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GEOCHEMICAL STUDY ON THE STRANDLINE GLACIER, TERRA NOVA BAY, ANTARCTICA

Abstract: GHERMANDI G., MENEGHEL M. & SIGHINOLFI G.P., *Geochemical Study on the Strandline Glacier, Terra Nova Bay, Antarctica.* (IT ISSN 0391-9838, 1993).

A chemical study has been carried out on ice samples, collected from the Strandline Glacier during the Italian Antarctic Expedition to Terra Nova Bay (Antarctica) in 1989-90, in order to investigate sources and mode and type of transport of elements and compounds present. Main lithophile (Na, K, Ca, Mg, Fe), trace lithophile (Ti, V, Cr, Mn) and heavy metals (Zn, Cu, Ni) were determined by flame and flameless A.A. spectroscopic and PIXE (Particle Induced X-ray Emission) analysis in a series of samples collected in a longitudinal section of the frontal portion of the glacier. After collection, samples were melted and acidified with HNO_3. Analysis was performed on the whole sample without filtration of the particulate matter. Element abundances for both main and trace lithophile and heavy metals are much higher than literature data for polar ice and snow. In particular, samples from the frontal cliff zone are especially enriched in «crustal» lithophiles. Element overabundancies derive from the presence of solid particles of different origin (continental terrestial and cosmic) and of seasalt by local strong aerosol. Excess of heavy metals correlates to improper control of contamination problems from field sampling to laboratory analysis. Calculation of crustal enrichment factors (EF) taking Ti as normalizing element suggests that the chemistry of samples from the frontal zone is essentially controlled by the amount of rock particles from the substratum inglobed in the glacier during its movement. On the contrary, the chemistry of the surface ice samples derives from atmospheric or tropospheric introduction of dissolved constituents and solid particles of different origin (primary marine aerosol, continental and cosmic dust, etc.). In these samples, the abundances of cosmogenic elements like Ni and Fe-Ni ratios confirm that in polar ice the ratio of cosmic dust to terrestrial dust is significantly high. This study suggests that chemical data may constitute valuable support to investigate interactions between glacier and substratum rock and thus to reconstruct past and present dynamics of glaciers.

KEY WORDS: Glaciology, Geochemistry, Antarctica.

Riassunto: GHERMANDI G., MENEGHEL M. & SIGHINOLFI G.P., *Studio geochimico sul Ghiacciaio Strandline, Baia Terra Nova, Antartide.* (IT ISSN 0391-9838, 1993).

Uno studio chimico è stato effettuato su campioni di ghiaccio, raccolti sul Ghiacciaio Strandline durante la Spedizione Italiana 1989-90 nel territorio di Baia Terra Nova (Antartide), per ricercare la provenienza e il tipo di trasporto degli elementi e dei composti presenti. Gli elementi litofili principali (Na, K, Ca, Mg, Fe), gli elementi litofili in traccia (Ti, V, Cr, Mn) e i metalli pesanti (Zn, Cu, Ni) sono stati determinati con spettroscopia di A.A. (alla fiamma e in fornetto di grafite) e con analisi PIXE (Particle Induced X-ray Emission) in una serie di campioni raccolti lungo una sezione longitudinale della porzione frontale del ghiacciaio. Dopo la raccolta, i campioni sono stati sciolti e acidificati con HNO_3. L'analisi è stata condotta sull'intero campione senza filtraggio del particolato. L'abbondanza degli elementi sia litofili principali e in traccia, sia dei metalli pesanti è particolarmente elevata in confronto con i dati della letteratura su ghiaccio e neve delle regioni polari. In particolare i campioni raccolti lungo la falesia frontale del ghiacciaio sono assai arricchiti di elementi litofili «crostali». La sovrabbondanza degli elementi deriva dalla presenza di particelle solide di differente origine (terrestre continentale e cosmica) e di sali marini di provenienza locale. L'eccesso di metalli pesanti è legato a contaminazione durante la raccolta dei campioni. Il calcolo dei fattori di arricchimento crostale (EF) utilizzando il Ti come elemento normalizzante suggerisce che la chimica dei campioni della zona frontale è essenzialmente legata ai detriti rocciosi del substrato inglobati nel ghiaccio alla base del ghiacciaio. Al contrario, la chimica dei campioni della superficie deriva dall'introduzione per via atmosferica di costituenti dissolti e di particelle solide di origine differente (aerosol marino, polveri di origine continentale e cosmica, ecc.). In questi campioni l'abbondanza di elementi cosmogenici quali Ni e i rapporti Fe-Ni confermano che nel ghiaccio polare il rapporto tra la polvere cosmica e quella terrestre è alto in modo significativo. Questo studio dimostra che i dati chimici costituiscono un valido strumento per indagare le interazioni tra il ghiacciaio e le rocce del substrato e così ricostruire la dinamica presente e passata dei ghiacciai.

TERMINI CHIAVE: Glaciologia, Geochimica, Antartide.

INTRODUCTION

In recent times an increasing number of chemical data on snow and ice from polar areas have been used in the tentative of solving stimulating problems such as those of the composition of the present and past Earth's atmosphere, of the extent of element pollution from natural sources and human activities, of the assess of the variation in time of cosmic dust deposition, etc.

To face such problems, materials usually used by scientists consist of ice and snow samples collected on the sur-

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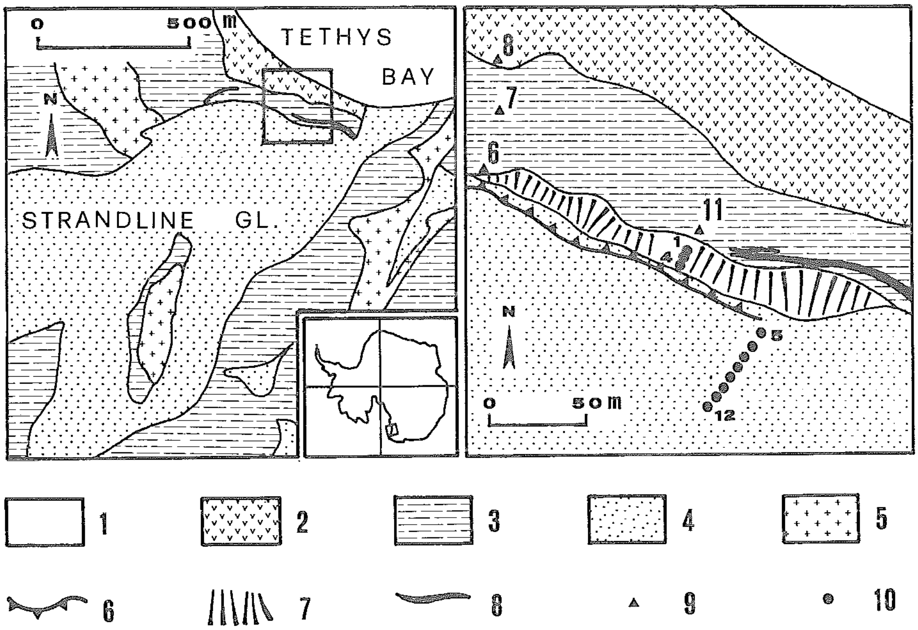

FIG. 1 - General view of the Strandline Glacier and of the collecting sample area. 1: sea; 2: beach deposits; 3: glacial deposits and other deposits of various origin; 4: glacier and snow fields; 5: rock outcrops; 6: ice cliff; 7: apron; 8: moraine; 9: check point of the glacier front position; 10: sampling point.

Mode of occurrence of elements and compounds

face of the inlandsis or from ice cores. Less studies were carried out on dynamically active masses like outlet and local glaciers, whose movements are very sensitive to the global conditions of the polar environment.

In glacier ice foreign elements and compounds may accumulate either by atmospheric transport and by direct contribution from bedrock. Estimate of the relative amounts of these two components in different parts of a glacier may thus provide information on the internal dynamics and ice-rock interaction processes.

On the basis of these observations, we carried out a preliminary study on different portions of the Strandline Glacier, a small glacier localized on the coast of Terranova Bay, Antarctica. Additional purposes are to present comparative results for different sample collection and analytical procedures to allow optimization of these last in facing different scientific problems.

GENERALITIES ON THE CHEMISTRY OF POLAR ICE SAMPLES

The diffuse use of chemical and isotopic parameters for solving a number of different problems leads to an increased knowledge about general processes controlling the chemistry of polar ice. Important topics, such as mode of occurrence of elements and compounds, short- and long-distances transport mechanisms, identification of source regions, etc. are now rather well known. These knowledges, together with the nature of the specific problem that should be faced, result to be critical in the choice of the experimental procedure from field sampling to laboratory analysis.

The following are some informations about main processes and parameters affecting ice chemistry.

Mode of occurrence of elements and compounds

According to current studies elements and compounds are present in ice and snow essentially as dissolved species and solid particles of extremely varying size and different origin. Usually, available data reported in literature refer to melted ice previously submitted to filtration with 0.45 μm pore diameter filter. In this manner, any contribution from particles larger than this size is driven out. This last fraction, however, contains most of the cosmic dust (THOMPSON, 1977; LAVIOLETTE, 1983, 1985) and part of the weathering products of continental areas. Thus the literature data strongly underestimate the true abundance levels of «extraterrestrial» (e.g. Pt, Ir, Ni, etc.) and «crustal» lithophile (e.g. Si, Al, Ti, K, etc.) elements. On the other hand, filtration with 0.45 μm filter should not affect abundance levels of the elements present essentially as dissolved form such as heavy metals (Pb, Zn, Cu, Hg, etc.) and «marine» constituents (Cl, Na, Mg, SO_4).

Sources of elements and compounds

According to current views main possible elements sources are the following: a) weathering of continental crustal rocks, b) marine and maritime-related aerosol, c) cosmic dust and debris, d) pollution and derived products, e) volcanic activity (ash and fumarole condensates), f) unknown sources.

When the abundance levels for elements in ice and snow are compared with those in the earth's crust, they have been distinguished in «crustal» and «enriched» elements. The enrichment correlates to some sort of process that may be natural or anthropogenic and may be active either over short or long distance. Possible natural sources for element enrichments (see e.g. BOUTRON & *alii*, 1984;

LAJ & BOUTRON, 1990) includes volcanoes, metal-enriched sea surface microlayers, gaseous emission from deep-seated rocks, etc. Still debated is the general extent of industrial pollution for elements like Pb and Zn in polar areas (see e.g. NG & *alii*, 1981; BOUTRON & PATTERSON, 1983; BOUTRON & WOLFF, 1989).

Problems for interpretation of chemical data

There are several reasons for difficulties in interpreting glacial record data. One problem concerns the diversity of possible natural and anthropogenic sources and of mode and range of element transport. For example, volcanic emission may provide material which is enriched in certain elements to the same degree as industrial emissions (DUCE & *alii*, 1975). Another problem arises from the partial lack of understanding of aerosol transport from the atmosphere and its incorporation into snow (DAVIDSON & *alii*, 1981). However, the major problem associated with the analysis of most trace constituents (especially of heavy elements like Pb, Cd, Zn, Cu, Hg, etc.) is contamination. Recently, some authors (e.g. GÖRLACH & BOUTRON, 1991) remark that most published time series (e.g. previous data of BOUTRON, 1980, 1982) must be considered highly erroneous because of improper control of contamination problems. The simple use of accurate and sophisticated metal detection instruments and ultraclean laboratories (BOUTRON, 1990) will not provide correct element analyses, as reliability of them depends primarily on exclusion of artifact contamination during sample collection, transport and treatment. For this reason, a number of authors have worked developing procedures to minimize as far as possible contamination risk. This essentially appears to be attained maintaining the sample frozen until laboratory and reducing contamination from external sources by mechanical removing of the external layer of ice. Detail of theses procedures are reported in a number of papers (BOUTRON & *alii*, 1984, 1987, 1990; BATIFOL & *alii*, 1989; LAJ & BOUTRON, 1990; GÖRLACH & BOUTRON, 1991).

FEATURES OF THE STRANDLINE GLACIER

The Strandline Glacier is a small coastal alpine-type glacier (0.79 km^2) which front reaches the coast of the Gerlache Inlet, Terra Nova Bay, Victoria Land. First glaciological measurements on the Strandline Glacier were made by CHINN (1985). More recently, scientists involved in the Italian Antarctic Programme of interdisciplinary researches (MANZONI & ZUCCHELLI, 1991) have conducted systematic monitoring of glaciological parameters (see e.g. OROMBELLI, 1986; BARONI & OROMBELLI, 1987; ZANON, 1988; BARONI, 1988; CHINN & *alii*, 1989; MENEGHEL & SMIRAGLIA, 1991).

One important reason for investigating small coastal glaciers in Antarctica is that they are very sensitive to even small climatic changes and therefore they can give indications of glacial Holocene fluctuation records.

The Strandline Glacier is a cold glacier with accumulation and ablation areas irregularly distributed and controlled by wind regimes. Main ablation areas are in the terminal convex zone, crossed by some small crevasses. The front of the glacier, opening in the small Tethys Bay (fig. 1), presents in the central part an ice cliff 25 m high, changing laterally into a short dome and ramp margin. The foliation is well evident along the frontal cliff, showing a syncline structure. A small and discontinuous apron of snow and ice is present at the base of the cliff. Moraines are visible along the lateral margins of the front. Two Holocene ice advances, possibly younger than 4500 yr B.P. were recognized. Presently, the glacier is stable or in a weak retreat phase.

ANALYZED MATERIAL

Ice samples were collected, during the Italian Antarctic Expedition to Terra Nova Bay in 1989-90, on the front of the glacier starting from the apron at the base of the cliff and on the terminal convex zone, following a line ap-

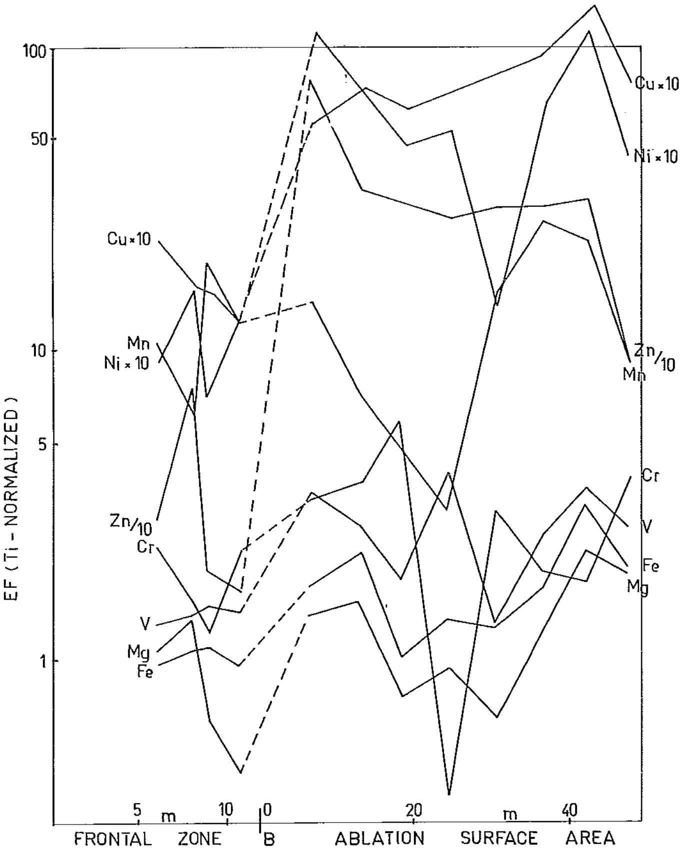

FIG. 2 - Crustal element enrichment factors EF$_{crust}$ (Ti-normalized) for samples from the frontal zone (numbers: height from the base) and from the ablation surface area (numbers: distances from the cliff margin).

proximately perpendicular to the foliation. Thus the collected samples will constitute a sequence of decreasing age, although it is very difficult to prospect an even roughly age of oldest samples (probable maximum age: few hundreds years).

Samples 201-204 were collected on the frontal cliff in the apron zone at distances variable between 1 and 3 m (see also fig. 2). The remaining samples were collected on the terminal ablation surface starting from the margin of the cliff at distances of approximately 6 m between each other.

For purpose of comparison, two samples of surface ice from the Boomerang Glacier, another local glacier localized in the Terra Nova Bay region, some dozens kilometres far from the coast, were also analyzed.

SAMPLING PROCEDURES

Ice pieces of adequate size were collected using cleaned steel tools (ice hammer) and immediately stored in one litre polyethilene bottles. Cleaning procedures for tools and containers are those standard. Additionally, the set of tools before sampling were cleaned by several successive rinsing in the snow. Since there was no possibility to maintain frozen the samples until analysis, they were immediately acidified with Suprapure Grade Merck HNO_3 adding 1 ml conc. acid to about 500 ml sample. Such a procedure results in possible contaminations by the inner side of the container but presents the following advantages: a) sample solutions result stabilized in time by preventing removing of elements exchange with the polyethilene wells (Murozumi & *alii*, 1969); b) the acidification results in an almost complete dissolution of the present solid particles, thus avoiding further sample treatment in laboratory (Boutron & Patterson, 1983; Bolshov & *alii*, 1989). Consequently, the analytical results refer to sample as a whole, including either dissolved constituents and solid particles. Only in two cases (samples 201 and 202) a solid residue was found by filtration after acidification with HNO_3. Thus, for these two samples bulk element abundances result underestimated.

INSTRUMENTAL ANALYSIS

Main lithophile elements (Ca, Mg, Na, K and Fe) and few trace elements were determined directly on the melted sample by flame and flameless A.A. spectroscopy using Perkin-Elmer Mod. 603 and Mod. 3030 Zeeman spectrophotometers. All other trace constituents were determined by PIXE (Particle Induced X-ray Emission) analysis using 1.8 MeV proton beam from Van de Graaf accelerator of Laboratory I.N.F.N. of Legnaro (Padua). Element preconcentration was made inside clean laboratory (Cecchi & Ghermandi, 1991) of the Modena University using NaDDTC-APDC extraction at pH 4 starting from 15 ml solution (Aprilesi & *alii*, 1984; Cecchi & *alii*, 1987).

The analytical error is difficult to estimate on the basis of the overall evaluation of relative contributions of different kind of errors in the entire procedure. For example, for heavy metals, the measurement error includes both the standard deviation of the blank, the percentage error during sample treatment and preconcentration procedures (generally less then 10%), and the error in the fit of PIXE spectrum (see Cecchi & *alii*, 1990). For the main elements Na, K, Mg, Fe, Ca and for some trace lithophiles (Ti, Cr) errors may estimated to be 5-20%.

ANALYTICAL RESULTS

Analytical data for 12 ice samples from the Strandline Glacier and for 2 samples of the Boomerang Glacier are reported in table 1 and 2 together with some data drawn from the literature for ice and snow of polar areas. Comparison between our data and literature data indicates that abundances levels for pratically all elements are extremely higher (by factors up to several hundreds) in the material here analyzed.

At first sight, one could think that the observed overabundancies correlate to analytical errors or contaminations, taking also into account the different procedure used for sample collection and storage. This is supported also by recent affirmation of Görlach & Boutron (1991) that most of the previous published data on polar ice should be considered to be highly erroneous because of improper control of contamination problems.

In our case, however, although contamination to some extent (especially for heavy metals) are highly probable, element overabundance can be considered to be correlated essentially to the contribution of solid particles present in the unfiltered sample and to the strong input of primary marine aerosol.

The localization of the glacier near the coast favours the concentration of seasalt elements (Na, Ca, K, Mg). As regards possible element contribution by particulate matter, it should be noted that the fraction of solid particles larger than 0.45 μm, especially those of cosmic origin, is significant when compared to the total mass of solids present in polar ice.

Analytical results from tables 1 and 2 indicate that ice samples collected in the frontal cliff zone of the Strandline Glacier are much more higher in pratically all the constituents when compared to samples collected on the ablation surface area of the same glacier and to samples from the Boomerang Glacier. On the basis of the whole chemistry (and element ratios), one can conclude that samples from the surface of the glaciers are quite similar (apart a generalized element overabundance) to ice from polar areas. On the contrary, samples from the frontal cliff of the Strandline present a distinct chemistry in terms of both absolute element abundances and element ratios, being particularly enriched in some lithophile «crustal» elements like Fe, Ca, Ti, V, Cr, Mn.

TABLE 1 - Element abundances in ice samples from the Strandline and Boomerang glaciers.

Sample	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	Fe mg/l	Ni µg/l	Ti µg/l	Zn µg/l	V µg/l	Cr µg/l	Mn µg/l	Cu µg/l
Strandline Glacier												
900130 201	(15)	1.8	0.34	1.55	3.44	4.35	356	122	11	14	64	7.8
202	3.25	0.34	0.23	0.39	0.74	1.46	70	64	2.3	1.8	7.4	1.10
203	2.20	0.62	0.044	0.53	2.26	1.90	207	48	7.5	4.3	70.9	3.1
204	1.56	0.84	0.01	0.58	3.18	3.58	331	67	11.7	12.5	73.6	4.12
205	0.73	0.20	0.10	0.062	0.190	0.78	11	101	0.93	0.63	2.69	1.29
206	0.93	0.155	0.044	0.062	0.215	0.91	9.7	40	0.64	0.62	1.26	0.76
207	0.75	0.155	0.10	0.056	0.179	1.09	17.8	66	0.78	1.82	5.55	1.05
208	0.52	0.10	0.044	0.048	0.169	0.86	12.5	41	1.24	0.08	0.63	—
209	0.45	0.155	0.062	0.038	0.133	0.26	14.4	52	0.44	0.75	3.75	—
210	1.34	0.21	0.062	0.076	0.258	1.32	15.3	55	0.93	0.50 +	6.90 +	1.40
211	1.29	0.10	0.027	0.046	0.161	0.76	5.0	19	0.44	0.15	1.93	1.03
212	2.40	0.21	0.044	0.160	0.406	1.18	20.6	23	1.34	1.35	3.43	1.58
Boomerang Glacier												
900131 201	0.154	0.10	0.027	0.105	0.241	0.61	22.6	41	0.79	1.96	7.17	1.56
202	1.90	0.33	0.062	0.206	0.329	2.33	36.8	22	0.33	4.37	1.93	2.94

TABLE 2 - Element concentration ranges in the Strandline and Boomerang Glacier and in other polar snow and ice samples.

	Na ug/l	K ug/l	Mg ug/l	Ca ug/l	Fe ug/l	Mn ng/l	Ti ng/l	Cu ng/l	Ni ng/l	Cr ng/l	Zn ng/l
Strandline Glacier	450-3250	100-600	38-530	10-62	161-740	63C	>5000	760-7800	260-4350	150-14000	>1900
Boomerang Glacier	154-1900	100-330	105-206	27-62	241-329	>19D	>2000	>1560	>1610	>1960	>22000
(this paper)											
Vegetation Island	450-820	57-78	119-165	159-162							
Mount Crunner	268-436	20-37	42-64	41-47							
Campbell Glacier	816	74	67-136	65-158							
Priestley Glacier-snow	190	41-57	86-139	53-54							
Reeves Glacier	330	172	394	115							
(Piccardi et al., 1989)											
Reeves-Campbell-Priestely								140-240	180-340	18-42	
(*Saini et al., 1989*)											
Recent snow Greenland and Antarctica											
near the coast	350	13-16	42-45	13-17							
far from the coast	32	1-2	4	1-2							
(*Murozumi et al., 1969*)											6-44
Ice core, Dome C Antarctica								3-18			
(*Batifol et al., 1969*)											

SOURCES OF ELEMENTS AND COMPOUNDS AND TRANSPORT MECHANISM

To define the source for element and compounds in ice and, consequently, their transport mechanisms, it is appropriate to compare their abundance levels with those for various possible source regions or processes (ocean, continental areas, volcanoes, industrial activities, etc.). Particularly indicative is the computation of the crustal enrichment factor (EF_{crust}, RAHN, 1976) with respect to average crustal material (TAYLOR, 1964), usually calculated taking aluminium as normalizing element. On the basis of the EF_{crust} values, the elements present in polar ice and snow have been distinguished (see e.g. LAJ & BOUTRON, 1990) in «crustal» and «enriched» elements, these last resulting concentrated with respect to their crustal abundances by some sort of enrichment processes.

In the present study, for the calculation of the EF_{crust} values we used titanium as normalizing element on the basis of the following considerations: a) Ti is a typical lithophile crustal element and the Al/Ti ratio in most rocks (either magmatic and sedimentary) is quite constant; b) the analytical precision for Ti at ultratrace levels is much better than that for Al for many techniques (including flameless A.A. spectroscopy and PIXE).

The calculated X element EF_{crust} expressed as X/Ti sample / X/Ti crust are graphically reported on fig. 2 while in table 3 average EF values for samples collected on the frontal cliff and on the ablation surface of the Strandline Glacier are reported. From these data the following considerations can be drawn:

1) for samples collected in the frontal section of the glacier the EF values for most main and trace crustal lithophile elements (e.g. Ca, K, Fe, Cr, Mn, V) and for nickel are not much dissimilar from the unity. This indicates that bulk chemistry of these samples is essentially controlled by the presence of compounds of «average» crustal composition. Taking into account the very high element abundances, these compounds should consist of solid particles.

2) The EF values for samples collected on the surface of the glacier (both Strandline and Boomerang) tend to be higher than for samples of the frontal cliff zone. The increase of the EF values is not similar for all elements. For a group (e.g. Fe, Cr, V, Mg) the increase is quite limited. For other elements (e.g. Ni, K, Na and heavy metals in general) the increase may be very strong (up to 10-100 times).

On the basis of these observations some hypotheses can put forward about the mode of occurrence, the source regions and the transport mechanism for elements in the different parts of the glacier. For samples from the frontal cliff whose chemistry is controlled by the content of solid particles of «average» crustal composition, we should prospect a transport mechanism which does not cause element fractionation. We suggest that almost the totality of these solid particles are or bedrock material inglobated at the glacier sole and uplifted, or material coming from nearby slopes to the glacier by gravity.

Much more complicate is the interpretation of the chemistry of ice samples from the surface of the glacier. The much lower absolute abundances of crustal elements together with the «enriched» character for most of them are consistent with the atmospheric input of constituents present under form of dissolved elements and particulate matter compositionally distinct from that of samples from the glacier front. In this case ice chemistry appears to be controlled by the following main components: a continental crustal one with short- or long-range transport, a sea salt fraction by local marine aerosol and a cosmic dust. Windblown dust from crustal rocks and debris appear to be the main natural sources for the first component and a tropospheric transport is highly probable. The values of the crustal enrichment factors show that, during this transport, the crustal material suffered some sort of element fractionation process that lead to an enrichment of most elements with respect to Ti. The observed very high enrichment in heavy metals is difficult to be interpreted since contamination may have severely affected element abundance levels. In any case, similar enrichments have been widely observed and interpretation of them are still controversial. Arguments were presented favouring either natural sources like volcanoes or human activities at emisphere scale (see e.g. NRIAGU, 1979; NG & PATTERSON, 1981; NRIAGU & PACYNA, 1988; BATIFOL & *alii*, 1989; BOUTRON & *alii*, 1990).

The chemistry from surface ablation areas of glaciers provides information as regards the cosmic component. It is well known (e.g. BROCAS & PICCIOTTO, 1967) that polar ice and snow have the advantage over ocean and lake sediments of containing a relatively indisturbed record of deposited material thus the influx rate of cosmic dust can be assessed. Elements like noble metals, nickel (and partially Cu) are known to be cosmic dust indicators so any enrichment of these constituents measures roughly an increased fraction of cosmic dust within the deposited material. The EF_{crust} values for nickel in surface samples are much higher than those in samples from the front of the glacier whose chemistry is merely controlled by terrestrial material. Also the Ni-Fe ratios are notably higher than ter-

TABLE 3 - Average element crustal enrichment factors (EF_{crust}) in ice samples from different part of the Strandline Glacier.

	Na	K	Ca	Mg	Fe	Ni	Zn	V	Cr	Mn	Cu
Frontal cliff zone (4 samples)	6.2	1.	0.15	0.87	1.	1.1	35	1.4	1.8	1.3	1.7
Ablation surface zone (8 samples)	22.3	3.6	0.7	1.3	1.8	6.	337	2.8	3.	1.5	10.6

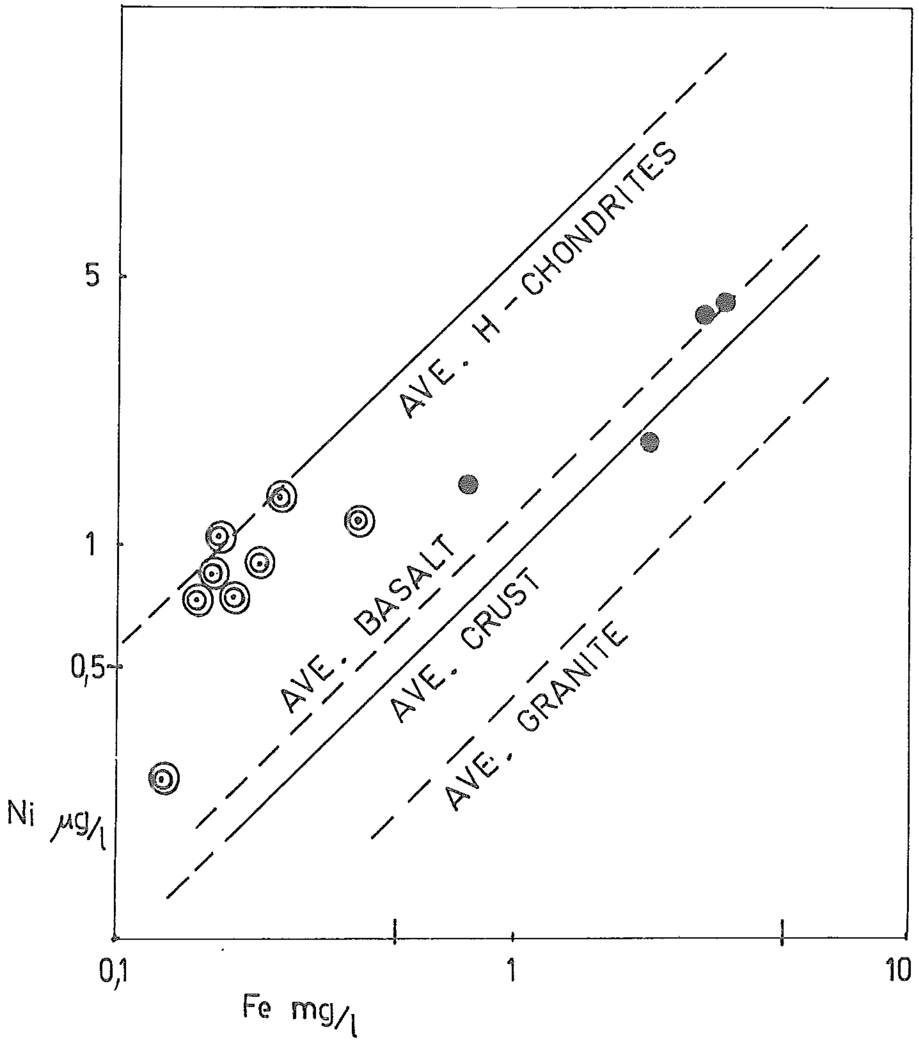

FIG. 3 - Ni-Fe ratios in samples from the frontal zone (closed circle) and from the ablation surface area (open circle) of the Strandline Glacier.

restrial ratios (fig. 3) and approximates those of chondritic material, this confirming that in these samples the ratio of cosmic dust to terrestrial dust is significant and could be estimated on the basis of simple calculations of element ratios.

CONCLUSIONS

a) The results of this study indicate that the analytical procedure used, rather different from standard procedures, if on one hand is not adequate for some environmental studies because of uncontrolled contaminations for elements like Pb, Zn, etc., on the other should be preferred for investigating other important topics such as the origin of the particulate matter and the mode of transport of both dissolved and solid constituents.

b) Analysis of whole samples including all particulate matter allows a rather simple calculation of the influx rate of cosmic dust and of the ratio of cosmic dust to terrestrial dust.

c) Systematic chemical study on different parts of a glacier permits to distinguish the origin and the accumulation mechanism of foreign material. In particular, the existence of even limited amounts of bedrock material inglobed in ice during its movement.

d) The individuation of areas in a glacier where the dust of cosmic origin in particularly abundant allows us to deduce that the zone has been submitted to ablation (by sublimation) for a rather long period (the same situation happens for meteorites, but cosmic dust is much more widespread).

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