concentrated into two maxima (see figure 140). HG11C features a broad single maximum that degrades to an essentially random fabric for coarser-grained crystals in HG11C(1+2+3) and HG11B2. The two maxima observed in fine grained HG11C(1+2+3) could have resulted from compressive forces near Inexpressible Island.

HG 16

Structurally, HG16 consists of 62.7% of granular crystals intermixed with much coarser-grained platelet-like and 37.3% of wave-like crystals. This texture of crystals is quite unlike

Figure 138. ICE FABRIC DLAGRAM FOR ICE CORE HG10






Figure 140. ICE FABRIC DLAGRAM FOR ICE CORE HG11





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any observed in previously described cores of marine ice from Hells Gate. This particular core was retrieved 240m from S1 (see topographic profile drawn by Baroni for the location of this core, figure 25). The thin section profile showing the structural characteristics of HG16 is given in figure 119. Section HG16B2 shows a strong vertical girdle arrangement of caxes (see figure 142). Section HG16B3PC (based on the analysis of the small crystals in the ice) shows the same vertical girdle-like pattern of c-axes without the concentration of caxes observed in HG16B2. In section HG16B4, the pattern of caxes appears to be random. The crystallographic profile is presented in figure 143.

HG17

Obtained approximately 200 m from S3 (see Baroni's topographic profile for more precise location, figure 25), this core consists of 13.7 % of coarse-grained granular ice and 86.3% of wave-like frazil (see figure 119). The structural profile of the core shows frazil intersecting coarser crystals in HG17(2).

The c-axis distribution in HG17I(6) shows a girdle-like orientation of the c-axes in the vertical plane, very similar to the pattern observed near the top of HG16. The fabric diagram is shown in figure 144. The crystallographic profile is presented in figure 145.

Figure 142. ICE FABRIC DLAGRAM FOR ICE CORE HG16











Figure 143. Crystallographic profile of HG16.

Figure 144. ICE FABRIC DLAGRAM FOR ICE CORE HG17



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HG18

HG18(1) and HG18(2), 20 cm apart, are two cores retrieved near an accumulation of serpulid worm tubes and sponge spicules. A photograph of the sponge spicules can be found in figure 26. Both cores consist of medium-grained granular ice (see figure 128). The c-axes are oriented in the vertical plane and show a girdle-like disposition in HG18A6. The c-axes are broadly concentrated into one maximum in HG18B6 and are randomly oriented in HG18(2)B3. The fabric diagrams are presented in figure 146. The crystallographic profile is shown in figures 147a and 147b.

HG20

This ice core was obtained between N11 and SE4 (see Baroni's topographic profile for precise location, figure 25). This ice core was not selected for chemical analysis. Its relative interest resides in the fact that the isotopic values show a contribution of continental water to the seawater from which the ice was formed.

The c-axes of the one and only vertical thin section are aggregated into one broad maximum (see figure 148). Figure 149 is the crystallographic profile.

Figure 146. ICE FABRIC DLAGRAM FOR ICE CORE HG18









Figure 148. ICE FABRIC DLAGRAM FOR ICE CORE HG20





HG23

Situated 500 m from HG22 and 500 m from HG24, this ice core consists entirely of coarse-grained granular ice (see figure 128). The c-axes of HG23(3) are randomly oriented. The fabric diagram is presented in figure 150. The crystallographic profile is shown on figure 151.

HG24

This ice core comprises layers of fine-grained (2.5%), medium-grained (11.5%) and coarse-grained granular ice (7.7%) mixed with layers of rectangular frazil ice (53.9%) (see figure 128). In general, the texture of this core resembles wave-like rectangular frazil. Because of the difficulty in distinguishing between rectangular and wave-like frazil, these two types were combined as a single ice-type in the factor analysis.

The c-axes are very strongly concentrated into a single maximum in the vertical. The fabric diagrams are shown in figure 152. The vertical orientation of the c-axes almost certainly results from the manner in which the crystals, formed in the water column, piled up as plates beneath the existing ice sheet. The crystallographic profile is presented on figure 153.

Figure 150. ICE FABRIC DLAGRAM FOR ICE CORE HG23





Figure 151. Crystallographic profile of HG23.

Figure 152. ICE FABRIC DLAGRAM FOR ICE CORE HG24



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Figure 153. Crystallographic profile of HG24.

HG25

Situated 3 m from the ice shelf front and 200 m from HG24, this ice core is composed of 91% of rectangular frazil, 3.9% of wave-like frazil, and 5.1% of coarse-grained granular ice (see figure 119).

Section HG25A3 from near the top shows a vertical girdlelike distribution of c-axes of the crystal plates. Section HG25B6 also shows a vertical girdle-like pattern of c-axes with some localized concentration of c-axes near the vertical. The fabric diagrams are shown in figure 154. The crystalllographic profile is presented in figure 155.

Figure 154. ICE FABRIC DLAGRAM FOR ICE CORE HG25

7/18/98







Figure 155. Crystallographic profile of HG25.

IV. INTERPRETATION AND CONCLUSION

A. <u>Correlation and Factor Analysis of Cationic Content and</u> <u>Ice Types</u>

1. Analysis by Ice Cores

For each ice core, the sample chemical values form a cloud in the four-dimensional space formed by the four cations (Na, K, Ca, Mg). Given the high correlations between the cations, this cloud is highly oriented. It is concentrated within a linear subspace of dimension less than four - actually within planes. Thus, four variables are not necessary to describe the data. In order to explore the pattern of variables, correlation and factor analysis techniques were applied to each ice core and to the entire data set.

Table 28 summarizes the correlation analysis. Correlation coefficients between all cations were calculated for all ice cores. Asterisks indicate the level of significance of the t-test of nullity of the population correlation coefficient. Denoting

- * q the population correlation coefficient
- * r the sample correlation coefficient, and
- * n the sample size,

Table 28: Correlations between all cations

Ice Core	Na-K	Na-Ca	Na-Mg	K-Mg	Ca-Mg	K-Ca	Sample Size
A11	.956**	.987**	.951**	.994**	.939**	.946**	576
1	.510**	.940**	.411*	.892**	.329*	.460*	36
2	.593**	.749**	.586**	.921**	.633**	.605**	55
3	.213	.997**	.171	.993**	.166	.213	30
4	.569**	.155	.758**	.817**	.160	.040	66
6	.232	.810**	.168	.945**	.065	.162	30
16	.520**	.981**	.555**	.938**	.570**	.532**	51
17	.399*	.995**	.419*	.993**	.418*	.399*	48
18	.912**	.914**	.954**	.980**	.873**	.833**	113
23	.439*	.168	.803**	.476*	.104	.095	38
24	.235	.744**	.157	.925**	.160	.294*	43
25	.672**	.984**	.685**	.954**	.651**	.644**	66

- Correlation significantly different from zero, with
 a 5% level of significance
- ** Correlation significantly different from zero, with a 1% level of significance

it can be shown, under usual assumptions (bivariate normality, mutually independent observations) that the statistic

$$t_{n-2} = r \frac{\sqrt{n-2}}{\sqrt{1-r^2}}$$

has a Student's t distribution with n-2 degrees of freedom, if $\varrho=0$. Cells with one asterisk indicate that the null assumption H_o : $\varrho=0$ is rejected at a level of significance of 5%. Two asterisks indicate rejection at a level of significance of 1%.

Highly significant positive correlations are obtained, for most ice cores, between K and Mg, Na and K, Na and Ca, and Na and Mg. Weaker correlations seem to exist between K and Ca, and Ca and Mg. For all combinations of cations, figures 156 to 166 show, for all ice cores, data plots of the entire sample, with the simple regression line.

Following a suggestion by Meese (1990), all chemical species were normalized to Na to determine if there are secondary processes that affect cation concentration, or if concentration is entirely dependent on salinity. It may indeed be the case that the strong correlation between, say, Ca and Mg, is in fact spurious, and only due to salinity. Then those correlations would disappear once the salinity effect has been removed through normalization to Na. Table 29 shows that, for all ice cores, a strong linear dependence between K and Mg persists, after normalization. Correlations between K and Ca, and between Ca and Mg, on the other hand, have reduced to non-significant levels.

Table 29: Correlations between all cations, normalized to Na

Ice Core	K-Ca	K-Mg	Ca-Mg	Sample Size
All	.078*	.710**	.079*	576
1	.138	.877**	.154	36
2	.110	.832**	.203	55
3	.133	.995**	.100	30
4	.053	.622**	.015	66
6	.212	.975**	.239	30
16	.820**	.814**	.030	51
17	.060	.979**	.018	48
18	.118	.695**	.084	113
23	.082	.054	.105	38
24	.012	.960**	.087	43
25	.020	.871**	.151	66

- Correlation significantly different from zero, with a
 5% level of significance
- ** Correlation significantly different from zero, with a 1% level of significance

Figure 156.

Ice Core 1













Figure 157. Ice Core 2













Figure 158. Ice Core 3











Figure 159. Ice Core 4













Figure 160. Ice Core 6



Figure 161. Ice Core 16



Figure 162. Ice Core 17



Figure 163. Ice Core 18













Figure 164. Ice Core 23





Figure 165. Ice Core 24



Figure 166. Ice Core 25


An alternative way to control for salinity is to compute the partial correlation coefficients between all cations, given Na. For instance, the partial correlation coefficient between K and Ca, given Na, is computed by the formula

$$r_{KCa,Na} = \frac{r_{KCa} - r_{KNa}r_{CaNa}}{\sqrt{(1 - r_{KNa}^2)(1 - r_{CaNa}^2)}}$$

and tested using the same t-test.

Table 30 presents these partial correlation coefficients, and confirms the preceding analysis. With the exception of ice core 23, all partial correlations between K and Mg, keeping Na constant, are large, and significantly positive at the 1‰ level. Partial correlations between K and Ca, and between Ca and Mg, are non-significant, with just one exception. Table 30: Partial correlations between all cations, given Na

Ice Core	K-Ca	K-Mg	Ca-Mg
A11	.051	.935**	.007
1	066	.870**	184
2	.301*	.879**	.362*
3	.008	.994**	059
4	059	.719**	.066
6	045	.945**	123
16	.132	.914**	.158
17	.022	.992**	.012
18	003	.894**	.009
23	.024	.231	053
24	.183	.925**	.065
25	131	.915**	177

Correlation significantly different from zero,
 with a 5% level of significance

^{**} Correlation significantly different from zero, with a 1% level of significance

Correlation analysis only deals with two variables at a To better identify the relationships among the four time. interrelated variables, the use of a multivariate statistical procedure, like factor analysis, is required. Factor analysis is a data reduction technique. The analysis derives a small number of linear combinations of a set of variables (called factors or principal components) that retain as much of the information in the original variables as possible. It aims at reducing the number of variables necessary to describe the data, while losing the smallest possible amount of information. Very often, a small number of factors can be used in place of the original variables. Given a data set with four variables, four principal components can be computed. Each one is a linear combination of the original variables, with coefficients equal to the eigenvectors (customarily taken with unit norm) of the correlation matrix. The principal components are sorted by descending order of the eigenvalues, which are equal to the variances of the components. Principal components have a variety of useful properties.

- * The eigenvectors are orthogonal. So the factors represent jointly perpendicular directions in the space of the original variables.
- * The first factor has the largest variance of any unit-length linear combination of the original variables. It is the

best summary of linear relationships in the data.

- * The second factor is the second-best linear combination of the variables, which is orthogonal to the first. It has the largest variance of any unit-length linear combination orthogonal to the first factor.
- * The j-th principal component has the largest variance of any unit-length combination orthogonal to the first j-1 factors.
- * The last principal component has the smallest variance of any linear combination of the original variables.
- * The first j factors are the best linear predictors of the original variables among all possible sets of j variables.

For the entire data set and four ice cores (2, 16, 18, 25), factor analysis shows that a single principal component provides an excellent summary of the data. Over 75% of the total variance is explained by the first factor. The correlations between the cations and the selected factor are extremely high. To visualize the situation, it can be said that the data have a "hot-dog" shape in the four-dimensional space of the cations. The principal component is like a "skewer" that goes through the length of the hot dog.

For the remaining seven ice cores (1, 3, 4, 6, 17, 23, 24), the data are not oriented along a single axis. Two factors are necessary to describe the data. The observations are concentrated around a plane in the cations space. They can be visualized as a "hamburger" in a four-dimensional

space. The two selected principal components are like two perpendicular skewers going through the thin part of the hamburger.

One of the difficulties of factor analysis lies in the interpretation of the factors. Figure 167, for instance, is a plot of the position of the four cations, for ice core 6, in a plane whose axes are the first two factors. The fact that all cations are away from the axes makes their interpretation difficult. If two factors are selected, it is still possible to rotate them in their plane, in order to obtain a better interpretation of the data. Rotation does not affect the goodness of fit. The percentage of total variance explained does not change. The percentage of variance accounted by each factor does, however, change. Figure 167 shows, for ice core 6, the position of the four cations after rotation. It is now clear that the first axis is highly correlated to K and Mg, and that the second correlates with Na and Ca. This behavior is quite typical of the results obtained for most ice cores: one of the factors is usually highly related to Ca and Na, while K and Mg load highly on the other factor.

The factor analyses were performed on the statistical software SPSS. Consider for instance Ice Core 18.





Table 31: Correlation matrix between all cations - Ice Core 18

Cor	relation	Matrix -	Ice	Core	18	
	Na	к		Ca		Mg
Na	1.000					
ĸ	.912	1.000				
Ca	.914	.833	1			
Mg	.954	.980		.873		1.000

The correlation matrix (table 31) shows the high degree of linear dependence between all variables. Various tests and measures (Bartlett's test of sphericity, the Kaiser-Meyer-Ohlin measure of sampling adequacy, the anti-image correlation matrix,...) all provide satisfactory results, that justify the use of factor analysis.

Several techniques can be used to extract the factors: the principal components method, principal axis factoring, the method of unweighted least squares, the maximum likelihood method, and the alpha method. They differ in the criterion used to define "good fit." The principal components method was used here; it selects factors that account for the largest amount of variance in the sample. For simplicity, all variables and factors are expressed in standardized form, with a mean of 0 and a standard deviation of 1. Since there are 4 variables in the sample, the total variance is 4.

Table	32: Initial Sta	atistics - ice (ore 18
Factor	Eigenvalue	Pct of Var	Cum Pct
1	3.735	93.4	93.4
2	.195	4.8	98.2
3	.059	1.5	99.7
4	.011	0.3	100.0

The total variance explained by each factor is listed in the column labeled "Eigenvalue", in table 32. The next column contains the percentage of the total variance attributable to each factor. Those percentages are then cumulated in the last column. The table shows that over 93% of the total variance is explained by the first factor. Very little information is thus lost if, instead of the four original variables, the first factor is used.

Table 33: Factor matrix - Ice Core 18

Cation	Factor	1
Na	.979	
K	.965	
Ca	.935	
Mg	.986	

The factor matrix (table 33) contains the factor loadings, the coefficients used to express each standardized variable in terms of the factors. The factor loadings are also the correlations between the factors and the variables. For instance, the correlation between the selected factor and cation Na is .979. Ice Core 18 is unique in the sense that it shows the highest correlations between all variables. The four cations basically represent the same information. Each could be used to summarize the data, nearly as well as the factor. The data are organized like a very thin "hot dog" around the factor.

Now consider Ice Core 17.

Table	e 34:	Correlation	matrix - Ice	Core 17
	Na	К	Ca	Mg
Na	1.00	00		
K	.39	99 1.000		
Ca	.99	95 .399	1.000	
Ma	. 4	.993	.419	1.000

The correlation coefficients (table 34) between the four cations are all significantly different from zero, but smaller than for Core 18. The data are oriented, but less clearly than in Core 18.

Table 35: Initial Statistics - Ice Core 17

Factor	Eigenvalue	Pct of Var	Cum Pct
1	2.812	70.3	70.3
2	1.177	29.4	99.7
3	.007	0.2	99.9
4	.005	0.1	100.0

As shown in table 35, the first factor accounts for 70.3% of the total variance; the data are not as concentrated around the first factor as they are for Ice Core 18. The second factor explains a further 29.4% of the total variance, for a total of 99.7%. Using two factors instead of four variables loses almost no information at all. The data are extremely concentrated around a plane in the four-dimensional cation space.

 Table 36: Factor Matrix - Ice Core 17

 Factor 1
 Factor 2

 Na
 .839
 -.542

 K
 .832
 .552

 Ca
 .839
 -.542

 Mg
 .844
 .534

The factor loadings (table 36) are the correlations between the factors and the variables. They are also the standardized regression coefficients in the multiple regression equation with the original variable as the dependent variable, and the factors as the explanatory variables. So, for example, the best linear prediction of Na is

Na = 0.839 (factor 1) - 0.542 (factor 2)

The factor matrix shows that all cations are strongly positively correlated with the first factor. Factor 2

correlates positively with K and Mg, and negatively with Na and Ca. The correlations are however weaker. To facilitate the interpretation of the factors, a rotation is then performed. Several rotation techniques are available: varimax, quartimax, equamax. Varimax enhances the interpretability of the factors, by attempting to minimize the number of variables that have high loading on a factor. It was selected here for this reason.

Table 37: Rotated factor matrix - Ice Core 17

	Factor 1	Factor 2	
Na	.977	.209	
K	.199	.978	
Ca	.976	.210	
Ma	.220	.974	

Correlations after rotation (table 37) emphasize the strong relationship between Na and Ca, on the one hand, and K and Mg, on the other hand. The first factor is extremely closely related to Ca and Na, and more or less independent of K and Mg. The second factor loads highly on K and Mg, and very little on Na and Ca. Clearly, two variables only are sufficient to describe the data: the two factors, or (nearly equivalently), Na and K, or Na and Mg, or K and Ca, or Mg and Ca. The presence of Na automatically implies the presence of Ca. Similarly, K and Mg (nearly) always come together. A high measure of Na or Ca does not imply a high measure of K or Mg, since they are nearly unrelated (perpendicularity of the factors). The data has a very thin "hamburger" shape in the cation space.

Tables 38, 39 40, and 41 summarize the factor analysis for all ice cores. Ice cores are sorted in decreasing order of the percentage of total variance explained by the first factor. The "default" factor selection of SPSS consists in retaining all factors with an eigenvalue at least equal to 1. A factor is only selected if it explains more variance than a variable. This was the case for ice cores 17, 3, and 24. However, the eigenvalue of the second factor for four of the ice cores was only slightly less than one. For ice cores 6, 1, 4, and 23, it was at least 0.96. For all other ice cores, it was under 0.68. The ice cores can then be partitioned in two groups: ice cores 18, 25, 16, and 2, for which a single factor is sufficient to summarize the data (75% of the total variance is accounted for) and ice cores 6, 1, 17, 3, 24, 4, and 23, for which two factors are needed.

Ice Core	(1)	(2)	(3)
All	97.2	2.4	99.6
18	93.4	4.9	98.4
25	82.4	16.1	98.5
16	75.2	15.5	91.8
2	75.2	21.8	98.0
6	72.1	24.2	96.3
1	71.9	24.4	96.3
17	70.3	29.4	99.7
3	59.2	40.6	99.8
24	56.9	35.1	92.0
4	55.5	25.0	80.5
23	51.4	24.7	76.1

Table 38: Summary Table - Factor Analysis of all Ice Cores

(1): Pct of the total variance explained by the first factor
(2): Pct of the total variance explained by the second factor
(3): Pct of the total variance explained by the two factors

Table 39: Correlations between the cations and the first factor (ice cores with one factor selected)

Ice Core	Na	K	Ca	Mg
A11	.988	.988	.982	.985
18	.978	.964	.935	.986
25	.921	.899	.904	.906
16	.878	.854	.886	.875
2	.832	.900	.851	.907

Table 40: Correlations between the cations and the first factor, after varimax rotation (ice cores with two factors selected)

Ice Core	Na	K	Ca	Mg
6	.316	.949	.190	.968
1	.939	.275	.961	.224
17	.977	.199	.976	.220
3	.995	.119	.995	.069
24	.090	.968	.127	.982
4	.753	.866	.036	.938
23	.889	.682	.042	.883

Table 41: Correlations between cations and the second factor, after varimax rotation (ice cores with two factors selected)

	Na	К	Ca	Mg
6	.913	.287	.953	.221
1	.291	.938	.213	.953
17	.209	.978	.210	.974
3	.095	.991	.092	.996
24	.929	.176	.926	.057
4	083	.052	.994	.160
23	.084	.015	.999	.010

For ice cores 6, 1, 3, and 24, varimax rotation results in the same factor loadings as ice core 17. Na and Ca correlate strongly with one factor, K and Mg with the other. Ice cores 4 and 23 do not follow the same pattern: the first factor is a linear combination of Na, K, and Mg, and is nearly orthogonal to Ca. The second factor consists of Ca only.

Figures 168 a and 168 b show the factor loading plots for all ice cores. It is readily noticed that three ice cores, cores 4, 18, and 23, do not show the same cation position as the other cores. For ice core 18, all four cations are very close. Ice cores 4 and 23 are the only ones for which the



Figure 168a. Factor loading plots - Ice Cores 1 to 17.



Figure 168b. Factor loading plots - Ice Cores 18 to 25.

positions of Na and Ca are clearly separated. Although the percentage of variance explained by the first, or first two, factors may vary, the position of the cations for all other cores is similar. K and Mg, on the one hand, and Ca and Na, on the other hand, clearly cluster together.

Figures 169 to 172 show, for four different ice cores, the projection of all observations on the plane formed by the first two factors (called the factor scores). The observations are standardized: their mean is zero, and their standard deviation is one. Those plots are useful to identify outliers. For instance, four observations in ice core 23 are situated more than three standard deviations away from the mean. Identification of the corresponding observations enables us to check for unusual laboratory conditions, or possible material errors, leading to the deletion of the observations.

2. Analysis by Ice Types

The significant results obtained above led to another statistical analysis, cations by ice types. In fact, each ice core contains several types of ice. This may introduce an element of fuzziness in the data, and reduce the significance of the results obtained. It was therefore decided to form a single data base of all observations, and to subdivide them



Figure 169. Factor scores - Ice Core 4.



Figure 170. Factor scores - Ice Core 23.



Figure 171. Factor scores - Ice Core 24.



Figure 172. Factor scores - Ice Core 25.

according to ice type. The different types of ice are indicated in table 42, along with the sample sizes.

Table 42: Ice types and sample sizes.

Ісе Туре	Sample Size
Congelation ice	16
Fine-grained frazil ice	54
Medium-grained frazil ice	139
Coarse-grained frazil ice	108
First year congelation ice	8
First year granular ice	17
Platelet ice	31
Wave-like rectangular ice + rectangular frazil ice	378

Table 43 presents the total correlation coefficients. As before, an * indicates rejection of the test of nullity of the population correlation coefficient, at a level of significance of 5%. A ** indicates rejection at a level of significance of 1%. Highly significant positive correlations are observed for most cation combinations, and for most ice types. The only

Ісе Туре	Na-K	Na-Ca	Na-Mg	K-Mg	Ca-Mg	K-Ca
Congelation	.4294	.9333	.1514	.8386	.2709	.5288
ice	*	**	1. 10	**		*
Fine-grain	.9302	.9623	.9237	.9853	.9056	.9170
frazil	**	**	**	**	**	**
Medium-grain	.3850	.9886	.4113	.9187	.4743	.4448
frazil	**	**	**	**	**	**
Coarse-grain	.8254	.9586	.7657	.9645	.7307	.7901
frazil	**	**	**	**	**	**
First year	.1816	051	378	.1601	.0000	.4101
congelation						
First year	.9507	.9617	.9392	.9230	.9757	.9411
granular	**	**	**	**	**	**
Platelet	.8591	.9316	.9217	.9637	.8342	.7868
Ice	**	**	**	**	**	**
Rectangular	.9531	.9837	.9533	.9967	.9431	.9439
frazil	**	**	**	**	**	**

Table 43: Correlations by ice types

exception is first year congelation ice. Obviously, with a sample size of only 8, statistical results are unlikely to be significant.

Table 44 presents the partial correlation coefficients, given Na. With the exception of first-year ice, the results are quite spectacular. A highly significant positive correlation between K and Mg is observed for all ice types, when the effect of salinity is removed. Partial correlations between K and Ca, and between Ca and Mg, are not significantly different of zero, with a few exceptions. The correlations obtained are much higher than in the study by ice core. The data in this second study are much more homogeneous, which leads to highly significant results.

Table 44: Partial correlations by ice types

Ісе Туре	K-Ca	K-Mg	Ca-Mg
Congelation ice	.3948	.8666**	.3651
Fine-grain frazil	.2190	.8965**	.1605
Medium-grain frazil	.4619**	.9038**	.4932**
Coarse-grain frazil	007	.9157**	018
First year congelation	.4270	.2513	021
First year granular	.3154	.2827	.7700**
Platelet ice	072	.8657**	173
Rectangular frazil	.1164*	.9639**	.0983

Table 45 summarizes the factor analysis study. First year congelation ice data have been removed, due to their lack of significance. The table shows that five of the seven ice types can be summarized by one factor only. This factor explains at least 88% of the total variance. As indicated in table 46, the factor highly correlates with the four cations. Those five ice types (rectangular frazil ice, first year granular ice, fine-grained frazil ice, platelet ice, and medium-grained frazil) are quite similar in their cations contents and correlations. The two other ice types, coarsegrained granular ice and congelation ice, have to be assigned to another group. For those types, the first factor does not explain more than 70.3% of the total variance. Two factors are needed to explain 95% of the total variance. After orthogonal rotation, the first factor highly correlates with Na and Ca. The second factor is correlated with K and Mg (see table 47). All results are similar to those obtained in the first part of the study, but much more significant.

Table	45:	Summary	table -	Factor	analysis	by ice	type.	
-			12		10		1 (2)	

Ісе Туре	(1)	(2)	(3)
Rectangular frazil	97.2	2.4	99.5
First year granular	96.1	2.2	98.3
Fine-grain frazil	95.3	3.4	98.7
Platelet ice	91.0	6.5	97.6
Medium-grain frazil	88.0	10.3	98.3
Coarse-grain frazil	70.3	27.4	97.8
Congelation	64.9	30.8	95.7

(1) Percentage of the total variance explained by the first factor

(2) Percentage of the total variance explained by the second factor

(3) Percentage of the total variance explained by the two factors

Table 46: Correlations between cations and first factor

Ісе Туре	Na	K	Ca	Mg
Rectangular frazil	.9865	.9876	.9816	.9874
First year congelation	.9820	.9725	.9890	.9786
Medium-grain frazil	.9772	.9816	.9691	.9770
Platelet ice	.9684	.9465	.9251	.9755
Medium-grain frazil	.9465	.9546	.9275	.9225
Coarse-grain frazil	.9793	.2040	.9633	.2361
Congelation ice	.9796	.3473	.9555	.0378

Table 47: Correlations between cations and second factor

Ісе Туре	Na	K	Ca	Mg
Coarse-grain frazil	.1912	.9584	.2596	.9504
Congelation ice	.1068	.9031	.2330	.9750

3. Interpretation.

The statistical analysis demonstrated that Na and Ca on the one hand, and K and Mg on the other hand, are highly correlated in our marine ice samples.

Richardson (1976), in his study of the phase relations in sea ice as a function of temperatures, indicated that CaCO₃, calcium carbonate, is the first salt to precipitate from seawater at a temperature close to its freezing point.

Table 48 (Richardson, 1976) also indicates that Na_2SO_4 and CaSO₄ precipitate from seawater at -8° C and -10° C.

Since our marine ice samples, during their formation process and at an early stage of their transfer in the basal zone of the ice shelf, have been submitted to progressively lower temperatures, the first salts likely to precipitate soon after CaCO₃ are Na₂SO₄ and CaSO₄, while no K or Mg salts could Table 48: The Distribution of Ions, Water, Hydrated Salts, and Ice That Constitutes the Quasi-Equilibrium Conditions in a One Kilogram Sample of Copenhagen Sea-Water at Sub-Freezing Temperatures*

Sea-water chlorinity 19.373%; sea-water salinity 34.998%

Temp. °C	к+	Ca ²⁺	Ions Mg ²⁺	Ions SO4 ²⁻	Na ⁺	CI-	Unknown	Total Ions	Liquid Water	Brine Salinity
0.0	0.387	0.408	1.297	2.701	10.763	19.352	0.090	34.998	965.002	34.998
-2		0.402					0.081	34.983	860.825	39.052
-4		0.391	1000				0.065	34.956	488.714	66.752
-6		0.386					0.057	34.943	335.001	94.455
-8	-	0.376		2.377	10.608		0.042	34.439	247.534	122.135
-10		0.366		1.495	10.187		0.030	33.114	196.921	143.952
-12		0.362		1.063	9.983			32.474	173.412	157.728
-14		0.356		0.765	9.848			32.035	154.769	171,490
-16		0.350		0.535	9.745			31.696	139.783	184.839
-18		0.344		0.349	9.662			31.421	127.042	198.286
-20		0.399		0.207	9.599			31.211	116.225	211.685
-22		0.337		0.122	9.561			31.086	106.673	225.655
-24	2	0.336		0.073	6.523	14.717		23.363	77.481	231,675
-26		0.335		0.045	3.620	10.273	0.027	15.984	52.347	233.905
-28			1	0.029	2.054	7.880	0.024	12.006	39.177	234.570
-30				0.016	1.232	6.627	0.021	9.915	32.104	235.966
-32				0.0?	0.844	6.041	0.019	8.923	27.397	245.677
-34	0.336		1.211		0.623	5.399	0.016	7.920	23.393	252.930
-36	0.309		1.048		0.459	4.651	0.013	6.815	19.720	256.830
-38	0.281		0.918		0.362	4.101	0.010	6.007	17.005	261.038
-40	0.251		0.817		0.274	3.643	0.007	5.327	14.893	263.452
-42	0.209		0.757	16.57	0.209	3.331	0.005	4.848 .	13.507	264.044
-44	0.100		0.631		0.159	2.789	0.0?	4.014	10.988	267.564
-46	0.039		0.419		0.117	2.050	1	2.960	7.804	274.991
-48	0.015		0.212		0.076	1.365		2.003	5.150	280.022
-50	0.009		0.076		0.050	0.922		1.392	3.404	290.242
-52	0.008		0.015		0.029	0.710		1.097	2.645	293.159

Temp. °C	CaCO ₃ .6H ₂ O	Na2SO4 .10H2O	CaSO ₄ .2H ₂ O	NaCl .2H ₂ O	ксі	MgCl ₂ .12H ₂ O	MgCl ₂ .8H ² O	Unknown Salts	Salts' Water	Ice
0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-2	0.031								0.016	104.161
-4	0.088								0.046	476.242
-6	0.115								0.060	629.941
-8	0.166	1.086			-				0.693	716.775
-10	0.208	4.029	0.009						2.362	765.719
-12		5.452	0.024						3.161	788.429
-14		6.402	0.051						3.698	806.535
-16	-	7.121	0.078		1				4.105	821.114
-18		7.698	0.104			-			4.433	833.527
-20		8.137	0.124					19.07	4.682	844.095
-22		8.403	0.134						4.833	853.496
-24		8.556	0.139	12.360					9.629	877.892
-26		8.647	0.141	24.211				0.003	14.196	898.459
-28		8.709		30.592				0.006	16.663	909.162
-30		8.748		33.934				0.009	17.956	914.942
-32		8.799		35.497				0.011	18,581	919.024
-34				36.403	0.101	1.106		0.014	19.694	921.915
-36				37.075	0.148	3.198		0.017	21.401	923.879
-38				37.471	0.201	4.852		0.020	22.701	925.296
-40				37.833	0.259	6.147		0.023	23.738	926.371
-42				38.098	0.339	6.912		0.025	24.345	927.125
-44				38.302	0.546	7.234	0.994	0.030	25.269	928.745
-46				38.474	0.663		3.083		26.593	930,605
-48				38.642	0.708		5.116		27.883	931.969
-50				38.751	0.720		6.451		28.727	932.871
-52				38.836	0.722		7.055		29.123	933.234

C. Richardson, 1976, p 510.

be involved in that temperature range (see table 48).

Thus the potential exists for a similar behavior of Ca and Na on the one hand, and/or K and Mg on the other hand.

Since CaCO, precipitates virtually at the same time when marine ice forms (congelation ice) or begins to agglomerate (frazil ice), the possibility exists for the migration of CaCO, particles out of the system. Therefore, a great variability exists in the Na/Ca ratio in our marine ice samples.

Note that, during the chemical analyses of the ice samples, the techniques used did not permit discrimination between an element stored in a precipitated salt or in the brine.

B. <u>Chemical and Isotopic Evidence for Diluted Seawater at the</u> <u>Bottom of the Hells Gate Ice Shelf.</u>

Table 49 shows the complete chemical data. The concentration in Na, K, Ca, and Mg is expressed in ppm and in meq/l. Σ 4 represents the sum of the concentrations of the four elements, in meq/l. The next four columns are the ratios, calculated in meq/l: Na/K, Na/Ca, Ca/Mg, K/Mg. The last column, noted A./A.E., represents the ratio of the alkalis (Na+K) to the alkaline-earths, (Ca+Mg).

It can be shown from Richardson (1976) that no K or Mg salt would precipitate in the early phase of the formation or

Tante

335

FAST ICE: Granular

SAMPL	E	1 cc	NCENTRAT	ION (ppm)	1		CC	NCENTRAT	ION (meq/l)	1		R	ATIOS (calcul	ated in meq/l)	Mr. Su
		Na	К	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
7(1)	h	246,00	6,52	7,96	24,00	10,701	0,167	0,397	1,974	13,239	64,182	26,941	0,201	0,064	4,583
7(1)		207,80	8,45	6,92	33,05	9,039	0,216	0,345	2,719	12,319	41,823	26,177	0,127	0,079	3,021
7(1)	í	212,20	8,35	6,54	32,20	9,231	0,213	0,326	2,649	12,419	43,238	28,285	0,123	0,081	3,174
7(1)		202.10	7.42	6.02	28,15	8,791	0,190	0,300	2,316	11,597	46,352	29,266	0,130	0,082	3,433
7(1)	d	240.00	7.52	6.90	28,50	10,440	0,192	0,344	2,344	13,321	54,287	30,322	0,147	0,082	3,954
7(1)	6	255.20	7.11	7.07	27,40	11,101	0,182	0,353	2,254	13,890	61,088	31,467	0,157	0,081	4,328
7(1)	b	252.30	8,21	6,80	31,70	10,975	0,210	0,339	2,608	14,132	52,273	32,344	0,130	0,081	3,795
7(1)		263.10	6.97	7.22	26.80	11,445	0,178	0,360	2,205	14,188	64,226	31,767	0,163	0,081	4,532
7(3)	ĩ	462.00	10.04	14.11	39,45	20,097	0,257	0,704	3,245	24,303	78,287	28,543	0,217	0,079	5,154
7(3)		443.00	9.69	13.15	37,30	19,271	0,248	0,656	3,068	23,243	77,739	29,367	0,214	0,081	5,241
7(3)	h	472.00	7.04	14.09	25.60	20.532	0.180	0,703	2,106	23,521	114,091	29,202	0,334	0,085	7,374
7(4)		466.50	10.97	15.30	44.30	20,293	0,281	0,763	3,644	24,981	72,338	26,580	0,210	0,077	4,668
7(4)	h	489.00	11.11	16.29	45.65	21,272	0.284	0,813	3,755	26,124	74,885	26,168	0,216	0,076	4,719
7(4)	6	439.00	10.59	14.85	43.55	19,097	0,271	0,741	3,582	23,691	70,512	25,771	0,207	0,076	4,480
7(4)	d	420.00	10.21	14.57	41,55	18,270	0,261	0,727	3,418	22,676	69,968	25,129	0,213	0,076	4,471
7(4)		457.50	9.38	14.87	35,65	19,901	0,240	0,742	2,933	23,816	82,940	26,821	0,253	0,082	5,481
7(4)	b	444.00	10.35	13.77	41.80	19,314	0.265	0,687	3,438	23,704	72,980	28,109	0,200	0,077	4,746
7(4)		523.00	10.52	15.64	42.80	22,751	0,269	0,780	3,521	27,321	84,555	29,151	0,222	0,076	5,352
7(4)	i	472,50	6,35	14,24	22,60	20,554	0,162	0,711	1,859	23,286	126,626	28,925	0,382	0,087	8,062

FAST ICE: Congelation

	AMPLE CONCENTRATION (ppm)			1	CONCENTRATION (meq/l)						RATIOS (calculated in meg/l)				
SAMPL		Na	K	Ca	Mg	Na	к	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
7(0)		272.50	6.67	6.74	25.55	11 897	0.169	0.336	2,102	14,505	70,242	35,374	0,160	0,081	4,949
7(2)	a	213,50	8.00	756	30.40	13.607	0.205	0.377	2,501	16,689	66,484	36,069	0,151	0,082	4,799
7(2)	D	227 60	8,60	814	32 75	14 251	0.222	0.406	2,694	17,573	64,104	35,084	0,151	0,063	4,668
7(2)	c	327,00	0,09	0,14	32,10	15,207	0,222	0,100	2 710	18.677	67 238	35 785	0.157	0.064	4.936
7(2)	d	351,80	8,90	8,57	33,05	15,303	0,220	0,420	2,/17	10,077	07,250	00,700	0134	0.083	4 495
7(2)	e	339,70	9,42	7,92	35,90	14,777	0,241	0,395	2,953	18,366	61,358	37,390	0,134	0,062	4,400
7(2)	h	+ 442.00	9,83	11,92	38,30	19,227	0,251	0,595	3,151	23,224	76,475	32,325	0,189	0,060	5,201
7(3)		490.00	10.01	13.53	38.90	21,315	0,256	0,675	3,200	25,446	83,318	31,571	0,211	0,080	5,567
7(3)	h	489.00	10.83	14.35	42.95	21.272	0.277	0,716	3,533	25,798	76,792	29,706	0,203	0,078	5,071
7(2)	6	488 50	11 32	15.01	44.35	21,250	0.289	0.749	3,648	25,936	73,440	28,371	0,205	0,079	4,898
7(3)		500,50	12.08	15.05	52 10	22 120	0 234	0.796	4 286	27 536	66.159	27.792	0.186	0.078	4,419
7(3)	d	508,50	13,08	12'23	52,10	22,120	0,339	0,790	4,200	21 000	00,107	200.044	0,202	0.0777	4.020
7(3)	e	464,50	10,45	13,99	42,10	20,206	0,267	0,698	3,463	24,634	75,593	28,944	0,202	0,0//	4,920

CONGELATION ICE

SAMPLE		1	CONCENTRATION (ppm)					ION (meg/l)		1		RATIOS (calculated in meq/l)			
JAMI LL		Na	K	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
(4/3)		228.10	12.25	8.22	50.10	9.922	0.313	0.410	4,121	14,767	31,684	24,190	0,100	0,076	2,259
64(4)	8	374.60	13.11	10.25	52.95	16,295	0.335	0.511	4,356	21,497	48,610	31,859	0,117	0,077	3,417
CA(4)	1	462.00	13.77	18.55	50.25	20.097	0.352	0.926	4,134	25,508	57,096	21,711	0,224	0,085	4,042
6 4 (4)		462,00	17.75	17.89	65 30	20.054	0.441	0.893	5,372	26,759	45,464	22,464	0,166	0,082	3,272
64(4)	n	467 50	14.73	18.77	58.80	20.336	0.377	0.937	4,837	26,486	53,987	21,712	0,194	0,078	3,588
64(4)	8	+ 338.80	12.59	8.15	48.35	14,738	0.322	0,407	3,977	19,444	45,771	36,239	0,102	0,081	3,435
64(4)	h	453.50	12 70	16.27	47.00	19,727	0.325	0.812	3,866	24,730	60,767	24,298	0,210	0,084	4,286
6A(4)		494.50	15.70	17.67	63.50	21,511	0.401	0.882	5,224	28,017	53,591	24,396	0,169	0,077	3,589
6A(5)		474.00	15.70	17.26	49.55	20,619	0,401	0,861	4,076	25,958	51,370	23,940	0,211	0,098	4,258
6A(5)	b	544.00	16.53	20.00	57,80	23,664	0,423	0,998	4,755	29,839	56,002	23,711	0,210	0,089	4,187
6A(5)	c	554.00	17.22	20.06	58,65	24,099	0,440	1,001	4,825	30,365	54,746	24,075	0,207	0,091	4,212
6A(5)	d	492.50	18.18	19.89	62.45	21,424	0.465	0,993	5,137	28,018	46,082	21,585	0,193	0,090	3,571
6A(5)	e	557.50	14.77	21.76	52.80	24,251	0.378	1,086	4,343	30,058	64,230	22,334	0,250	0,087	4,536
6A(5)	1	589,50	12.28	21.05	44,50	25,643	0,314	1,050	3,661	30,668	81,653	24,413	0,287	0,086	5,510
6A(5)		515.00	13.04	18.16	46,65	22,403	0,333	0,906	3,837	27,480	67,182	24,722	0,236	0,087	4,793
6A(5)	h	485,50	15,21	18,08	55,60	21,119	0,389	0,902	4,574	26,984	54,286	23,409	0,197	0,085	3,928

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PLATELET ICE

SAMPLE		1 co	NCENTRAT	ION (ppm)	1		CO	NCENTRATI	ION (meg/l)			R	ATIOS (calcul	ated in meq/l)	1
		Na	к	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
6B(1)	h	443.00	11.52	16.64	41.95	19,271	0,260	0,830	3,451	23,812	74,096	23,208	0,241	0,075	4,562
68(1)		450.00	11.25	16.90	40.10	19,575	0,254	0,843	3,299	23,971	77,114	23,212	0,256	0,077	4,787
6B(1)	î	442.50	10.14	16,75	35,60	19,249	0,229	0,836	2,928	23,242	84,082	23,030	0,285	0,078	5,174
6B(1)		420.00	10.38	15.81	38.95	18,270	0,234	0,789	3,204	22,497	77,951	23,158	0,246	0,073	4,634
6B(1)		378.60	17.42	8.56	63.15	16.469	0,393	0.427	5,195	22,484	41,882	38,556	0,082	0,076	2,999
68(2)		437 50	7.83	16.66	27.70	19.031	0.177	0,831	2,279	22,318	107,669	22,892	0,365	0,078	6,176
68(2)		517 50	10.63	19.84	37.80	22,511	0.240	0,990	3,109	26,851	93,864	22,738	0,318	0,077	5,550
68/3)		497.00	10,70	18.64	39.25	21,620	0.241	0.930	3,229	26,020	89,564	23,243	0,288	0,075	5,256
6B(A)	d	452 50	16.87	16.52	64 70	19,684	0.381	0.824	5,322	26,211	51,695	23,878	0,155	0,072	3,264
6D(4)	a	420 50	16.63	19.01	61 25	18 683	0.375	0.949	5.038	25.046	49,780	19,696	0,188	0,074	3,183
(D(4)		429,50	14 84	15 12	55 20	21 685	0 335	0.904	4.549	27 473	64,764	23,983	0.199	0.074	4,038
6B(4)	a	567,00	16,15	20,41	67,45	24,665	0,364	1,018	5,548	31,596	67,682	24,217	0,184	0,066	3,811

SAMPLE		1 00	NCENTRAT	ION (ppm)	1	CC	NCENTRAT	ION (meq/l)		1		R	TIOS (calcula	ated in meq/l)	-
		Na	K	Ca	Mg	Na	K	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	A/A.E.
168/11		42 70	0.52	1.63	2.80	1.857	0.013	0.081	0.230	2,182	140.371	22,836	0,353	0,057	6,002
10D(1)	1	12,00	0,52	0.58	1.07	0.783	0.014	0.029	0.088	0.914	55,474	27.054	0,329	0,160	6,815
100(1)		10,00	1.10	0,55	1.02	0.805	0,010	0.032	0.158	1.025	26.519	24.811	0.205	0,192	4,387
168(1)	n	18,50	1,19	0,65	1,92	1,021	0,010	0.042	0 114	1 205	54.105	24.596	0.369	0.168	6.755
168(1)	g	23,70	0,75	0,04	1,50	0.087	0,019	0,012	0 170	1 218	45 875	25 370	0.729	0.126	4.823
16B(1)	1	22,70	0,84	0,78	2,07	0,987	0,022	0,039	0,170	1 777	63 736	24 130	0.336	0.129	6.159
16B(1)	e	34,60	0,94	1,25	2,26	1,505	0,024	0,062	0,100	1,627	44 085	24,130	0.282	0.155	5 553
16B(1)	d	31,20	1,18	1,10	2,3/	1,357	0,030	0,055	0,195	1,03/	44,900	24,720	0,472	0.187	7 913
16B(1)	ь	55,70	1,55	2,00	2,57	2,423	0,040	0,100	0,211	2,774	01,300	24,270	0,472	0,183	9 546
16B(1)	а	53,00	1,10	1,80	1,88	2,306	0,028	0,090	0,155	2,5/8	81,6/1	23,000	0,001	0,103	5 104
16B(2)	а	39,90	0,77	1,42	3,32	1,736	0,020	0,071	0,2/3	2,099	87,834	24,495	0,239	0,072	10.266
16B(2)	b	87,90	1,07	2,72	2,91	3,824	0,027	0,136	0,239	4,226	139,819	28,171	0,567	0,114	10,200
16B(2)	c	59,70	1,79	2,13	4,05	2,597	0,046	0,106	0,333	3,082	56,612	24,433	0,319	0,138	6,014
16B(2)	e	63,10	1,23	2,33	3,91	2,745	0,031	0,116	0,322	3,214	87,401	23,608	0,361	0,098	6,340
16B(2)	f	68,50	1,20	2,47	3,56	2,980	0,031	0,123	0,293	3,427	97,062	24,176	0,421	0,105	7,235
16B(2)	g	48,70	1,32	1,72	4,52	2,118	0,034	0,086	0,372	2,610	62,537	24,683	0,231	0,091	4,703
16B(2)	ĥ	53,10	1,17	1,95	3,85	2,310	0,030	0,097	0,317	2,754	77,011	23,738	0,307	0,095	5,652
16B(2)	1	81,50	1,50	3,03	4,98	3,545	0,038	0,151	0,410	4,144	92,599	23,448	0,369	0,093	6,389
16B(3)	a	53,80	1,90	1,92	6,12	2,340	0,046	0,096	0,503	2,986	50,822	24,427	0,190	0,091	3,982
16B(3)	b	43,20	2,01	1,46	7,65	1,879	0,051	0,073	0,629	2,633	36,602	25,794	0,116	0,082	2,749
168(3)	c	39,10	1,64	1,30	5,99	1,701	0,042	0,065	0,493	2,300	40,676	26,219	0,132	0,085	3,125
25B(5)	a	30,64	1.57	0,96	5,87	1,333	0,040	0,048	0,483	1,904	33,279	27,823	0,099	0,083	2,587
25B(5)	b	24,02	1,79	0,86	3,38	1,045	0,046	0,043	0,278	1,412	22,866	24,348	0,154	0,164	3,398
258(5)	c	25,19	0,45	0,74	1,72	1,096	0,011	0,037	0,141	1,286	95,549	29,675	0,261	0,081	6,206
6B(3)	k	472.00	15,46	17,09	57,30	20,532	0,395	0,853	4,713	26,493	51,952	24,076	0,181	0,084	3,760
6B(4)	i	692,00	15,04	18,37	58,60	30,102	0,385	0,917	4,820	36,224	78,263	32,839	0,190	0,080	5,314
1B(1)	k	60,50	2,86	2,15	11,10	2,632	0,073	0,107	0,913	3,725	36,030	24,530	0,117	0,080	2,651
18(1)	1	40,10	2,08	- 1,59	8,36	1,744	0,053	0,079	0,688	2,565	32,738	21,985	0,115	0,077	2,344
18(1)	i	58,10	1,19	2,30	8,36	2,527	0,031	0,115	0,688	3,360	82,802	22,021	0,167	0,044	3,188
18(1)	h	29,10	1,33	1,41	5,75	1,266	0,034	0,070	0,473	1,843	37,174	17,991	0,149	0,072	2,392
18(1)	æ	24,20	0,56	1,07	2,09	1,053	0,014	0,053	0,172	1,292	73,661	19,716	0,311	0,083	4,736
18(1)	f	36.00	0.97	1.47	4,24	1,566	0,025	0,073	0,349	2,013	62,950	21,349	0,210	0,071	3,769
18(1)		36.60	1.08	1.68	4,45	1,592	0,028	0,084	0,366	2,070	57,845	18,992	0,230	0,075	3,600
18(1)	6	45.90	0.80	1.73	3.30	1,997	0,020	0,086	0,271	2,375	97,558	23,129	0,318	0,075	5,638
18(1)	h	52.00	0.93	2.27	4.69	2,262	0.024	0,113	0,386	2,785	94,968	19,969	0,294	0,062	4,580
10(1)	h	60.40	2.86	2 23	6.37	2 627	0.073	0.111	0,524	3,336	35,884	23,611	0,212	0,140	4,251
10(3)		77.40	2,86	2 79	6.46	3 367	0.073	0.139	0.531	4,111	46.095	24,184	0,262	0,137	5,129
10(3)	1	120 70	5.50	6.03	18 47	6.077	0.143	0.301	1,519	8.040	42.523	20.196	0,198	0,094	3,417
10(2)	D	139,70	3,39	6,05	14.96	6.964	0,089	0.286	1 222	8 4 6 2	77.194	23.965	0.234	0.073	4,608
1C(2)	c	157,80	3,90	5,74	14,00	5,004	0,007	0 245	0.971	6.934	78.824	23.092	0.252	0.074	4,702
1C(2)	e	129,80	2,80	4,90	11,01	5,040	0,079	0,240	1.079	6.874	68.596	24,805	0.203	0.074	4,254
1C(2)	1	125,20	3,10	4,40	13,12	5,440	0,0/3	0,245	0.922	7 394	91 632	25 140	0.266	0.073	5,335
1C(2)		141,60	2,63	4,91	11,21	6,160	0,067	0,245	0,522	6 202	107.012	25 860	0.316	0.076	6.270
IC(2)	1	123,70	1,97	4,17	8,00	5,381	0,050	0,208	0,008	6.024	03 076	18 196	0 380	0.073	5.059
1C(2)	k	131.50	2.38	6.30	10,07	5,720	0,061	0,514	0,010	0,924	33,370	10,190	0,000	A. 101	o forda

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$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	ated in meq/l)
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	K/Mg AJA.E.
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	0,077 2,851
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0,075 2,387
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0.076 2.656
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0.076 4.489
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0.158 9.058
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0.074 2.898
1D(1) a 96,70 5,31 3,39 17,21 4,206 0,136 0,169 1,416 5,227 50,963 24,867 61,119 1D(2) b 101,00 3,06 3,29 12,78 4,394 0,078 0,164 1,051 5,687 56,085 26,762 0,156 1D(2) c 107,60 3,60 3,60 15,31 4,681 0,092 0,180 1,259 6,212 50,822 26,055 0,143 1D(2) d 99,60 3,33 3,39 14,12 4,333 0,085 0,169 1,162 5,748 50,842 25,612 0,146 1D(2) e 70,80 3,38 3,48 14,22 3,060 0,086 0,174 1,170 4,510 35,624 17,735 0,145 1D(2) f 100,60 4,12 3,54 17,22 4,376 0,105 0,177 1,417 6,507 41,546 24,7773 0,125 1D(2) f 100,60 4,54 18,63 5,479 0,105 0,177	0.005 2.740
1D(2) b 101,00 3,06 3,29 12,78 4,394 0,078 0,164 1,051 5,887 56,085 26,762 0,156 1D(2) c 107,60 3,60 3,60 15,31 4,681 0,092 0,180 1,259 6,212 50,852 26,762 0,136 1D(2) d 99,60 3,33 3,39 14,12 4,333 0,085 0,169 1,162 5,748 50,842 25,612 0,146 1D(2) e 70,80 3,38 3,48 14,22 3,060 0,086 0,174 1,170 4,510 35,624 17,735 0,148 1D(2) f 100,60 4,12 3,54 17,22 4,376 0,105 0,177 1,417 6,075 41,546 24,773 0,125 1D(2) f 100,60 4,54 18,63 5,479 0,105 0,177 1,417 6,075 41,546 24,773 0,125 1D(2) f 100,60 4,54 18,63 5,479 0,105 0,177 1,417	0.075 3.670
1D(2) c 107,60 3,60 3,60 15,31 4,681 0,092 0,180 1,259 6,212 50,822 26,055 0,143 1D(2) d 99,60 3,33 3,39 14,12 4,333 0,085 0,169 1,162 5,748 50,842 25,612 0,146 1D(2) e 70,80 3,38 3,48 14,22 3,080 0,086 0,174 1,170 4,510 35,624 17,735 0,148 1D(2) f 100,60 4,12 3,54 17,22 4,376 0,105 0,177 1,417 6,075 41,546 24,773 0,125 1D(2) f 100,60 4,54 18,63 5,429 0,116 0,277 1,533 7,304 46,263 23,963 0,148	0,073 3,079
1D(2) d 99,60 3,33 3,39 14,12 4,333 0,085 0,169 1,162 5,748 50,842 25,612 0,146 1D(2) e 70,80 3,38 3,48 14,22 3,080 0,086 0,174 1,170 4,510 35,624 17,735 0,148 1D(2) f 100,60 4,12 3,54 17,22 4,376 0,105 0,177 1,417 6,075 41,546 24,773 0,125 1D(2) f 100,60 4,54 18,63 5,429 0,116 0,227 1,533 7,304 46,763 23,963 0,148	0,073 3,317
1D(2) e 70,80 3,38 3,48 14,22 3,080 0,086 0,174 1,170 4,510 35,624 17,735 0,148 1D(2) f 100,60 4,12 3,54 17,22 4,376 0,105 0,177 1,417 6,075 41,546 24,773 0,125 1D(2) f 100,60 4,54 18,63 5,429 0,116 0,227 1,533 7,304 46,763 23,963 0,148	0,073 3,320
1D(2) f 100,60 4,12 3,54 17,22 4,376 0,105 0,177 1,417 6,075 41,546 24,773 0,125	0,0/4 2,35/
124.60 4.54 18.63 5.420 0.116 0.227 1.533 7.304 46.763 23.963 0.148	0,074 2,813
1D(2) g $124,90$ $4,94$ $4,94$ $10,05$ $5,425$ $0,110$ $0,227$ $1,000$ $10,000$ $10,000$	0,076 3,152
2A(4) a 29,50 0,70 0,78 2,53 1,283 0,018 0,039 0,205 1,548 72,013 32,970 0,187	0,086 5,267
2A(4) b 21,20 0,59 0,65 2,05 0,922 0,015 0,032 0,169 1,138 61,493 28,432 0,192	0,089 4,661
2A(4) c 17,50 0,68 0,97 3,63 0,761 0,017 0,048 0,299 1,126 43,583 15,727 0,162	0,058 2,244
2A(4) d 26,40 0,73 1,61 2,97 1,148 0,019 0,080 0,244 1,492 61,406 14,294 0,329	0,077 3,595
2A(4) e 44,10 0,72 1,29 2,76 1,918 0,019 0,064 0,227 2,228 103,552 29,801 0,284	0,082 6,647
2A(4) f 32,00 0,77 1,27 2,99 1,392 0,020 0,063 0,246 1,721 71,078 21,965 0,258	0,080 4,563
2A(4) g 32,40 0,55 1,36 1,97 1,409 0,014 0,068 0,162 1,653 99,854 20,768 0,419	0,087 6,191
2A(4) h 34,90 0,58 1,21 2,08 1,518 0,015 0,060 0,171 1,764 102,437 25,144 0,353	0,087 6,622
2B(1) e 124,40 1,91 3,61 11,22 5,411 0,049 0,180 0,923 6,563 110,726 30,040 0,195	0,053 4,950
2B(1) d 84.50 2.04 3.79 11.08 3.676 0.052 0.189 0.911 4.828 70.623 19.436 0.207	0,057 3,387
28(1) c 96,00 1.97 3,28 10,28 4,176 0,050 0,164 0,846 5,236 83,049 25,514 0,194	0,059 4,187
2B(1) b 79,30 1,37 2,58 9,75 3,450 0,035 0,129 0,802 4,415 98,249 26,794 0,161	0,044 3,744
2B(1) a 66,30 1,95 1,79 11,23 2,884 0,050 0,089 0,924 3,947 57,966 32,289 0,097	0,054 2,896
3 A3 a 76,40 2,26 2,73 13,38 3,323 0,058 0,136 1,101 4,618 57,429 24,396 0,124	0,053 2,734
3 A3b 70,70 2,24 2,48 11,47 3,075 0,057 0,124 0,944 4,200 53,635 24,852 0,131	0,061 2,935
3 A3 c 90,30 1,89 3,22 8,38 3,928 0,048 0,161 0,689 4,826 81,254 24,447 0,233	0,070 4,678
3 A3 d 122,80 1,60 4,22 6,78 5,342 0,041 0,211 0,558 6,151 130,503 25,367 0,378	0,073 7,006
3 A3 e 86,10 0,95 3,16 5,02 3,745 0,024 0,158 0,413 4,340 153,827 23,752 0,382	0,059 6,606
17 1 i 44.20 1.55 1.68 5.36 1.923 0.040 0.084 0.441 2.487 48,650 22,935 0.190	0,090 3,739
17 1 47.20 1.51 1.75 5.42 2.053 0.039 0.087 0.446 2.625 53,138 23,512 0.196	0,087 3,923
171 b 37.10 1.06 1.33 3.56 1.614 0.027 0.066 0.293 2.000 59,785 24,317 0.227	0,092 4,568
171 e 33.20 1.55 1.15 5.44 1.444 0.040 0.057 0.447 1.989 36,543 25,167 0.128	0,068 2,939
171 f 43 20 1 55 1 58 5.15 1.879 0.040 0.079 0.424 2.421 47,549 23,835 0,186	0,093 3,818
171 e 41 30 1 52 1 52 5 37 1 797 0 039 0 076 0 442 2 353 46,285 23,686 0 172	0,088 3,546
171 4 40 90 0.82 149 2.52 1.779 0.021 0.074 0.207 2.082 84,739 23,929 0.359	0,101 6,392
171 c 59.50 0.90 2.26 3.73 2.588 0.023 0.113 0.307 3.031 112,845 22.951 0.368	0,075 6,223
171 b 49.50 110 2.12 3.87 2.153 0.028 0.106 0.318 2.606 76.277 20.354 0.332	0,089 5,143
172 2 45 00 1 54 1 83 5 75 1 958 0.039 0.091 0.473 2.561 49.753 21.436 0.193	0,083 3,539
772 2840 095 096 324 1235 0.024 0.048 0.267 1.574 51.110 25.789 0.180	0,091 4,006
1771 1980 0.95 0.70 3.34 0.861 0.024 0.035 0.275 1.195 35.375 24.658 0.127	0,089 2,860

FRAZIL ICE: Wave-like

SAMPLE	1 co	NCENTRAT	ION (ppm)	1	CC	NCENTRAT	ION (meq/l)		1		R	ATIOS (calcula	ated in meq/l)	1
	Na	K	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
172 a	17,90	0.90	0,61	2,99	0,779	0,023	0,030	0,246	1,078	33,689	25,581	0,124	0,094	2,901
173a	26.20	0.86	0.94	2,98	1,140	0,022	0,047	0,245	1,454	52,094	24,298	0,191	0,089	3,977
173b	27.40	0.88	0,92	3,07	1,192	0,022	0,046	0,253	1,513	53,193	25,963	0,182	0,089	4,069
173 c	34.70	0.89	1.27	3,25	1,509	0,023	0,063	0,267	1,863	66,321	23,819	0,237	0,085	4,633
173 d	45.50	0.84	1.56	2,96	1,979	0,022	0,078	0,243	2,322	91,952	25,426	0,320	0,088	6,226
173.0	116.00	0.94	4.10	3,38	5,046	0,024	0,205	0,278	5,553	210,295	24,664	0,736	0,086	10,505
1736	750.50	1.35	21.21	6.20	32,647	0,034	1,058	0,510	34,250	948,911	30,846	2,075	0,067	20,837
173 0	89.30	1.14	3.23	4.16	3,885	0.029	0,161	0,342	4,417	133,437	24,101	0,471	0,085	7,775
1736	53.40	2.04	1.86	8.35	2.323	0.052	0,093	0,687	3,155	44,630	25,027	0,135	0,076	3,046
1731	20,60	1.08	2.69	4.01	3.071	0.028	0,134	0,330	3,563	110,870	22,879	0,407	0,084	6,677
1731	70,90	2.31	2.76	9.76	3.084	0.059	0,138	0,803	4,084	52,181	22,394	0,172	0,074	3,342
174.	96 70	2.06	3.58	8.38	4.206	0.053	0.179	0,689	5,127	80,005	23,547	0,259	0,076	4,907
174b	83.20	2.93	3.10	12.14	3,619	0.075	0,155	0,999	4,847	48,380	23,396	0,155	0,075	3,203
1740	63.70	2.51	2.26	10.43	2.771	0.064	0.113	0,858	3,806	43,147	24,571	0,131	0,075	2,921
174C	56.70	2.43	2.08	10.32	2.466	0.062	0.104	0,649	3,481	39,715	23,763	0,122	0,073	2,654
174.0	73.00	1.50	2.69	5.75	3,176	0.038	0,134	0,473	3,821	82,942	23,657	0,284	0,081	5,293
1746	91.30	1.25	3.42	4.75	3,972	0.032	0,171	0,391	4,565	124,366	23,272	0,437	0,082	7,131
174	95.30	1.86	3.68	7.36	4,146	0.048	0,184	0,605	4,982	87,024	22,575	0,303	0,079	5,314
174 b	86.10	1.59	3.13	6.12	3,745	0,041	0,156	0,503	4,446	91,897	23,980	0,310	0,081	5,740
1741	78.40	1.86	2.80	7,33	3,410	0,045	0,140	0,603	4,201	71,592	24,409	0,232	0,079	4,656
1741	68,60	1.50	2.52	5.51	2,984	0.038	0,126	0,453	3,601	77,942	23,731	0,277	0,084	5,220
1751	47.90	1.73	1.83	6.79	2,084	0.044	0,091	0,559	2,778	47,051	22,818	0,163	0,079	3,274
1751	54.00	1.69	1,99	6,58	2,349	0,043	0,099	0,541	3,033	54,342	23,655	0,183	0,080	3,735
175h	61.90	1.49	2.34	5,80	2.693	0.038	0,117	0,477	3,325	70,656	23,060	0,245	0,080	4,598
1750	42.30	1.04	1.53	3,86	1,840	0,027	0,076	0,318	2,261	69,067	24,101	0,240	0,084	4,739
175f	35,90	0,83	1,33	2,97	1,562	0,021	0,066	0,244	1,894	73,760	23,531	0,272	0,087	5,095
175e	26,30	0,74	. 0,92	2,63	1,144	0,019	0,046	0,216	1,425	60,601	24,920	0,212	0,087	4,434
175d	25,90	1,02	0,90	3,65	1,127	0,026	0,045	0,300	1,498	43,147	25,087	0,150	0,087	3,340
175 c	29,50	0,99	1,07	3,66	1,283	0,025	0,053	0,301	1,663	50,862	24,034	0,177	0,084	3,691
175b	24,50	1,07	0,85	3,84	1,066	0,027	0,042	0,316	1,451	38,971	25,127	0,134	0,087	3,051
175a	37,60	1,37	1,43	5,37	1,636	0,035	0,071	0,442	2,184	46,820	22,921	0,162	0,079	3,256

		1 00	NCUNTRATI	ON (nom)	1		CO	NCENTRATI	ION (meg/l)	- 1		R	ATIOS (calcul	ated in meq/l)	1
SAMPLE		Na	K	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
		14.55	0.19	0.43	0.26	0.633	0.005	0.021	0.021	0,680	137,975	29,497	1,003	0,214	14,880
23A(4)	a	14,55	0,15	0,45	0.24	0 339	0.004	0.009	0.020	0.372	87,414	37,776	0,455	0,197	11,947
25A(4)	D	7,00	0,15	0,10	0,24	0.310	0,004	0.007	0.025	0.355	90.485	42.657	0.303	0.143	10,037
25A(4)	c	7,34	0,14	0,15	0,50	0,319	0,003	0,007	0.025	0 392	105 628	35,480	0.404	0.136	10,313
25A(4)	d	8,14	0,13	0,20	0,30	0,354	0,003	0,010	0,025	0.435	118 086	36.058	0.445	0.136	11,196
25A(4)	e	9,10	0,13	0,22	0,30	0,396	0,003	0,011	0,025	0,435	08 500	34,830	0 371	0 131	9 515
25A(4)	f	• 8,79	0,15	0,22	0,36	0,382	0,004	0,011	0,030	0,427	77 840	35,030	0,371	0.107	6 828
25A(4)	g	8,84	0,19	0,22	0,56	0,385	0,005	0,011	0,046	0,447	77,640	33,020	0,230	0,107	6 024
25A(4)	h	8,22	0,17	0,19	0,52	0,358	0,004	0,009	0,043	0,414	09,999	37,714	0,222	0,074	6.062
25A(4)	1	8,29	0,12	0,19	0,52	0,361	0,003	0,009	0,043	0,416	113,551	38,036	0,222	0,074	0,902
25A(4)	j	10,10	0,12	0,29	0,52	0,439	0,003	0,014	0,043	0,500	138,343	30,361	0,338	0,0/4	7,730
25A(5)	a	9,53	0,25	0,24	0,46	0,415	0,006	0,012	0,038	0,471	65,268	34,615	0,316	0,168	8,449
25A(5)	b	8,03	0,22	0,20	0,40	0,349	0,006	0,010	0,033	0,398	61,869	35,001	0,303	0,172	8,277
25A(5)	c	7,88	0,21	0,21	0,36	0,343	0,005	0,010	0,030	0,388	64,761	32,711	0,354	0,179	8,682
25A(5)	d	8,88	0,21	0,22	0,38	0,386	0,005	0,011	0,031	0,434	70,625	35,187	0,351	0,175	9,275
25A(5)	e	8,56	0,20	0,27	0,38	0,372	0,005	0,013	0,031	0,422	72,776	27,637	0,431	0,164	8,439
25A(5)	f	8,59	0,19	0,20	0,35	0,374	0,005	0,010	0,029	0,417	78,440	37,441	0,347	0,165	9,761
25A(5)	g	10,94	0,19	0,83	0,80	0,476	0,005	0,041	0,066	0,588	96,332	11,490	0,629	0,075	4,484
25A(5)	h	11,20	0,23	0,46	0,80	0,487	0,006	0,023	0,066	0,582	83,678	21,225	0,349	0,068	5,554
25A(5)	1	8,64	0,23	0,27	0,50	0,376	0,006	0,013	0,041	0,436	64,552	27,896	0,328	0,142	6,990
25A(5)	i	8,64	0,26	0,28	0,48	0,376	0,007	0,014	0,039	0,436	56,058	26,900	0,354	0,170	7,156
258(1)	1	10,59	0.44	0,28	1,52	0,461	0,011	0,014	0,125	0,611	40,797	32,971	0,112	0,090	3,395
25B(1)	h	14.87	0.95	0,47	3,54	0,647	0,024	0,023	0,291	0,986	26,761	27,580	0,061	0,083	2,133
25B(1)	0	19.84	0.36	0.60	1.34	0,863	0,009	0,030	0,110	1,012	94,069	28,826	0,272	0,083	6,223
25B(1)	Ê	22.05	0.22	0.76	1,01	0,959	0,006	0,038	0,083	1,086	169,890	25,292	0,456	0,068	7,973
258(1)		25,85	0.22	0,83	0,97	1,124	0,006	0,041	0,080	1,251	199,168	27,150	0,519	0,071	9,324
25B(1)	d	25,38	0.25	0.84	1.02	1,104	0,006	0,042	0,084	1,236	173,820	26,339	0,500	0,076	8,825
258(1)		72.74	0.32	0.74	1.23	0.967	0,008	0,037	0,101	1,114	119,203	26,199	0,365	0,080	7,064
258(1)	h	19.97	0.41	0.66	1.48	0.869	0.011	0.033	0.122	1.034	82,061	26,377	0,271	0,087	5,685
258(1)		12.08	1.16	0.31	2.30	0.525	0.030	0.015	0.189	0,760	17,728	33,970	0,082	0,157	2,712
250(1)		13.71	0.41	0.49	1.52	0.596	0.011	0.024	0.125	0.756	56.337	24,391	0,196	0,085	4,060
250(2)	e	16.60	0.36	0.55	1 30	0.772	0.009	0.027	0.114	0.873	78,707	26.311	0.240	0,080	5,158
250(2)		10,00	0,30	0,33	1.45	0.478	0.010	0.010	0.119	0.617	48.342	45.580	0.088	0.083	3,757
250(2)	B	10,90	0,39	0.20	1.60	0.549	0,010	0.014	0.132	0.705	53,604	37.906	0.110	0.078	3,825
258(2)	n	12,01	0,40	0,29	1,00	0.559	0,010	0.014	0123	0 705	54 582	39.976	0.114	0.083	4,166
258(2)	1	12,04	0,40	0,28	2.45	0,539	0,010	0.014	0 202	0 785	24 116	33.073	0.082	0.112	2,602
258(3)	a	12,52	0,88	0,33	2,45	0,545	0,025	0,010	0 160	0.892	41 702	31 165	0.130	0.097	3,661
25B(3)	Б	15,/3	0,64	0,44	2,06	0,004	0,010	0,022	0.143	1 1 77	75 508	20 522	0.234	0.091	5.664
25B(3)	c	22,69	0,51	0,67	1,74	0,907	0,015	0,033	0,145	1.472	83 248	29 111	0.271	0.092	6.071
25B(3)	d	28,70	0,59	0,89	1,99	1,240	0,013	0,014	0,109	1,074	63 578	21 221	0176	0.086	4 749
25B(3)	e	19,34	0,52	0,54	1,86	0,841	0,013	0,027	0,155	1,034	34 405	34 103	0,088	0.087	2 843
25B(3)	f	19,56	0,96	0,50	3,44	0,851	0,025	0,025	0,283	1,183	34,093	34,103	0,000	0,005	2184
25B(3)	8	21,26	1,36	0,61	4,97	0,925	0,035	0,030	0,409	1,399	20,000	30,382	0,074	0,085	2,104
25B(3)	h	26,22	1,35	0,76	4,95	1,141	0,035	0,038	0,407	1,620	32,983	30,075	0,093	0,085	2,040
25B(4)	a	34,78	0,88	1,08	2,98	1,513	0,023	0,054	0,245	1,835	66,993	28,073	0,220	0,092	5,135

SAMPLE		1 co	NCENTRATI	ON (ppm)	- 1		cc	NCENTRAT	ION (meg/l)	1		R	ATIOS (calcula	ated in meq/l)	1
SAMI LL		Na	K	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
25B(A)	h	35.23	0.58	1.05	2.01	1.533	0.015	0.052	0.165	1,765	103,405	29,249	0,317	0,090	7,106
250(4)	0	27.74	0,50	0.83	1.85	1 207	0.013	0.041	0.152	1.413	94,991	29,135	0,272	0,083	6,299
25D(4)	e d	26.22	0,50	1 17	2.44	1.667	0.017	0.058	0.201	1,943	95,433	28,551	0.291	0,087	6,501
25B(4)	a	30,52	0,00	1,04	2 24	1 505	0.017	0.052	0.192	1.766	90,752	29.002	0.270	0.086	6.227
258(4)	e	34,00	1,08	0.02	2,51	1,303	0.028	0.046	0.297	1 703	48.394	28 702	0.156	0.093	3,959
258(4)		30,62	1,08	0,93	3,01	1,332	0,020	0.052	0.256	1 718	61,929	26,484	0.205	0.088	4,575
258(4)	h	31,90	0,88	1,05	3,11	1,300	0,022	0,052	0.271	2111	72 508	27,656	0.234	0.089	5,320
25B(4)	1	40,29	0,95	1,27	3,29	1,/33	0,024	0,005	0,2/1	1 654	112 028	28 434	0.356	0.089	7.524
25B(5)	d	33,27	0,50	1,02	1,74	1,44/	0,013	0,051	0,143	2 219	116 817	25,454	0,506	0 111	8 694
25B(5)	e	47,38	0,69	1,61	1,93	2,061	0,018	0,080	0,159	2,310	06 402	26,004	0,335	0.091	6 639
25B(5)	f	54,40	0,96	1,81	3,28	2,366	0,025	0,090	0,270	2,751	90/492	20,200	0,535	0,091	4 810
25B(5)	g	56,97	1,52	1,78	5,27	2,478	0,039	0,089	0,434	3,039	63,840	27,901	0,205	0,090	6,029
25B(5)	h	68,70	1,30	2,20	3,96	2,968	0,033	0,110	0,326	3,457	89,620	27,222	0,337	0,102	5,930
25B(5)	i	47,46	1,32	1,62	4,10	2,065	0,034	0,081	0,337	2,516	60,945	25,539	0,240	0,100	5,019
25B(6)	a	51,03	1,41	1,70	3,50	2,220	0,036	0,085	0,288	2,629	61,674	26,168	0,295	0,125	6,052
25B(6)	b	43,19	1,68	1,35	5,55	1,879	0,043	0,067	0,457	2,446	43,821	27,889	0,148	0,094	3,668
25B(6)	c	42,83	2,04	1,41	7,51	1,863	0,052	0,070	0,618	2,603	35,796	26,480	0,114	0,084	2,783
25B(6)	d	38,56	1,59	1,17	5,83	1,677	0,041	0,058	0,480	2,256	41,156	28,730	0,122	0,085	3,194
25B(6)	e	27,26	0,97	0,87	2,92	1,186	0,025	0,043	0,240	1,494	47,667	27,315	0,181	0,104	4,269
25B(6)	f	25,46	1,13	0,72	3,94	1,108	0,029	0,036	0,324	1,496	38,276	30,826	0,111	0,089	3,157
25B(6)	g	26,15	1,02	0,83	3,63	1,138	0,026	0,041	0,299	1,504	43,563	27,465	0,139	0,087	3,422
25B(6)	h	29,15	1,17	0,84	3,16	1,268	0,030	0,042	0,260	1,600	42,527	30,252	0,161	0,115	4,300
2B(2)	d	58,00	2,06	2,28	5,85	2,523	0,053	0,114	0,481	3,171	47,987	22,176	0,236	0,109	4,329
2B(2)	e	65,00	1,41	2,19	6,28	2,828	0,036	0,109	0,517	3,490	78,175	25,874	0,212	0,070	4,575
2B(2)	f	62,80	1,14	2,04	6,62	2,732	0,029	0,102	0,545	3,407	93,839	26,836	0,187	0,053	4,271
2B(2)	g	59,70	1,13	1,93	6,02	2,597	0,029	0,096	0,495	3,217	89,751	26,965	0,194	0,058	4,439
28(2)	h	55,70	1,36	1,73	8,01	2,423	0,035	0,086	0,659	3,203	69,711	28,067	0,131	0,053	3,298
2B(2)	1	59,80	2,23	2,04	9,68	2,601	0,057	0,102	0,796	3,556	45,647	25,554	0,128	0,072	2,960
28(3)	a	57,50	2,83	2,58	11,85	2,501	0,072	0,129	0,975	3,677	34,577	19,428	0,132	0,074	2,332
28(3)	b	70,50	2,37	2,91	10,14	3,067	0,061	0,145	0,834	4,107	50,529	21,120	0,174	0,073	3,193
28(3)	c	80,50	2,63	2,62	11,27	3,502	0,067	0,131	0,927	4,627	52,093	26,784	0,141	0,073	3,374
28(3)	d	76,70	2.07	2.72	8,70	3,336	0,053	0,136	0,716	4,241	63,035	24,582	0,190	0,074	3,981
28(3)	e	80,60	2.48	3,43	10,58	3,506	0,063	0,171	0,870	4,611	55,354	20,485	0,197	0,073	3,427
28(3)	f	92.30	2.70	3.53	11.29	4,015	0,069	0,176	0,929	5,189	58,053	22,794	0,190	0,074	3,697
28(3)		102.90	2.84	3.67	12.01	4,476	0,073	0,183	0,988	5,720	61,728	24,442	0,185	0,073	3,884
28(3)	b	103.00	3.22	2.91	13.64	4.481	0.082	0,145	1,122	5,830	54,379	30,856	0,129	0,073	3,601
20(3)		80.60	2.06	2.64	8.46	3.506	0.053	0.132	0.696	4,386	66,685	26,615	0,189	0,076	4,300
20(3)		67.20	1 70	2.05	710	2 923	0.046	0.102	0.584	3,655	63,724	28,576	0,175	0,079	4,326
20(3)	1	56.20	1,73	1.88	6.62	2.445	0.044	0.094	0.545	3,127	55,204	26,060	0,172	0,061	3,899
28(3)	K	30,20	1,75	2 21	0.84	2158	0.062	0.110	0.809	3,139	34,840	19,565	0,136	0,077	2,413
2B(4)		49,00	2,42	2,21	10.97	2 501	0.067	0.134	0.894	3,596	37.604	18,634	0.150	0.074	2,497
2B(4)	D	57,50	2,60	2,09	0,67	2,501	0,007	0.165	0 797	4162	52 511	19.073	0.207	0.075	3,328
28(4)	c	72,20	2,34	3,30	9,09	3,191	0,000	0,100	1 185	5 652	47 966	22 034	0.160	0.074	3.109
2B(4)	e	96,30	3,42	3,81	14,41	4,109	0,067	0,190	1,105	5,052	20.034	22,0.9	0128	0.073	2 603
28(4)	f	88.50	3.86	3.45	16,35	3,850	0,099	0,172	1,345	3/403	39,034	22,002	0,120	10,000 - 5	erboury.

SAMPLE		1 co	NCENTRATI	ON (ppm)	1		cc	NCENTRAT	ION (meq/l)	1		R	ATIOS (calcul	ated in meq/l)	
SAMILL		Na	K	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
						4.000	0.005	0.125	1 179	5.600	40 413	31 189	0.114	0.072	3.266
2B(4)	g	96,60	3,33	2,70	14,32	4,202	0,085	0,135	1,1/8	5,000	49,415	31,107	0.148	0.076	3,003
2B(4)	h	75,00	2,86	2,87	11,76	3,263	0,073	0,143	0,967	4,490	44,000	22,701	0,140	0,070	4 258
2B(4)	1	51,20	2,36	3,21	8,31	3,532	0,060	0,160	0,684	4,436	58,538	22,052	0,234	0,000	4,2.50
2B(4)	j	83,30	1,88	2,65	4,96	3,624	0,048	0,132	0,408	4,212	75,507	27,402	0,324	0,118	0,790
2B(4)	k	72,50	1,66	2,78	3,54	3,154	0,042	0,139	0,291	3,626	74,479	22,734	0,4/6	0,145	1,454
2C(1)	k	. 73,40	1,86	3,05	6,95	3,193	0,048	0,152	0,572	3,964	67,026	20,979	0,266	0,083	4,4/0
2C(1)	i	85,40	3,17	4,18	13,10	3,715	0,081	0,209	1,078	5,082	45,873	17,810	0,194	0,075	2,951
2C(1)	h	133,20	3,64	3,98	15,85	5,794	0,093	0,199	1,304	7,390	62,198	29,175	0,152	0,071	3,919
2C(1)	g	110,00	3,40	3,84	14,50	4,785	0,087	0,192	1,193	6,256	55,012	24,972	0,161	0,073	3,519
2C(1)	f	111,10	2,98	3,77	12,50	4,833	0,076	0,188	1,028	6,125	63,407	25,690	0,183	0,074	4,036
2C(1)	e	89,80	3,14	4,29	13,44	3,906	0,060	0,214	1,106	5,306	48,660	18,248	0,194	0,073	3,021
2C(1)	a	135,40	4.20	4.09	17,59	5,890	0,107	0,204	1,447	7,648	54,816	28,859	0,141	0,074	3,632
2C(2)		119.60	3.88	4.26	15,18	5,203	0,099	0,213	1,249	6,763	52,376	24,474	0,170	0,080	3,628
20(2)	h	152.60	2.62	4.30	11.42	6,638	0,067	0,215	0,939	7,859	99,010	30,937	0,228	0,071	5,810
20(2)	c	123.30	2.16	3.45	9,17	5,364	0,055	0,172	0,754	6,345	97,124	31,155	0,228	0,073	5,849
20(2)	d	115.50	3.26	4.29	14.06	5,024	0,063	0,214	1,157	6,478	60,205	23,470	0,185	0,072	3,726
20(2)		127.40	3.89	4.10	16.77	5,542	0,100	0,205	1,380	7,225	55,693	27,088	0,148	0,072	3,561
20(2)	F	155.40	6.07	4.28	19,52	6,760	0,155	0,214	1,606	8,734	43,539	31,652	0,133	0,097	3,801
20(2)		123.50	6.11	4.34	19.29	5,372	0,156	0,217	1,587	7,332	34,406	24,807	0,136	0,098	3,066
20(2)	h	130.20	5.66	3.39	15.40	5,664	0,145	0,169	1,514	7,491	39,148	33,481	0,112	0,096	3,452
20(2)		108.40	5.76	3.89	18.22	4,715	0.147	0,194	1,499	6,556	32,008	24,292	0,130	0,098	2,872
20(3)		203.80	2.10	4.13	6.55	8,865	0.054	0,206	0,539	9,664	165,288	43,017	0,382	0,100	11,973
20(3)	d	12010	3.35	3.58	14.40	5.224	0.086	0.179	1,185	6,673	61,054	29,245	0,151	0,072	3,895
20(3)		107.90	2.95	3.70	12.69	4,694	0.076	0,185	1.044	5,998	62,157	25,422	0,177	0,072	3,882
20(3)		109.40	2.19	3.76	9.38	4.759	0.056	0,188	0,772	5,774	85,088	25,364	0,243	0,072	5,020
2 446		112.60	1 71	4 14	6.70	4,898	0.044	0.207	0.551	5,700	111,943	23,710	0,375	0,079	6,522
2 44 4		104.70	2.00	3.80	12.64	4.554	0.077	0.190	1.040	5,860	59,479	24,019	0,182	0,074	3,767
2 446		97.00	2.98	3.45	12.70	4 220	0.076	0.172	1.045	5,513	55,360	24,510	0,165	0,073	3,530
3 44 1		85.60	1.80	3.09	715	3 724	0.046	0.154	0.588	4,512	80,862	24,149	0,262	0,078	5,078
3 441		65,60	1.87	2.45	7.25	2 854	0.048	0.122	0.596	3.620	59.682	23,341	0,205	0,080	4,037
3 441		49.10	1,67	1.77	6.68	2,092	0.043	0.086	0.549	2.771	48,603	24,378	0,156	0,078	3,361
3 A9 K		40,10	1,00	3.37	4.88	3 902	0.033	0.163	0.401	4,500	117,637	23,913	0,406	0,063	6,970
3 ADa		77.80	1,50	2.87	6.74	3 384	0.043	0.143	0.554	4.125	78.614	23,631	0,258	0,078	4,913
3 A50		49.20	1,00	1.68	7.50	2101	0.047	0.084	0.617	2.849	44.435	25.063	0.136	0,077	3,066
3 ADC		10,00	1,63	1,00	1.75	1,680	0,010	0.058	0.144	1.893	164,212	28,782	0.406	0.071	8,356
2411		30,03	0,40	1,17	1.26	1,000	0.007	0.051	0.112	1 641	203,255	28,607	0.459	0.065	9,050
2411		33,50	0,28	1,05	1,30	0.858	0,007	0,029	0.114	1.008	121 612	29.152	0.259	0.062	6,053
241h		19,73	0,28	0,59	1,30	0,656	0,007	0,029	0.176	1.056	79.390	28.546	0.167	0.060	4,142
241g		19,32	0,41	0,59	2,19	0,040	0,011	0,029	0.215	1 148	84 321	29 325	0.142	0.049	3,684
2411		20,52	0,41	0,61	2,01	0,893	0,017	0,033	0 103	1 224	83 386	29 930	0.170	0.061	4.409
241e		22,66	0,46	0,66	2,35	0,980	0,012	0,030	0.246	1 132	54 752	28.070	0.122	0.062	3.102
24 2 g		19,32	0,60	0,60	2,99	0,840	0,015	0,000	0,246	1 212	73 032	26,070	0 169	0.060	3.831
24 2 h		21,89	0,50	0,73	2,62	0,952	0,013	0,036	0,216	1,217	73,932	20,140	0.175	0.073	4 653
2421		26,12	0,60	0,74	2,56	1,136	0,015	0,037	0,211	1,399	74,022	30,770	0,1/5	0,0/3	4,033

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FRAZIL ICE: Rectangular

SAMPLE	1 co	NCENTRATI	ON (ppm)	1		CC	NCENTRATI	ION (meg/l)	1		R	ATIOS (calcul	ated in meq/l)	
	Na	K	Ca	Mg	Na	K	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	A/A.E.
24.2 i	31.85	0.75	0.96	3,36	1,385	0,019	0,048	0,276	1,729	72,710	28,922	0,173	0,069	4,331
24.3 a	32,56	0.61	0,96	2,74	1,416	0,016	0,048	0,225	1,705	90,199	29,567	0,213	0,070	5,240
24.3 c	31,29	0.54	0,93	2,81	1,361	0,014	0,046	0,231	1,652	98,905	29,330	0,201	0,060	4,953
2430	25.47	0.67	0.70	4,96	1,108	0,017	0,035	0,408	1,568	64,739	31,719	0,086	0,042	2,540
2436	26.30	0.86	0.77	3.99	1,144	0.022	0,038	0,328	1,533	51,875	29,775	0,117	0,067	3,181
24.4 a	20.32	1.19	0.63	6.00	0.884	0.030	0,031	0,494	1,439	29,128	28,117	0,064	0,061	1,741
24 4 h	17.38	1.12	0.54	5.41	0.756	0.029	0.027	0,445	1,257	26,289	28,057	0,061	0,065	1,663
2440	20.30	1.33	0.69	636	0.883	0.034	0.034	0,523	1,475	25,933	25,647	0,066	0,065	1,645
2440	21 34	0.86	0.57	3.72	0.928	0.022	0.028	0,306	1,285	42,091	32,637	0,093	0,072	2,842
2440	30.15	0.91	1 13	5 24	1,703	0.023	0.056	0.431	2,214	73,125	30,202	0,131	0,054	3,542
2440	37,13	0.92	0.98	4 47	1 462	0.023	0.049	0.368	1.902	62,305	29,897	0,133	0,064	3,566
29.91	23,65	0,92	0.72	5.51	1.029	0.025	0.036	0.453	1.543	41,650	28.634	0.079	0,054	2,154
24 4 g	23,03	1.07	2.80	4.64	1.421	0.027	0.144	0.382	1.974	51,951	9.852	0.378	0,072	2,753
24 4 h	34,00	0.82	1.12	4,04	1,486	0.021	0.056	0 347	1.911	70,206	26,596	0.161	0.061	3,741
24.4.1	34,17	0,85	1,12	5.24	2,920	0,025	0,115	0.431	3.404	79 908	23.943	0.273	0.082	5,202
245a	64,82	1,38	2,30	5,29	2,820	0,033	0,001	0,951	2 726	102 902	25 788	0 324	0.081	6369
24 5 b	53,84	0,89	1,82	3,41	2,342	0,023	0,091	0,281	2,730	102,902	24,480	0.247	0.064	6353
245 c	44,65	0,57	1,59	2,78	1,942	0,015	0,079	0,229	2,260	132,033	24,400	0,347	0,004	0,000

FRAZIL ICE: Granular line

SAMPLE	t	1 00	NCENTRATI	ON (ppm)	1		CO	ONCENTRA I	ION (meq/l)			R	ATIOS (calcula	ated in meq/l)	
		Na	К	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
		774	0.15	0.44	0.29	0.316	0.004	0.022	0.024	0,366	81,362	14,384	0,920	0,163	6,978
4A(4)	a	7,20	0.14	0.26	0.30	0.327	0.004	0.013	0.025	0,368	88,172	25,180	0,526	0,150	8,775
4A(4)	D	7,51	0,14	0,20	0.20	0.315	0.003	0.009	0.024	0.351	93,949	35,063	0,377	0,141	9,693
4A(4)	c	7,24	0,13	0,18	0,29	0,313	0,003	0.014	0.026	0.364	82 259	22.064	0.550	0,147	7,922
4A(4)	d	7,34	0,15	0,29	0,32	0,319	0,003	0.019	0.024	0.415	110.040	19.979	0.774	0.141	8,796
4A(4)	e	8,48	0,13	0,37	0,29	0,309	0,003	0,018	0.022	0.325	86 942	34 357	0.382	0.151	9,605
4A(4)	1	• 6,70	0,13	0,17	0,27	0,291	0,003	0,006	0,022	0.246	80 742	52 014	0.243	0.157	10 283
4A(4)	g	7,16	0,15	0,12	0,30	0,311	0,004	0,000	0,025	0,540	61,128	22,014	0,245	0145	6 508
4A(4)	h	7,19	0,20	0,27	0,43	0,313	0,005	0,013	0,035	0,36/	61,120	23,214	0,301	0,173	0.686
4A(4)	i	6,62	0,17	0,11	0,30	0,288	0,004	0,005	0,025	0,322	68,007	52,463	0,222	0,172	5,000
4A(4)	j	6,58	0,13	0,54	0,30	0,286	0,003	0,027	0,025	0,341	85,385	10,622	1,092	0,136	5,009
4A(4)	k	5,35	0,15	0,21	0,34	0,233	0,004	0,010	0,028	0,275	59,957	22,209	0,375	0,139	0,154
4B(1)	а	6,90	0,14	0,47	0,32	0,300	0,004	0,023	0,026	0,354	81,010	12,798	0,891	0,141	6,104
4B(1)	ь	7,08	0,15	1,14	0,32	0,308	0,004	0,057	0,026	0,395	79,345	5,414	2,161	0,147	3,748
4B(1)	c	10,03	0,14	0,88	0,32	0,436	0,004	0,044	0,026	0,510	117,758	9,936	1,668	0,141	6,265
4B(1)	d	7,64	0,13	0,47	0,29	0,332	0,003	0,023	0,024	0,383	99,140	14,170	0,983	0,141	7,096
4B(1)	e	7,08	0,17	0,77	0,49	0,308	0,004	0,038	0,040	0,391	69,824	8,016	0,953	0,109	3,968
4B(1)	f	7,19	0,14	0,50	0,32	0,313	0,004	0,025	0,026	0,368	84,415	12,536	0,948	0,141	6,172
4B(1)	g	7.24	0,14	0,78	0,31	0,315	0,004	0,039	0,026	0,383	85,002	8,092	1,526	0,145	4,946
4B(1)	h	7,07	0,23	0,64	0,62	0,308	0,006	0,032	0,051	0,396	52,822	9,630	0,626	0,114	3,778
4B(1)	i	7,17	0.24	0,56	0,47	0,312	0,006	0,028	0,039	0,385	50,508	11,161	0,723	0,160	4,775
48(1)	i	6.79	0.20	0,35	0,45	0,295	0,005	0,017	0,037	0,355	57,727	16,912	0,472	0,138	5,515
48(2)	a	7.35	0.19	1.24	0,50	0,320	0,005	0,062	0,041	0,427	67,117	5,167	1,504	0,116	3,150
48(7)	b	7,21	0.14	0.45	0,30	0,314	0,004	0,022	0,025	0,364	88,882	13,967	0,910	0,143	6,729
48(2)	c	7.30	0.14	0,11	0,31	0,318	0,004	0,005	0,026	0,352	85,706	57,852	0,215	0,145	10,367
48(2)	d	9.25	0.14	0.36	0.33	0,402	0,004	0,018	0,027	0,451	108,601	22,399	0,662	0,136	9,002
48(2)		716	0.14	0.73	0.33	0.311	0.004	0,036	0,027	0,379	88,266	8,550	1,342	0,130	4,955
48(2)	ĩ	725	0.14	0.50	0.30	0.315	0.004	0.025	0.025	0,369	85,119	12,640	1,011	0,150	6,429
40(2)		711	014	0.65	0.31	0 309	0.004	0.032	0.026	0.371	87.649	9,536	1,272	0,138	5,399
40(2)	8	7,11	0.14	0,03	0.31	0 305	0,004	0.016	0.026	0.350	82.164	19.069	0.626	0,145	7,432
40(2)	n	820	0,14	0,52	0.21	0 357	0.004	0.038	0.026	0.424	101.057	9.406	1.487	0.138	5,680
40(2)	1	7.45	0,14	0.76	0.28	0 324	0,004	0.013	0.031	0.372	83 492	74.979	0.415	0.124	7.414
48(2))	7/45	0,15	0,20	0,50	0,323	0,004	0.021	0.030	0 387	RO AOR	15 489	0.725	0.125	6,580
48(3)	a	7,64	0,14	0,43	0,30	0,332	0,004	0,021	0.024	0366	87350	22 365	0.607	0.155	8.541
48(3)	b	7,44	0,14	0,29	0,29	0,324	0,004	0,014	0,024	0.363	100 402	21 300	0,569	0121	7 799
48(3)	c	7,33	0,12	0,30	0,32	0,319	0,003	0,015	0,020	0.347	04.460	62 463	0,225	0.151	11 766
4B(3)	d	7,28	0,13	0,10	0,2/	0,317	0,003	0,005	0,022	0,297	94,409	11 258	1 173	0.136	6130
4B(3)	e	7,49	0,13	0,58	0,30	0,326	0,003	0,029	0,025	0,565	97,199	11,230	0,607	0.170	5 217
4B(3)	f	7,60	0,28	0,49	0,49	0,331	0,007	0,024	0,040	0,403	45,702	13,321	0,007	0,179	7 217
4B(3)	g	7,46	0,16	0,29	0,37	0,325	0,004	0,014	0,030	0,373	79,969	22,425	0,475	0,133	7,004
4B(3)	h	7,30	0,14	0,38	0,32	0,318	0,004	0,019	0,026	0,36/	85,706	16,/4/	0,720	0,141	6.013
4B(4)	а	7,22	0,19	0,18	0,46	0,314	0,005	0,009	0,038	0,366	63,575	34,967	0,237	0,131	0,513
4B(4)	b	7,33	0,17	0,55	0,39	0,319	0,004	0,027	0,032	0,383	75,301	11,618	0,855	0,132	5,428
4B(4)	c	7,38	0,17	0,25	0,47	0,321	0,004	0,012	0,039	0,377	72,782	25,734	0,323	0,114	6,364
4B(4)	d	7,20	0,15	0,17	0,34	0,313	0,004	0,008	0,028	0,354	80,690	36,921	0,303	0,139	8,699

SAMPLE		1 co	NCENTRATI	ON (ppm)	1		CC	NCENTRAT	ION (meq/l)	1		R	ATIOS (calcula	ated in meq/l)	1
		Na	К	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
40/45		9.54	0.17	0.42	0.35	0 377	0.004	0.021	0.029	0.427	87.937	17354	0.745	0.147	7,495
4D(4)	e	7.63	0.14	0,45	0.31	0 332	0.004	0.030	0.026	0.391	94.060	10.904	1,194	0,138	5,996
4D(4)	1	7,03	0,14	0.56	0.46	0.321	0.005	0.028	0.038	0.391	64,896	11,473	0.738	0.131	4,949
48(4)	g	0.22	0,19	0,30	1 58	0.402	0.011	0.014	0.130	0.557	36.122	27.745	0.111	0.086	2,857
4C(1)	a	9,23	0,45	0,29	1,50	0.251	0,004	0.019	0,029	0.404	90,552	18.061	0.676	0.135	7.365
4C(1)	D	8,08	0,15	0,39	0,35	0,551	0,004	0,015	0,020	0 398	83 399	13.043	0.876	0.137	6.164
4C(1)	c	7,78	0,16	0,52	0,36	0,330	0,004	0,020	0,007	0 385	88 983	38,454	0 331	0.143	9.668
4C(1)	d	7,94	0,15	0,18	0,33	0,345	0,004	0,002	0,027	0,000	01 450	10126	1 232	0136	5.655
4C(1)	e	7,79	0,14	0,67	0,33	0,339	0,004	0,033	0,027	0,405	91,439	10,130	0.381	0135	8 914
4C(1)	F	8,06	0,15	0,22	0,35	0,351	0,004	0,011	0,029	0,394	75 028	5 757	1 602	0.130	3,667
4C(1)	h	7,00	0,16	1,06	0,38	0,305	0,004	0,053	0,031	0,393	75,030	3,/3/	0.320	0,130	5 507
4C(1)	1	7,76	0,23	0,31	0,57	0,338	0,006	0,015	0,047	0,406	57,977	21,822	0,330	0,124	4 422
4C(1)	i	12,47	0,30	0,35	1,30	0,542	0,008	0,017	0,107	0,675	69,875	31,059	0,163	0,0/3	2.089
4C(1)	k	7,73	0,28	0,39	0,81	0,336	0,007	0,019	0,067	0,429	47,646	17,278	0,292	0,106	3,900
4C(2)	a	11,05	0,23	0,73	1,25	0,481	0,006	0,036	0,103	0,626	82,558	13,196	0,354	0,057	3,494
4C(2)	b	9,79	0,25	0,37	0,78	0,426	0,006	0,018	0,064	0,515	67,049	23,066	0,288	0,099	5,231
4C(2)	c	9,75	0,16	0,39	0,42	0,424	0,004	0,019	0,035	0,482	104,517	21,794	0,563	0,117	7,928
4C(2)	d	9,22	0,20	0,32	0,55	0,401	0,005	0,016	0,045	0,467	78,387	25,117	0,353	0,113	6,636
4C(2)	e	8,07	0,19	1,15	0,57	0,351	0,005	0,057	0,047	0,460	73,692	6,117	1,224	0,102	3,412
4C(2)	f	8,98	0,22	0,15	0,61	0,391	0,006	0,007	0,050	0,454	69,189	52,188	0,149	0,113	6,872
4C(2)	h	8,22	0,19	0,37	0,37	0,358	0,005	0,018	0,030	0,411	75,062	19,367	0,607	0,157	7,410
4C(2)	i	6,60	0,25	0,33	0,40	0,287	0,006	0,016	0,033	0,343	45,201	17,435	0,500	0,193	5,944
4C(2)	i	8,35	0,25	0,73	0,69	0,363	0,006	0,036	0,057	0,463	57,186	9,971	0,642	0,112	3,966
4C(3)	a	9,12	0,32	0,52	0,55	0,397	0,008	0,026	0,045	0,476	48,882	15,289	0,574	0,179	5,687
4C(3)	b	9,10	0,20	0,67	1,32	0,396	0,005	0,033	0,109	0,543	77,366	11,840	0,308	0,047	2,823
4C(3)	d	9,46	0,30	0,63	1,14	0,412	0,008	0,031	0,094	0,544	53,009	13,090	0,335	0,083	3,348
4C(3)	e	12,74	0,35	0,93	1,81	0,554	0,009	0,046	0,149	0,758	62,822	11,942	0,312	0,059	2,883
4C(3)	f	10,16	0,30	0,33	1,59	0,442	0,008	0,016	0,131	0,597	58,255	26,839	0,126	0,058	3,053
4C(3)	g	10,36	0,24	0,71	1,22	0,451	0,006	0,035	0,100	0,593	72,980	12,720	0,353	0,062	3,364
241 d	0	24,58	0,59	0,73	3,24	1,069	0,015	0,036	0,267	1,387	70,468	29,353	0,137	0,057	3,579
241c		24,95	0,63	0,72	3,40	1,085	0,016	0,036	0,280	1,417	66,864	30,208	0,128	0,058	3,490
241b		17.67	0,73	0,50	3,70	0,769	0,019	0,025	0,304	1,117	41,100	30,807	0,082	0,061	2,391
241.a		14.90	0.68	0.32	3,43	0,648	0,017	0,016	0,282	0,964	37,486	40,591	0,057	0,061	2,232
24 2 a		24.50	0.50	0,74	2,83	1,066	0,013	0,037	0,233	1,348	82,747	28,862	0,159	0,055	3,999
24 5 d		22.25	0.90	0.69	4.38	0.968	0,023	0,034	0,360	1,386	41,876	28,111	0,096	0,064	2,511
2450		30.92	0.58	1.04	2.72	1.345	0.015	0,052	0,224	1,635	90,755	25,918	0,232	0,066	4,933
2456		31.76	0.64	1.50	3.00	1,382	0,016	0,075	0,247	1,720	84,199	18,458	0,303	0,066	4,347
245 0		1847	0.43	0.51	2.07	0.803	0.011	0.025	0,170	1,010	72,283	31,571	0,149	0,065	4,162
2458		21.02	0.58	0.65	2 79	0.954	0.015	0.032	0,230	1,231	64.368	29,411	0,141	0,065	3,698
2451		21,23	0.50	1 22	2 28	1.537	0.013	0.061	0.188	1,798	120,982	25.040	0,327	0,068	6,225
24 51		33,33	0,50	فنقرا	2,20	10000	0,01.5	0,005	0,100		an op out	and a set			

CAMPLE 1	co	NCENTRATI	ON (ppm)	1		CO	NCENTRATI	ION (meg/l)	1		R	ATIOS (calcula	ited in meq/l)	
SAMILE	Na	K	Ca	Mg	Na	K	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	A./A.E.
						0.024	0.107	0.480	200	50 250	18 512	0.210	0.068	3 385
18 A1 j	45,66	1,31	2,15	5,95	1,986	0,034	0,107	0,489	2,010	39,230	10,515	0,215	0,000	2 844
18 A1 i	52,85	2,73	2,38	8,66	2,299	0,070	0,119	0,714	3,201	32,988	19,358	0,100	0,090	2,011
18 A1 h	48,77	1,69	1,92	6,28	2,121	0,043	0,096	0,517	2,777	49,079	22,143	0,185	0,004	3,333
18 A1 g	49,27	1,19	2,05	5,50	2,143	0,030	0,102	0,452	2,728	70,626	20,952	0,226	0,067	3,910
18 A1 f	46,80	1,00	2,45	4,19	2,036	0,026	0,122	0,345	2,528	79,577	16,652	0,355	0,074	4,415
18 A1 e	34,41	. 0,99	2,18	4,06	1,497	0,025	0,109	0,334	1,965	58,916	13,760	0,326	0,076	3,438
18 A1 d	25,63	0,83	1,21	3,42	1,115	0,021	0,060	0,281	1,478	52,224	18,465	0,215	0,076	3,325
18 A1 c	30,68	0,77	1,19	3,16	1,335	0,020	0,059	0,260	1,674	67,538	22,475	0,228	0,076	4,241
18 A1 b	39,74	0,61	1,61	2,50	1,729	0,016	0,080	0,206	2,030	110,090	21,517	0,391	0,076	6,100
18 A1 a	36,87	0,57	1,51	2,20	1,604	0,015	0,075	0,181	1,875	109,523	21,286	0,416	0,081	6,314
18 A2 a	20,60	0,75	0,69	2,70	0,896	0,019	0,034	0,222	1,172 .	46,596	26,026	0,155	0,087	3,568
18 A2 b	15,31	0,62	0,51	2,36	0,666	0,016	0,025	0,194	0,901	41,941	26,169	0,131	0,082	3,105
18 A2 c	12,10	0,58	0,35	1,18	0,526	0,015	0,017	0,097	0,656	35,515	30,137	0,180	0,153	4,725
18 A2 d	11.10	0.41	0,31	1,70	0,483	0,011	0,015	0,140	0,649	45,612	31,214	0,111	0,076	3,177
18 A2 e	11.29	0.32	0.32	1,38	0,491	0,008	0,016	0,114	0,629	59,225	30,756	0,141	0,073	3,857
18 A2 f	9,20	0.24	0.25	0,50	0,400	0,006	0,012	0,041	0,460	64,808	32,080	0,303	0,150	7,581
18 A2 g	10.55	0.24	0.32	1.09	0,459	0,006	0,016	0,090	0,571	74,318	28,740	0,178	0,069	4,403
18 A2 h	8.71	0.20	0.22	0.34	0,379	0,005	0,011	0,028	0,423	74,051	34,513	0,393	0,183	9,860
18 A2 i	8.39	0.20	0.25	0,36	0,365	0,005	0,012	0,030	0,412	71,330	29,256	0,421	0,173	8,793
18 A2 i	7.33	0.22	1.63	0.40	0,319	0,006	0,081	0,033	0,439	56,476	3,920	2,472	0,172	2,840
18 A3 a	7.31	0.26	0.29	0.66	0,318	0,007	0,014	0,054	0,393	48,711	21,974	0,267	0,120	4,719
18 A3 b	6.58	0.24	0.15	0,50	0,286	0,006	0,007	0,041	0,341	46,352	38,240	0,182	0,150	6,015
18 A3 c	7.06	0.20	0.09	0.40	0,307	0,005	0,004	0,033	0,350	60,023	68,383	0,136	0,155	8,349
18 A3 d	7.04	0.20	0.14	0,41	0,306	0,005	0,007	0,034	0,352	59,853	43,836	0,207	0,152	7,648
18 A3 e	7.07	0.20	0,14	0,38	0,306	0,005	0,007	0,031	0,351	60,108	44,023	0,223	0,164	8,175
18 A3 f	7.52	0.20	0,64	0,43	0,327	0,005	0,032	0,035	0,400	63,934	10,243	0,903	0,145	4,936
18 A3 g	7.91	0.23	0.17	0.47	0.344	0,006	0,008	0,039	0,397	59,098	40,562	0,219	0,151	7,422
18 43 6	849	0.23	0.17	0.47	0.369	0.006	0,005	0,039	0,422	63,431	43,536	0,219	0,151	7,957
18 431	7.75	0.21	0.15	0.42	0.337	0.005	0.007	0,035	0,384	63,693	45,040	0,217	0,153	8,146
18 431	716	0.15	0.16	0.30	0.311	0.004	0.008	0,025	0,348	80,242	39,011	0,324	0,157	9,655
18 44 2	726	010	0.18	0.18	0.316	0.003	0.009	0.015	0.342	119,331	35,160	0,607	0,179	13,387
18 44 6	6.41	0.21	0.10	0.23	0.279	0.005	0.005	0.019	0.308	50,981	55,879	0.264	0,289	11,891
18 44 0	6.25	012	0.09	0.17	0.276	0.003	0.004	0.014	0.298	92.095	61,506	0.321	0,214	15,113
10 A4C	610	0.12	015	017	0.265	0.003	0.007	0.014	0.290	83,554	35,451	0.535	0,227	12,507
10 /4 6	5.00	013	0.19	0.24	0.257	0.003	0.009	0.020	0.289	76.561	27.070	0.480	0,170	8,897
18 A41	4.53	0.03	1.94	0.05	0197	0.001	0.097	0.004	0.299	223,377	2.036	23,537	0,214	1,961
18 A7 D	4,55	0.03	7.48	0.08	0180	0.001	0.124	0.007	0.311	204.145	1,455	18,805	0,134	1,389
10 47 6	4.11	0.04	0.11	0.05	0179	0.001	0.005	0.004	0.189	168,888	32,572	1,335	0,257	18,730
18 A7 d	4,11	0,04	0.42	0,05	0,180	0,001	0.021	0.007	0,209	145.818	8.593	3,185	0.188	6,584
18 A7 C	4,14	0.07	0.57	0.11	0107	0,002	0.028	0.009	0.232	108.976	6.760	3,143	0,195	5,175
10 A/1	4,42	0.05	0.15	0.077	0184	0,001	0.007	0.006	0.198	148,636	24.525	1,300	0.214	13,955
18 A7g	4,22	0,05	0,15	0,07	0167	0,001	0,006	0.005	0.179	135,252	27,896	1,213	0,250	15,405
18 A7 h	3,84	0,05	0,12	0,06	0,10/	0,001	0,003	0.006	0155	116.936	41 346	0.607	0.214	15.744
18 A7 i	3.34	0,05	0,07	0,07	0,144	0,001	0,000	0,000	0,100	110,000	11,010	0,000		and as

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SAMPLE	co	NCENTRATI	ON (ppm)	1		CC	NCENTRATI	ON (meg/l)	1		R	ATIOS (calcula	ated in meq/l)	
	Na	K	Ca	Mg	Na	K ·	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	A./A.E.
18 A7 i	3.24	0.08	0.27	0.10	0.141	0.002	0,013	0,008	0,165	66,569	10,461	1,638	0,257	6,593
18 48 3	2.86	0.08	0.09	0.09	0.124	0.002	0.004	0,007	0,138	58,762	27,702	0,607	0,286	10,638
18 A8 c	3.52	0.06	0.09	0.05	0.153	0.002	0.004	0,004	0,163	96,429	34,095	1,092	0,386	17,981
18 B1 k	3.68	0.08	0.12	0.08	0.160	0.002	0.006	0.007	0,175	75,609	26,733	0,910	0,322	12,905
18 B1 b	3.80	0.07	0.11	0.07	0.165	0.002	0.005	0.006	0,178	93,690	30,115	0,953	0,306	14,854
16 B1 a	4.05	012	011	0.11	0.177	0.003	0.005	0.009	0.194	55,611	32,175	0,607	0,351	12,367
16 B7 a	4 78	0.09	0.20	0.12	0.208	0.002	0.010	0.010	0,230	90,655	20,835	1,011	0,232	10,590
10 02 4	4,10	010	0.16	0.09	0.203	0.003	0.008	0.007	0.221	76.596	25,390	1,078	0,357	13,346
10 02 0	4,00	0,10	0.26	0.10	0.202	0.003	0.013	0.008	0.226	76.431	15,591	1,577	0,322	9,666
10 D2 C	4,05	0.13	2.05	0.12	0 203	0.003	0.102	0.010	0.318	60,470	1.982	10,363	0,340	1,837
18 B2 d	00, P	0,15	2,05	0,12	0,210	0,000	0.016	0,010	0 240	59 419	12 733	1.668	0.357	8.095
18 B2 e	9,52	0,14	0,33	0,12	0,210	0,004	0,010	0,009	0,235	79 425	7.148	3,033	0.273	5.444
18 B2 F	4,51	0,10	0,55	0,11	0,196	0,002	0,027	0.012	0,196	52 036	31 779	0.445	0.272	9.977
18 B2 g	4,01	0,13	0,11	0,15	0,1/4	0,003	0,003	0,012	0,198	44.267	13 146	1 517	0.450	8.101
18 B2 h	3,77	0,14	0,25	0,10	0,164	0,004	0,012	0,006	0,100	71 857	4 873	6 376	0.429	4 266
18 B2 i	4,08	0,10	0,73	0,07	0,177	0,002	0,036	0,000	0,222	47 461	3 770	4 200	0 330	3.075
18 B3 a	3,85	0,14	0,90	0,13	0,16/	0,004	0,045	0,011	0,227	47,401	10.034	3,200	0 327	8 207
18 B3 b	4,39	0,08	0,35	0,07	0,191	0,002	0,017	0,006	0,216	98,397	10,934	3,033	0,515	20 581
18 B3 c	3,55	0,08	0,07	0,05	0,154	0,002	0,003	0,004	0,164	72,938	44,210	0,649	0,515	17 820
18 B3 d	3,48	0,08	0,09	0,05	0,151	0,002	0,004	0,004	0,162	78,000	33,707	1,092	0,472	16,010
18 B3 f	3,64	0,12	0,07	0,08	0,158	0,003	0,003	0,007	0,171	52,791	45,331	0,531	0,456	10,010
18 B3 g	3,82	0,10	0,07	0,07	0,166	0,003	0,003	0,006	0,178	62,789	47,572	0,607	0,460	15,248
18 B3 h	3,56	0,09	0,11	0,06	0,155	0,002	0,005	0,005	0,168	67,517	28,213	1,112	0,465	15,075
18 B3 j	3,38	0,11	0,30	0,08	0,147	0,003	0,015	0,007	0,171	52,084	9,822	2,275	0,429	0,903
18 B3 k	3,54	0,10	0,08	0,05	0,154	0,002	0,004	0,004	0,165	62,343	38,575	0,971	0,601	19,304
18 B4 a	3,76	0,10	0,17	0,10	0,164	0,002	0,008	0,008	0,183	66,217	19,281	1,031	0,300	9,937
18 B4 b	3,90	0,08	0,10	0,06	0,170	0,002	0,005	0,005	0,182	80,130	33,998	1,011	0,429	8 486
18 B4 c	3,94	0,07	0,31	0,06	0,171	0,002	0,015	0,005	0,194	97,142	11,080	3,134	0,357	5,071
18 B4 d	3,86	0,06	0,47	0,06	0,168	0,002	0,023	0,005	0,198	105,744	7,159	4,752	0,322	0,971
18 B4 e	3,85	0,07	0,26	0,05	0,167	0,002	0,013	0,004	0,186	94,923	12,909	3,154	0,429	9,903
18 B4 f	3,87	0,07	0,08	0,05	0,168	0,002	0,004	0,004	0,178	95,416	42,171	0,971	0,429	20,988
18 B4 g	3,93	0,08	0,46	0,06	0,171	0,002	0,023	0,007	0,203	80,746	7,448	3,488	0,322	5,860
18 B4 h	3,80	0,08	0,10	0,09	0,165	0,002	0,005	0,007	0,180	78,075	33,126	0,674	0,286	13,509
18 B4 j	3,99	0,08	0,10	0,08	0,174	0,002	0,005	0,007	0,187	81,979	34,783	0,758	0,322	15,183
18 B5 c	4,28	0,09	0,07	0,10	0,186	0,002	0,003	0,008	0,200	81,173	53,301	0,425	0,279	16,083
18 B5 f	4,37	0,09	0,10	0,08	0,190	0,002	0,005	0,007	0,204	82,880	38,095	0,758	0,349	16,627
18 B5 h	429	0,08	0,51	0,05	0,187	0,002	0,025	0,004	0,218	88,143	7,333	6,187	0,515	6,384
18 B5 i	4.44	0,08	0,10	0,06	0,193	0,002	0,005	0,005	0,205	99,518	38,705	1,011	0,393	19,654
18 B5 i	4.46	0,08	0.09	0,07	0,194	0,002	0,004	0,006	0,206	91,635	43,200	0,780	0,368	19,136
18 B5 k	4.55	0.12	0.11	0,15	0,198	0,003	0,005	0,012	0,219	65,989	36,058	0,445	0,243	11,270
18 B6 a	4.73	0.12	0.13	0.09	0,206	0,003	0,006	0,007	0,223	68,600	31,718	0,876	0,405	15,029
18 B6 b	4.68	0.14	0.10	0.10	0,204	0,004	0,005	0,008	0,220	57,693	40,798	0,607	0,429	15,671
18 B6 c	5.05	0.13	0.33	0,11	0,220	0,003	0,016	0,009	0,249	65,531	13,340	1,820	0,370	8,741
18 116 4	513	014	017	0.13	0.223	0.004	0.008	0.011	0,246	60,229	26,306	0,793	0,346	11,830

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FRAZIL ICE: Granular medium

SAMPLE	00	NCENTRATI	ON (nom)	1		CO	NCENTRAT	ION (meg/l)	RATIOS (calculated in meq/l)					
	Na	K	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	A./A.E.
10.00	E 10	015	0.78	015	0.226	0.004	0.014	0.012	0.256	58,164	16,158	1,132	0,315	8,728
18 B0 e	5,19	0,15	0,20	1.49	0.228	0.024	0.009	0.123	0,383	9,623	23,996	0,077	0,193	1,902
18 86 1	5,23	0,92	0.14	0.12	0.231	0.004	0.007	0.010	0.252	56.921	33,064	0,708	0,411	13,943
18 B6 g	5,51	0,16	0,14	0,12	0.286	0,004	0,008	0.013	0.311	73 630	33,690	0.645	0.295	13,383
18 B6 h	6,57	0,15	0,17	0,16	0,200	0,004	0,000	0.017	0317	64 597	28,550	0.578	0.255	10,616
18 B6 i	6,55	0,17	0,20	0,21	0,285	0,004	0,017	0,015	0 365	71 595	18 805	1.180	0.310	10,319
18 B6 j	7,55	• 0,18	0,35	0,18	0,328	0,005	0,017	0,015	0,305	(4.070	20,208	0124	0.060	3 510
243d	23,19	0,61	0,69	3,12	1,009	0,016	0,034	0,257	1,315	04,972	29,290	0,134	0,000	3,319
243e	14,49	0,50	0,42	2,64	0,630	0,013	0,021	0,217	0,881	48,939	30,075	0,097	0,059	2,701
243f	15,88	0,42	0,57	2,08	0,821	0,011	0,028	0,171	1,032	76,310	28,875	0,166	0,063	4,170
2431	30.97	0,67	0,88	4,34	1,347	0,017	0,044	0,357	1,765	78,719	30,679	0,123	0,048	3,403
243 j	36,55	1,01	1,05	5,73	1,590	0,026	0,052	0,471	2,140	61,303	30,345	0,111	0,055	3,085

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SAMPLE		1 co	NCENTRATI	ON (ppm)	1		co	NCENTRATI	ON (meq/l)	RATIOS (calculated in meq/l)					
		Na	К	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
14(4)		18.80	0.39	0.68	1.48	0.818	0.010	0.034	0.122	0.983	82,771	24,101	0,279	0,081	5,317
1/5(9)		12 70	0.31	0.43	1.35	0.552	0.008	0.021	0.111	0,693	69,583	25,747	0,193	0,071	4,229
1 A(4)	D	13.70	0.35	0.54	1.48	0.596	0.009	0.027	0.122	0.753	67,555	22,116	0,221	0,072	4,067
1.4(4)	c	13,70	0,35	0,54	1 64	0.544	0,010	0.025	0135	0.713	55.034	21.794	0.165	0.073	3,463
1A(4)	d	12,50	0,39	0,50	1,04	0,544	0,010	0.024	0145	0.750	50,466	23.306	0.169	0.078	3,434
1A(4)	e	13,10	0,44	0,49	1,70	0,570	0,011	0,024	0143	0.753	54 747	22,563	0.178	0.074	3,469
1A(4)	1	13,20	0,41	0,51	1,74	0,574	0,011	0,023	0,143	0,829	63 764	19 517	0.251	0.077	3.976
1A(4)	g	15,00	0,40	0,67	1,62	0,655	0,010	0,033	0,155	1.022	68 165	21 284	0.250	0.078	4.316
1A(4)	h	18,80	0,47	0,77	1,87	0,818	0,012	0,038	0,154	0,624	39 271	17 435	0,250	0.082	2 732
1A(4)	1	10,40	0,46	0,52	1,75	0,452	0,012	0,026	0,144	0,034	30,271	14 975	0,160	0.076	2145
1C(1)	j	48,80	2,59	2,86	10,67	2,123	0,066	0,143	0,878	3,210	31,999	14,073	0,105	0,070	2,404
1C(1)	i	44,50	2,06	1,52	8,77	1,936	0,053	0,076	0,721	2,786	36,694	25,521	0,105	0,073	5 415
1C(1)	d	109,80	3,50	5,00	7,89	4,776	0,069	0,250	0,649	5,764	53,395	19,143	0,364	0,138	3/413
1C(1)	c	179,80	1,48	6,77	3,95	7,821	0,038	0,338	0,325	8,522	206,187	23,152	1,040	0,117	11,039
1C(1)	a	178,30	3,93	4,69	15,25	7,756	0,101	0,234	1,254	9,345	77,123	33,141	0,187	0,080	5,278
2B(1)	i	34,10	0,80	1,72	3,30	1,483	0,020	0,086	0,271	1,861	72,478	17,283	0,316	0,075	4,209
2B(1)	h	46,00	0,75	2,06	3,05	2,001	0,019	0,103	0,251	2,374	104,050	19,466	0,410	0,077	5,712
2B(1)	8	52,00	0,90	4,29	5,71	2,262	0,023	0,214	0,470	2,969	98,621	10,567	0,456	0,049	3,342
3 A3f	-	64,50	1,04	2,33	4,63	2,806	0,027	0,116	0,381	3,330	105,315	24,132	0,305	0,070	5,697
3 A3 g		69,70	1,21	2,48	4,99	3,032	0,031	0,124	0,410	3,597	98,198	24,500	0,301	0,075	5,733
3 A3h		85,80	2,70	3,17	13,89	3,732	0,069	0,158	1,143	5,102	53,965	23,595	0,138	0,061	2,922
3 A4 a		57,30	2,04	2,03	8,43	2,493	0,052	0,101	0,693	3,340	47,728	24,606	0,146	0,075	3,202
3 A4 c		41,10	2,20	1,49	9,70	1,788	0,056	0,074	0,798	2,716	31,766	24,046	0,093	0,071	2,114
3 A4 d		54,80	2,53	1,95	10,76	2,384	0,065	0,097	0,885	3,431	36,815	24,498	0,110	0,073	2,492
3 A4e		110,50	1,81	3,91	7,10	4,807	0,046	0,195	0,584	5,632	103,985	24,636	0,334	0,079	6,229
3 A5 d		90,70	1,57	3,26	6,08	3,945	0,040	0,163	0,500	4,648	98,080	24,254	0,325	0,080	6,013
3 A5e		77,10	1,52	2,69	5,57	3,354	0,039	0,134	0,458	3,985	86,405	24,986	0,293	0,085	5,727
3 A5f		56,20	1,41	1,96	5,55	2,445	0,036	0,098	0,457	3,035	67,591	24,996	0,214	0,079	4,475
3 A5g		49,60	0,81	1,72	3,19	2,158	0,021	0,086	0,262	2,527	103,636	25,139	0,327	0,079	6,256
3 A5h		47,10	1,07	1,59	4,16	2,049	0,027	0,079	0,342	2,498	74,920	25,823	0,232	0,080	4,925
3 A51		56.30	0.70	1,93	2,68	2,449	0,018	0,096	0,220	2,784	137,435	25,430	0,437	0,081	7,788
3 451		72.60	1.86	2.56	7.32	3,158	0,047	0,128	0,602	3,935	66,542	24,722	0,212	0,079	4,392
3 463		45.20	2.34	1.68	9,83	1,966	0,060	0,084	0,809	2,918	32,874	23,454	0,104	0,074	2,270
3 466		61.00	2.03	2.07	8.59	2.654	0,052	0,103	0,707	3,515	51,155	25,689	0,146	0,073	3,340
3 460		82 80	2.46	2.85	10.44	3.602	0.063	0.142	0.859	4,666	57,344	25,326	0,166	0,073	3,661
3 A6C		101.60	2,40	3.63	12 29	4.420	0.074	0.181	1.011	5,686	59,785	24,399	0,179	0,073	3,769
3 460		06.40	2,09	3 32	11 30	4.193	0.069	0.166	0.937	5,365	60,478	25,312	0,177	0,074	3,866
3 A0e		96,50	2.02	3.05	# 27	3 763	0.052	0.152	0.680	4.647	72,788	24,723	0,224	0,076	4,582
3 A61		80,50	2,02	3,00	6,67	4.063	0.044	0.169	0 549	4 824	93,231	24.089	0.307	0.079	5,725
3 A6g		93,40	1,70	3,30	6,67	4,003	0.045	0.193	0.564	5 530	106.125	24,594	0.341	0.079	6,317
3 A6 h		108,90	1,75	3,00	4 70	5 181	0.033	0 214	0 394	5.821	157.873	24.258	0.542	0.083	8,581
3 A61		119,10	1,28	4,28	4,79	3,101	0,009	0.159	0.293	4 201	98 045	23,402	0.402	0.096	6.782
3 B1 c		85,10	1,48	3,17	4,78	3,702	0,057	0,103	0,705	3 270	42 104	23,486	0.146	0.061	3,060
3 B1 a		55,50	2,24	2,06	8,57	2,414	0,037	0,103	0,705	2 505	62 514	24 077	0.226	0.087	4.517
1721		46.40	1,26	1,68	4,50	2,018	0,032	0,004	0,370	2,000	02,014	14,011	wya.a.w	0,007	

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SAMPLE		1 co	NCENTRATI	ON (ppm)	1		ct	NCENTRAL	ION (meq/l)	1		RATIOS (calculated in meg/			0
Srini LL		Na	к	Ca	Mg	Na	к	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA,E,
						1.054	0.007	0.194	0.204	4 562	158 474	21 782	0.629	0.086	8,460
172h		93,20	1,00	3,73	3,60	4,054	0,026	0,180	0,290	2,244	146 216	22 400	0,530	0.087	8 281
172g		68,20	0,79	2,53	2,85	2,967	0,020	0,126	0,2.34	3,140	140,210	23,477	0,222	0.064	5 722
172 f		64,50	1,23	2,42	4,56	2,806	0,031	0,121	0,375	3,333	89,341	23,234	0,322	0,004	5,722
172 e		58,60	1,21	2,18	4,46	2,549	0,031	0,109	0,367	3,056	82,560	23,433	0,297	0,084	5,424
172d		39,30	1,13	1,41	4,14	1,710	0,029	0,070	0,341	2,149	59,082	24,298	0,207	0,085	4,231
16B(3)	d	. 40,70	1,68	1,33	6,52	1,770	0,043	0,066	0,536	2,416	41,126	26,680	0,124	0,080	3,009
168(3)	e	66,30	2,31	2,46	9,63	2,884	0,059	0,123	0,792	3,858	48,795	23,490	0,155	0,075	3,217
168(3)	f	44,00	1,59	1,62	5,63	1,914	0,041	0,081	0,463	2,499	47,167	23,680	0,175	0,088	3,593
16B(3)	8	57,10	1,21	2,25	4,38	2,484	0,031	0,112	0,360	2,987	79,989	22,120	0,312	0,086	5,322
16B(3)	h	56,20	1,53	1,93	5,84	2,445	0,039	0,096	0,480	3,061	62,416	25,380	0,200	0,082	4,307
16B(3)	i	97.20	1.74	3,55	5,06	4,228	0,044	0,177	0,416	4,866	95,099	23,870	0,426	0,107	7,201
16B(4)		101.40	1.41	3,61	5,47	4,411	0,036	0,180	0,450	5,077	122,551	24,490	0,400	0,080	7,057
16B(4)	b	72.00	1.43	2.54	5,64	3,132	0,037	0,127	0,464	3,759	85,757	24,710	0,273	0,079	5,364
16B(4)	c	71,70	1.21	2.57	4,43	3,119	0,031	0,128	0,364	3,643	100,442	24,320	0,352	0,085	6,394
16B(4)	d	82.70	1.48	3.53	5,52	3,597	0,038	0,176	0,454	4,265	95,280	20,420	0,388	0,083	5,768
16B(4)		72.80	2.74	2.97	9.74	3,167	0,070	0,148	0,801	4,186	45,212	21,370	0,185	0,087	3,409
16B(4)	F	61.20	1.73	2.51	6.63	2,662	0.044	0,125	0,545	3,377	60,356	21,260	0,230	0,081	4,035
16B(4)		58.20	1.77	2.20	6.04	2.532	0.045	0,110	0,497	3,184	55,834	23,060	0,221	0,091	4,248
16B(4)	b	40.00	2.73	1.42	10.34	1.740	0.070	0.071	0,851	2,731	24,904	24,560	0,083	0,082	1,964
168(5)		36.90	2.03	1.24	7.89	1.605	0.052	0.062	0,649	2,368	30,945	25,940	0,095	0,080	2,331
100(3)	1	30,60	136	1.25	5.60	1.723	0.035	0.062	0.461	2,280	49,561	27,620	0,135	0,075	3,360
168(5)		52 20	114	1.74	4 37	2 271	0.029	0.087	0.359	2,746	78,000	26,150	0,242	0,081	5,153
160(5)		61 10	1.41	2.08	5 37	2 658	0.036	0.104	0.442	3,240	73,485	25,610	0,235	0,082	4,938
100(5)	8	53 70	1.63	1.87	6.23	2,336	0.042	0.093	0.512	2,983	56,101	25,030	0,182	0,081	3,925
168(5)	e	40.40	2 25	1.29	7.42	1.757	0.058	0.064	0,610	2,490	30,554	27,300	0,105	0,094	2,690
168(5)	u	45 30	1.41	1.52	5.21	1.971	0.036	0.076	0,429	2,511	54,749	25,980	0,177	0,084	3,978
168/5)	h	51 30	1.68	1.77	5.93	2,232	0.043	0.088	0,488	2,851	51,837	25,270	0,181	0,088	3,948
16B(5)		65.80	4.06	2.38	9.87	2,862	0.104	0.119	0,812	3,897	27,544	24,100	0,146	0,128	3,187
160(3)		64.60	215	2.38	9.22	2,810	0.055	0.119	0,758	3,742	51,213	23,660	0,157	0,072	3,266
160(6)	h	73.00	2.88	2.66	12.23	3.176	0.074	0.133	1.006	4,388	43,161	23,920	0,132	0,073	2,853
160(0)		103.90	3.28	3.71	13.85	4.520	0.084	0.185	1,139	5,928	53,817	24,410	0,162	0,074	3,476
160(0)	d	103.40	4.01	3.64	15.42	4.498	0.103	0.182	1,268	6.050	43,879	24,760	0,143	0,061	3,173
160(6)	u	100.80	3.10	3.60	13.16	4.385	0.079	0.180	1.083	5,726	55,228	24,410	0,166	0,073	3,537
100(0)	6	81 70	3 72	2.05	15.84	3 554	0.095	0.147	1.303	5.099	37.372	24.140	0.113	0,073	2,516
100(0)		77.60	3,72	2,95	14 51	3 158	0.086	0.150	1.194	4.588	36,680	21.030	0.126	0.072	2,414
168(6)	8	50.50	2.20	3,01	0.07	2 588	0.059	0130	0.746	3 523	44.186	19.950	0.174	0.079	3.022
168(6)		59,50	1.00	2,00	717	3 603	0,039	0159	0.590	4 4 91	75 296	23,270	0.269	0.083	5,000
168(6))	04,90	1,92	3,10	1,17	0,490	0,019	0.012	0137	0.655	26 673	40 790	0.088	0.134	3.413
25B(2)	a	11,23	0,72	0,24	1,00	0,409	0,018	0,012	0,137	0,603	49 265	42 755	0.097	0.085	3.872
25B(2)	b	10,79	0,37	0,22	1,57	0,409	0,010	0,010	0.124	0.625	47 797	45.870	0.084	0.061	3.643
258(2)	c	11,05	0,39	0,21	1,51	0,401	0,010	0,010	0125	0,620	43 362	40 245	0.096	0.089	3,500
258(2)	d	11,08	0,43	0,24	1,52	0,402	0,011	0,012	0.006	0.260	81 942	49 254	0.867	0.521	23.146
233b		5,65	0,12	0,10	0,07	0,240	0,003	0,005	0,000	0.283	120 862	49,457	1 335	0.472	28 471
233c		6,24	0,08	0,11	0,05	0,2/1	0,002	0,000	0,004	0,203	137,003	17/132	1000	0/11/2	20/11



SAMPLE	1 co		CO	NCENTRATI	ON (meg/l)	RATIOS (calculated in meq/l)								
	Na	K	Ca	Mg	Na	К	Ca	Mg	Σ4	Na/K	Na/Ca	Ca/Mg	K/Mg	AJA.E.
233 g	6,36	0,08	0,07	0,07	0,277	0,002	0,003	0,006	0,288	130,673	79,204	0,607	0,368	30,134
234 a	6,89	0,10	0,12	0,10	0,300	0,003	0,006	0,008	0,317	113,250	50,053	0,728	0,322	21,272
234 c	6.31	0.13	0,15	0,18	0,274	0,003	0,007	0,015	0,300	81,881	36,671	0,506	0,226	12,464
23.4 d	7.03	0.17	0.08	0,22	0,306	0,004	0,004	0,018	0,332	72,219	76,604	0,221	0,234	14,036
234 e	6.44	0.18	0.11	0,26	0,280	0,005	0,005	0,021	0,312	61,069	51,037	0,257	0,214	10,594
234 f	7.18	0.14	0.08	0,21	0,312	0,004	0,004	0,017	0,337	88,512	78,239	0,231	0,204	14,852
23.4 0	12.86	0.23	0.23	0.32	0,559	0,006	0,011	0,026	0,603	96,081	48,742	0,436	0,221	14,953
23.4 h	11.91	0.21	0.13	0.30	0.518	0,005	0,006	0,025	0,555	97,881	79,865	0,263	0,214	16,794
24.2 c	25.03	0.46	0.76	2.96	1.089	0.012	0,038	0,243	1,382	92,108	28,710	0,156	0,049	3,911
24 2 d	17.97	0.48	0.56	2.67	0.782	0,012	0,028	0,220	1,042	63,294	27,974	0,127	0,056	3,207
242.0	18.10	0.37	0.60	2.60	0.787	0.009	0.030	0,214	1,041	84,200	26,298	0,140	0,044	3,268
24 2 f	21,22	0,43	0,65	2,11	0,923	0,011	0,032	0,174	1,140	84,385	28,459	0,187	0,063	4,534

agglomeration of marine ice. On the other hand, the diffusion coefficients of K and Mg in seawater are very different. Therefore, it may be possible to find evidence of selective diffusion by using K/Mg ratios.

Figures 173 to 176 show the K/Mg ratios versus the total amount of cations (Σ 4) respectively for the four groups of marine ice investigated:

- congelation and platelet ice
- congelation and granular fast ice
- granular frazil ice
- rectangular and wave-like frazil ice.

The study of these diagrams indicates that for concentrations higher than 10 meq/l for the $\Sigma4$, the K/Mg ratios are quite constant, slightly less than the K/Mg ratio in seawater.

This discrepancy can however be easily explained since, following Meese (1989), K is slightly depleted in the ice (1-2%) and Mg slightly enriched (1-2%). When coefficients approach the upper values of K depletion and Mg enrichment found by Meese, the K/Mg ratios in our marine ice samples above 10 meg/l for the four cations can then be understood.

In the case of frazil ice, either rectangular, wave-like, or granular, there is a substantial increase in the K/Mg ratio for concentrations lower than 10 meg/l for the $\Sigma4$ compared to the previous example. The increase is such that more than a



Figure 173. K/Mg versus Σ 4: congelation ice and platelet ice.

Figure 174. K/Mg versus ∑4: fast ice.



Figure 175. K/Mg versus ∑4: frazil ice, granular.



Figure 176. K/Mg versus Σ 4: frazil ice, rectangular and wave-like.



doubling of the seawater ratio is observed. It is quite possible that the highest values for granular ice may not be significant. A certain number of samples are grouped in the low concentration range below the ratio displayed in the ice for concentrations higher than 10 meq/1, but closer to these values than the samples enriched in K/Mg.

Furthermore, the increase in K/Mg ratio for the low salinity ice samples probably reflects the influence of a diffusional process as will be demonstrated below.

Ben Yaakov (1972), in an experiment, considered the evolution of the chemical composition of a distilled water reservoir in controlled contact with seawater over the course of time. The results indicate that the K/Mg ratios are quite high in the beginning of the process when only a few ‰ of the seawater content has been attained in the water reservoir.

Our interpretation is that a similar phenomenon has occurred under the Hells Gate Ice Shelf. Diluted seawater present at the interface, probably in the form of pockets where the underside of the ice shelf is domed (see the photographs of the Koettlitz Ice Tongue, figure 177, courtesy of A. Gow and the radio echo sounding diagram, figure 30), could progressively be invaded by salt migration in accordance with the chemical gradient between the water and the "normal seawater" underneath.

In agreement with the difference between the diffusion coefficient of K and Mg, K will increase faster than Mg and



consequently, the ice formed will have a higher K/Mg ratio. This interpretation implies that the pocket of diluted seawater is continuously replenished in the interval of time during which the frazil ice formed.

It is possible to infer the origin of the diluted water at the base of the Hells Gate Ice shelf by considering the isotopic analyses performed on the marine ice samples. The δ values of these marine ice samples are quite positive, precluding any influence of continental ice melt.

Seawater sampled near the edge of the Hells Gate Ice Shelf between 0 and 200 m depth has δ^{18} O values close to ice shelf water (Jacobs et al, 1985).

Seawater samples, congelation, platelet, and frazil ice samples are aligned on a $\delta D - \delta^{18}O$ diagram (figure 178), on a slope of 6.6 (correlation coefficient of 0.93).





This slope can be considered as a freezing slope. Indeed, the freezing slope on which ice samples, due to water freezing, are aligned on a $\delta D - \delta^{1*}O$ diagram can be calculated using the equation:

$$S = \left(\frac{\alpha - 1}{\beta - 1}\right) \times \left(\frac{1000 + \delta_{i}D}{1000 + \delta_{i}^{18}O}\right)$$

where α and β are the respective equilibrium fractionation coefficients for deuterium and oxygen 18 (taken usually at α = 1.0208 and β = 1.003), and $\delta_1 D$ and $\delta_1^{16}O$ are the respective δ values for the initial water at the beginning of the freezing process.

Taking $\delta_i D = -4\%$ and $\delta_i^{18}O = -0.6\%$ (mean values of seawater at the ice shelf's edge), the calculated slope is 6.9, which is fairly close to the measured value. The difference between the δ values of most frazil ice samples and seawater samples is higher than the maximum possible shift which can be obtained by a single freezing event, thus precluding seawater as a parent water for frazil ice. This would still be true if a 2‰ higher α value had been considered, a possibility that might exist for deuterium but only for seawater of high salinity (Beck and Münnich, 1988).

The parent water for frazil ice must be a water of relatively low salinity compared with seawater. Indeed, salinity of the parent water can be calculated if the frazil ice salinity and the distribution coefficient are known. Antarctic sea ice salinities given in the literature (Gow et al, 1987: Lange, 1988) usually range between 3 and 6 ppt for frazil ice, with very low values at 2 ppt or very high values around 15 ppt in freshly consolidated pancake ice (Eicken and Lange, 1989). Since this sea ice was formed from Antarctic surface seawater, deduced distribution coefficients (sea ice salinity/seawater salinity) will usually range between 0.09 and 0.17 with extreme values of 0.06 and 0.44.

It can be assumed that the ratio Na/salinity is 0.3074 in the ocean and is independent of the salinity level for a large range of salinities (Riley and Skirrow, 1965), and that the same ratio is valid for arctic sea ice (Meese, 1989). Using a Na content typical of the low salinity frazil population (0.025 ppt), a maximum salinity of less than 1.35 ppt is obtained for the parent water of the frazil ice samples at Hells Gate.

Such a low salinity is however not probable. Indeed, at the base of the Hells Gate Ice Shelf, the salinity of the water at the interface is governed by the thermodynamic equilibrium implying that at a given temperature below 0°C, the salinity of the interfacial water is fixed by the liquidus. In the summer, the temperature of seawater near the Hells Gate Ice Shelf is likely to be about -0.5°C at the level of the base of the ice shelf. This is a consequence of a warm water intrusion similar to the one described in Jacobs (1985). At such a temperature value, the salinity deduced from the liquidus at the interface is about 10% (Doake, 1976). The low salinity of the frazil ice can however be understood by taking into account such a 10% salinity pocket (or layer), by assuming that the frazil ice crystals formed in this water progressively agglomerate at the base of the ice shelf, the low salinity water remaining as brines. This gives a difference compared to the previous situation where the distribution coefficients were deduced from Antarctic sea ice formed from surface seawater.

On the other hand, the relatively low freezing rate occurring at the base of the ice shelf will also be responsible for a stronger salt expulsion.

Now, can water of such low salinity be surface meltwater from marine ice percolating through tide cracks to the underside of the ice shelf, such as Gow and Epstein (1972) considered for the Koettlitz Glacier Tongue near the Dailey Islands, McMurdo sound, Antarctica?

Meltwater ponds effectively exist at the surface of the Hells Gate Ice Shelf near its front. Several arguments can however be given which tend to indicate that this possibility is excluded here. First, not a single open crack has been encountered at the surface of the ice shelf where meltwater ponds are present and no islands with their attendant tide cracks exist in the ablation zone. Second, the zone of low salinity frazil ice appearing at the ice shelf surface is quite extensive and not restricted to the proximity of a possible break through percolation system. The zone of frazil ice at the shelf surface is in fact more extensive upstream than the zone where meltwater ponds are developed. Finally, there is no upper layer of water with low salinity in front of the ice shelf.

Thus, as shown by δ values as well as chemical measurements, only meltwater of marine ice from the bottom of the ice shelf can serve as the source of frazil ice. Such water originates from shelf bottom accreted congelation ice, the melting of which occurs without isotopic or chemical fractionation (Friedman *et al*, 1964; Moser and Stichler, 1980).

C. <u>Marine Ice Transfer Along the Bottom of the Hells Gate Ice</u> <u>Shelf.</u>

The decrease in salinity and the increase in δ values from congelation to platelet and frazil ice, and the development of frazil ice downstream from congelation and platelet ice (figure 179) indicate marine ice transfer along the bottom of the ice shelf (Souchez *et al*, 1991). The meltwater produced by the melting of congelation ice is less dense than surrounding water, because at temperatures close to the freezing point, the density of seawater is primarily a function of salinity (Dietrich *et al*, 1980).



Figure 179. Marine ice transfer along the bottom of Hells Gate Ice Shelf.



Consequently, melting of ice at depth can produce supercooled water since meltwater rises because of its lower density, and supercooling with respect to the *in situ* freezing point occurs since the pressure is reduced.

As developed by Jenkins and Doake (1991), turbulent entrainment can provide a mechanism which supplies the heat required to warm the ascending current and sustain basal melting further downstream. This process becomes less efficient as the water reaches more shallow depths, since the temperature contrast decreases. Then, supercooling, frazil ice formation, and basal accretion will result. The development of frazil ice within the water column as a result of supercooling seems sufficiently efficient to prevent upward flow of low salinity excess meltwater at the sea surface.

D. Conclusion

Using ice cores retrieved from Hells Gate Ice Shelf, a small ice shelf located in Terra Nova Bay, Victoria Land, this dissertation has analyzed chemical, isotopic and crystallographic characteristics to determine the origins of the ice contributing to this ice shelf. These studies were supplemented by detailed statistical analyses.

Several ice types were identified on the basis of crystallographic studies. They included continental ice (both glacier ice and basal ice) and marine ice (congelation and platelet ice, granular frazil ice, rectangular and wave-like frazil ice and fast ice). Isotopic analyses performed on these various ice types and on seawater underneath indicate that no water of continental origin exists in this environment and that meltwater from marine ice contributes to the formation of the ice types accreted at the base of the ice shelf.

In order to elucidate the mechanisms of formation of the various marine ice types, chemical analyses were also conducted.

Factor analysis of the results shows that, in most ice cores, Na and Ca on the one hand and K and Mg on the other, are highly correlated. This indicates that the first salts likely to precipitate after calcium carbonate are sodium sulfate and calcium sulfate with little or no K or Mg salts precipitating at temperatures warmer than -10°C.

The study of the K/Mg ratios in the various marine ice types shows that congelation ice, platelet ice and fast ice have ratios corresponding to those found in seawater. However, for rectangular, wave-like and granular frazil ice of low salinity (total cation contents of less than 10 meq/l), the K/Mg ratios may increase and depart significantly from the seawater ratio.

This situation can be interpreted on the basis of diffusional processes taking place in diluted water at the underside of the ice shelf where it is domed and could be progressively invaded by migration of cations in accordance

with the chemical gradient between the diluted water and normal seawater beneath it.

According to the difference between the diffusion coefficient of K and Mg, K will increase faster than Mg and the ice formed subsequently will have a higher K/Mg ratio. In order to maintain high K/Mg ratio, the pockets of diluted seawater would need to be continuously replenished during the time that frazil ice is forming.

The decrease in salinity and the increase in δ values from congelation to platelet and frazil ice indicate marine ice transfer along the bottom of the Hells Gate Ice Shelf.

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