The role of glacier system in migration of calcium carbonate on Svalbard

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Abstract: The general objective of this research has been to identify the factors and conditions of migration of $CaCO_3$ within glaciers and their marginal zones in Svalbard. Special attention has been paid to the cryochemical processes responsible for precipitation of calcium carbonate in icing (naled ice) formed near fronts of polythermal glaciers during winter. Estimates of the importance of those processes in respect of the general mineral mass transfer in the glacier system are attempted here. Field studies concerning the carbonate contents in proglacial sediments and icing fields were carried out in the Werenskioldbreen and the Elisebreen basins (S and NW Spitsbergen respectively). A functional model of $CaCO_3$ migration in a glacier system is proposed which indicates the various paths of the mineral mass flow. Considerations on intensity of glacial processes permitted quantitative estimation of the particular components in respect to the Werenskioldbreen basin. Cryochemical processes do not appear to be of overriding importance in such migration but, clearly, they play a specific role in retaining $CaCO_3$ in the proglacial zone on land. The crystalline forms present in the icings, which have many lattice defects, are very easily re-dissolved or removed by wind.

Key words: Arctic, Spitsbergen, glacier system, migration of calcium carbonate, icing, cryochemical processes.

Introduction

Studies of mass transfer within a glacial environment are important for a better understanding of the geologic processes operating there (Drewry 1986), especially when the components can be evaluated. $CaCO_3$ is one of more mobile chemical compounds in such environments. Its study is unquestionably important in respect that it might have a significant role as a sink or source of the greenhouse gas CO_2 (*e.g.* Martini *et al.* 2001; Wilson *et al.* 1999).

Rocks containing calcium carbonate are eroded sub-glacially and then transported in various physical ways. While it is generally appreciated that $CaCO_3$ mi-

gration is linked to freezing and melting cycles, both within glaciers and on their immediate forefields, such processes are still very little understood. They are connected with cryochemical processes. As Hallet (1976, 1979), Pulina (1984, 1990), Fairchild *et al.* (1994, 1999) and Bukowska-Jania (2003) emphasised, cryochemical processes in currently glaciated areas are now generally recognised as being much more important locally than has been appreciated in the past.

The cryochemical processes cause crystallisation of dissolved matter in glacial water. This is due to a freezing out of pure water and increase in the mineralisation of the remaining volume of the liquid. The process is affecting long lists of chemical compounds but $CaCO_3$ is usually the most common in the glacier environment (Pulina 1984). In the final stage, precipitation of crystals of calcium carbonate occurs from carbonate rich solutions, *e.g.* Ford *et al.* (1970), Hallet (1976, 1979), Jazuel and Souchez (1982), Pulina (1984, 1990), Sharp *et al.* (1990), Fairchild and Spiro (1990) and Fairchild *et al.* (1994). The phenomenon is apparently widespread and calcite encrustation in present subglacial bedrock and lodgement tills has been reported by Ford *et al.* (1970), Hallet (1976, 1979), Souchez and Lemmens (1985), Sharp *et al.* (1990), Fairchild *et al.* (1994), Vogt and Corte (1996) and others. However, information concerning the primary precipitation of calcium carbonate crystals from subglacial water, coming from glaciers when icing fields form during winter, is sparse (Åkerman 1982; Pulina 1984; Gokhman 1997; Hodgkins *et al.* 1997; Bukowska-Jania and Pulina 1999; Bukowska-Jania 2003). Nevertheless, the inventory of fields of icings in Svalbard has been done basing upon examination of aerial photos of 1990 and fieldwork (Bukowska-Jania and Szafraniec 2005). Icing fields were identified at fronts at 217 glaciers and covered more than 12 km^2.

With this background in mind the general objective of this research has been to identify the factors and conditions of migration of $CaCO_3$ within glaciers and their marginal zones in Svalbard. Special attention has been paid to the cryochemical processes responsible for precipitation of calcium carbonate in icing (naled ice) formed near fronts of polythermal glaciers. Estimates of the importance of those processes in respect of the general mineral mass transfer in the glacier system are attempted here.

The studied glaciers

The Werenskioldbreen basin (Figs 1 and 2 A) became the main area of interest in respect that it is one of the better described of the Svalbard glaciers but comparable field studies were also carried out in the Elisebreen basin (Figs 1, 2B and 3). Both glaciers are land-based, polythermal types and both erode calcium carbonate as they cross lenses of limestones and dolomites of the metamorphic Hecla Hoek Formation along their courses (Harland *et al.* 1997). It is worth noting that aerial

Fig. 1. Location of the studied area: W – the Werenskioldbreen and E – the Elisebreen. Note white
areas throughout Svalbard indicating glaciated areas.

extension of carbonate rocks within the Werenskioldbreen basin area has been
limited to thin layers or lenses of marbles, dolomites and carbonate schists within
Hecla Hoek Formation (Birkenmajer 1990; Czerny *et al.* 1993). By extrapolation
from surrounded unglaciated areas, one can estimate that the rocks with content of
calcium carbonate may constitute no more than 10% of the basin area (Pulina
1984; Bukowska-Jania 2003). Geology of the Elisebreen has been less precisely
studied. Nevertheless, the presence of some layers of rocks bearing calcium car-
bonate (limestones, marbles, sandstones, phylites, quartzites) has been noted
(Harland *et al.* 1997), but with larger aerial extension than the Werenskioldbreen
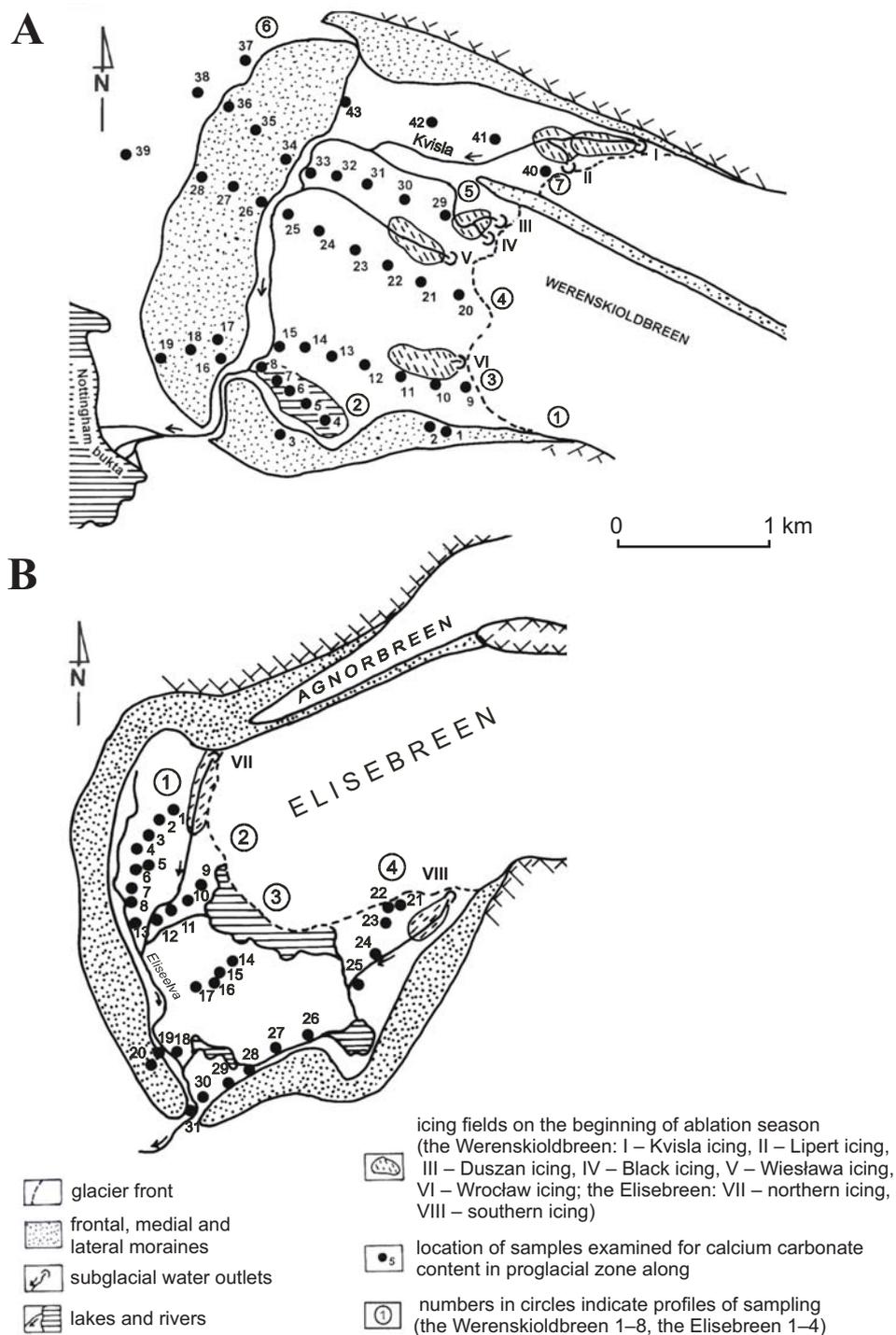proglacial zone.

Fig. 2. Sketch of the frontal parts of studied glaciers; Werenskioldbreen (**A**) and Elisebreen (**B**).

Fig. 3. Icing fields in the forefield of the Elisebreen – in August 2000.
Photo by courtesy of Marek Grześ.

The Werenskioldbreen (77°45' N, 15°20' E) is located north of Hornsund. It covers an area of 27.4 km², and its length is 9.5 km. It occupies *c.* 60% of its hydrological basin of 44 km² in area (Jania 1988; Hagen *et al.*1993). The highest point of the firn field is at *c.* 650 m a.s.l., the equilibrium line is situated at *c.* 330 m, and the front at *c.* 40–60 m. By comparison, the Elisebreen (78°38' N, 12°13' E) is located north of St. Jonsfjorden. It covers an area of 11.4 km², and it is 9 km long (Fig. 3). The maximum elevation of the firn field is at *c.* 850 m a.s.l.; the equilibrium line at *c.* 300 m and the front at *c.* 80 m (Hagen *et al.* 1993). At front of both glaciers, naled ice fields form every winter.

Methods

Studies of the influence of the cryogenic processes on the $CaCO_3$ content in proglacial sediments were carried out in the forefields of the Werenskioldbreen and the Elisebreen during summer seasons 1998–2000. Investigations regarding the calcium carbonate contents and the structure and texture of the different origin of proglacial deposits have been carried out on samples from the Werenskioldbreen and the Elisebreen (Figs 1, 2). Beside these glaciers, sediment samples were taken for comparison from proglacial areas of additional glaciers in Hornsund area

(Hansbreen, Gåsbreen, Paierlbreen, Mühlbacherbreen, Storbreen, Hornbreen, Sva-lisbreen, Nannbreen) and in Oscar II Land (Aavatsmarkbreen, Waldemarbreen).

Field studies were based on a collection of samples from sediments in the proglacial zones of the Werenskioldbreen and the Elisebreen (Fig. 2). Samples were taken from the superficial layer of deposits, down to 10 cm. In both cases, sample locations were established by a single frequency navigational type GPS receiver that has a horizontal accuracy of ±5 m. The volume of $CaCO_3$ in samples was gasometrically identified in the laboratory by means of the Scheibler method (*e.g.* Myślińska 1998). In total, 228 samples were collected and analysed in the laboratory.

Amounts of the suspended matter in water of proglacial river of the Weren-skioldbreen were analysed. Its mineralogical and chemical identities were per-formed. One litre samples were taken from proglacial waters. The samples were percolated through a hard filter. The collected dried suspended matter samples were examined thermally using a Derivatograph MOM (Hungary) and by a Roent-gen type difractometer Geigerflex (Rigaku-Denki, Japan). The crystallographic forms and structure of the calcite crystals were established by means of a scanning electronic microscope EMPA with a microsond JSM-35C (Jeol) at Laboratories of the Faculty of Earth Sciences, University of Silesia.

The extension of the icing at the fronts of both studied glaciers was examined using several different methods in 1999 and 2000. These included a precise kine-matic dual frequency GPS survey, the use of single frequency navigational type GPS receiver for kinematic contouring, tachometric survey and an analysis of the Terra-ASTER satellite image.

The inventory of icings fields completed by analysis of aerial photographs of the Norwegian Polar Institute taken in the summer of 1990 was used (Bukowska-Jania and Szafraniec 2005). In general, field and remote sensing data have been combined with those from published sources.

The crystalline calcium carbonate content of the ice from the icing field of the Werenskioldbreen has been measured. Samples of ice, *c.* 0.0225 m^3, were taken from the site by hand sow and melted to extract calcite crystals. They dropped to the bottom of the plastic container and their total volume was estimated. Individual crystals were analysed with JSM-35 scanning electron microscope (SEM).

Calcium carbonate content in proglacial sediments

Results of laboratory analyses of 228 samples of sediments of different origin and from the two analyzed glaciers forefields indicate that the $CaCO_3$ contents vary greatly but are significant in majority of cases (Tables 1, 2).

In the Werenskioldbreen forefield area, the samples from 43 locations orga-nized in 7 profiles were taken (Fig. 2A). The following sediments were collected

Table 1

Granulometric composition (% by weight) and content of CaCO$_3$ (% by volume) of samples from the Werenskioldbreen marginal zone (Fig 2A)

Number of sample	Depth (cm)	Granulometric composition (mm)													Content CaCO$_3$ (% by volume)
		>12.0	12.0–4	4.0–2	2.0–1	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.1	0.1–0.05	0.05–0.02	0.02–0.006	0.006–0.002	<0.002	
Profile 1 (basal moraine 0; lateral moraine 1; aeolian deposits 2–3)															
0a	0–10	3.1	15	13.2	10.6	10.8	8.2	9.2	7.1	3.4	6.6	7.8	2.5	2.5	3.3
0b	0–10	2.3	13.4	10.9	9.4	8.5	8.8	15.4	12.5	2.4	4.9	6.1	2.4	3	2.5
0c	0–5								2	1	21	53	18	5	0
1a	0–15		9.7	14.7	12.6	11.4	11	11.2	3.2	5.5	8.7	7.3	4.7		2.1
1b	20–30		14.2	13.2	11	10.7	10.5	9.9	3.2	4.6	5.7	10.7	4.1	2.2	1.8
1c	30–100		16.4	19.7	14.7	12.2	9.6	7.3	2.5	4.4	5.8	4.9	2.5		2.1
2a	0–5								1	1	7	57	29	5	0.0
2b	0–5							3	6	5	38	39	6	3	0
3a						2.8	1	5.3	6.9	30	35	13	6		6.8
Profile 2 (lacustrine deposits 4–8)															
4a	0–10						4	9	21	30	28	8			7.4
4b	10–20							10	26	39	18	7			8.4
4c	20–30							4	13	26	34	17	3	3	7.8
4d	30–40							7.3	7.7	18	28	29	2	8	7.5
4e	40–50								7	4	25	44	13	7	5.4
5a	0–10								7	14	37	33	4	5	6.2
5b	10–18							3	6	9	37	36	9		6.7
5c	18–28							2.8	8.2	23	36	24	6		7.8
5d	28–40							5.5	9.5	21	39	19	3	3	7.4
6a	0–10						2.2	6.8	7	16	33	27	5	3	6.7
6b	10–30								1	7	30	52	6	4	6
7a	0–10		9	9.4	7.8	6.7	5.5	5	3	8.6	16	15.4	6.2	7.4	7.2
8a	0–10						0.7	12.8	9.5	29	38	8	2		9.4
8b	10–30		2.4	3.1	2.7	2.9	27.4	47.7	3	10.8					8
8c	30–50					3.3	6.5	19.7	10.5	25	27	8			8.4
Profile 3 (basal moraine 9–12; fluvioglacial outwash deposits 13–15; frontal moraine 16, 18–19; aeolian deposits 17)															
9a	0–10	3.4	13.2	8.4	7.6	7	7	25.8	17.6	10					5.2
9b	10–30	5.6	12	9.8	10.2	6.1	5.2	5	3.1	6.5	9.5	12.4	8.6	6	5.5
10a	0–10	3.4	7.2	7.1	7.9	4.8	8.5	3.7	4.3	7.3	13.4	16.5	9.2	6.7	4.8
10b	10–40		21.5	27.5	24.2	10	9.5	2	0.2	5.1					2.9
11a	0–10	2.6	7	7.3	6.6	3.6	6.2	5	1.2	3.1	11.7	26.7	9.8	9.2	4.1
11b	10–25	2.8	9.6	7.7	8	4.5	8.2	6.6	2.6	3.7	11.6	17.9	8.9	7.9	6.7
12a	0–10								4	3	8	44	31	10	1.7
12b	10–30	12.3	11	8	6.3	5	3.5	1.1	2.7	5.4	11.3	17.8	8.1	7.5	6.7
12c	30–60	21.2	10.2	8.7	8.6	6.3	4	16.1	8.9	1.8	4	5.3	2.2	2.7	5.9
13a	0–30				10.1	3	5.2	19.2	11.5	34	13	3	1		9.8
13b	30–50		0.6	4.9	10.8	16.2	33.5	26.6	2.3	5.1					8.5
14a	0–5	0.6	19.9	14.6	11.4	9	7.7	8.9	2.5	11.5	9.9	3	1		7.2
14b	5–10	2.1	15.2	13.7	13.9	7.7	25.1	15.7	1.5	5.1					9.6
14c	10–20	0.9	15.9	18.7	19.2	10.4	20	8.4	1	5.5					8.4
14d	20–45	2.6	1.4	2	2.4	2.1	3.9	25.5	10.2	29.9	16	4			9.8
14e	45–55					5.8	5.2	16.2	7.8	24	28	12	1		7.8

Table 1 – *continued.*

Number of sample	Depth (cm)	Granulometric composition (mm)												Content CaCO₃ (% by volume)
		>12.0	12.0–4	4.0–2	2.0–1	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.1	0.1–0.05	0.05–0.02	0.02–0.006	0.006–0.002	<0.002	
15a	0–30	2.6	29.6	15.2	13.1	12.1	9.2	6	1.6	10.6					8.9
15b	30–40	3.2	7.7	2.7	1.5	1.3	6	37.8	8.8	20.1	8.7	2.2			10.2
15c	40–55		22.2	19	17.2	21	10.5	2.8	0.7	6.6					8.6
15d	55–60						1	16	18	32	27	6			9.7
16a	0–60	4.8	16.1	10	9.6	7.6	5.6	6.2	3.2	4	11.6	12.9	4.8	3.6	4.9
16b	60–80	3.1	14.3	9.1	8.3	6.4	11.3	5.2	9.1	5.2	10	11	4.2	2.8	3.8
16c	80–120	5.6	17.6	11.1	9.7	5.5	10.1	7.7	1.5	6.2	10.9	8.8	2.8	2.5	9.6
16d	150–170						2	84	5	4	1	4			0
16e	170–180			3.5	8	2.1	7.2	43.5	4.7	5	7	10	9		0
17a	0–10		1.1	1.2	1.4	2.6	13	30.6	8.7	24.5	13.3	1.6	0.8	1.2	9.6
17b	10–50				5	2.1	5.7	20.2	16	28	17	6			9
17c	50–60	6.9	12.8	9	8.8	7.1	5.7	6.7	2	7.8	13.9	11.9	3.7	3.7	5.2
18a	0–50	2.7	19.8	14.5	13.1	9	6.5	5.1	1	6.5	10.8	7.9	1.4	1.7	6.2
18b	10–150	2.8	21.6	17.8	16.7	10.8	6.5	4.7	1.1	4.5	6.5	4.9	0.7	1.4	6.9
19a	0–10	0.9	28.7	18.5	16.5	8	8.9	3	2	2.8	5.4	3.3	0.7	1.1	6.2
19b	10–65	1.4	10.2	9.8	14.7	14.3	11.4	6.3	1.6	6.7	12.1	9.4	2.1		7.4
19c	60–140	5.5	20.7	16.1	17.9	16.6	11.3	3.9	0.7	7.3					5.8
19d	140–150	3.3	17.1	15.5	11.4	6.1	12.4	10.5	3.2	5.1	6.5	5.6	1.4	1.9	4.2
Profile 4 (basal moraine 20–25; frontal moraine 26–28)															
20a	0–20	4.7	14	8.2	7.2	5.8	7.6	27.1	10.1	1.4	4.3	5.6	2	2	10.5
21a	0–5		1.1	3.1	3.3	3.4	4.8	17.5	8.5	21	22.8	9.3	5.2		10.1
21b	5–20		1.8	5.5	11.2	26.7	31.9	13	0.9	9					11.5
21c	20–30	0.7	6.8	8.9	8.1	7.7	7.3	13.4	15.4	5.1	9.5	10.4	3.2	3.5	8
22a	0–20	5.4	16.9	7.8	5.7	4.1	4	4.5	1.3	5.1	15.1	19.5	5.5	5.1	6.3
23a	0–5								3	9	40	40	5	3	5.2
23b	5–12								6	11	41	34	8		4.9
23c	12–32	3.1	13	7.1	5.9	6.1	4	2.4	4	4.5	11	19.5	9.7	9.7	8
23d	32–40	5.6	9.4	7.7	7.2	4.6	6.6	2.9	2.3	4.1	11.9	18.9	9.4	9.4	8.3
23e	40–50	1.9	8.9	8.8	8.8	6.6	7.3	4	2.9	5.2	13.9	15	7.5	9.2	6.9
24a	0–30	3.8	9.1	9.1	8.3	5	5.2	4.1	2.2	4.8	13.8	18.6	6.9	9.1	8.1
25a	0–30	6.6	17	9.6	8.7	8	6.2	5	3.3	0.9	14.8	11.9	4	4	6.7
25b	30–60	1.8	22.9	18.7	18.2	10.1	12.5	5.3	1.1	9.4					6.7
25c	60–80		0.6	2.8	5.4	11.5	30.8	24.8	4.6	10	6.6	1.7	1.2		5.2
25d	80–100	3.7	2.6	1.8	1.1	1.1	5	22.9	7.2	26.7	17	6.5	2.2	2.2	6.2
26a	0–40						4	2	1	4	31	38	13	7	3.9
26b	40–60	7.7	18.7	9.5	7.5	6.4	5.3	4	2.7	4.5	11.7	13.5	4.5	4	6.7
27a	0–50	4.1	18.9	14.7	13.1	8.2	8.3	4.9	1.5	4.1	8.2	9	2.9	2.1	6
27b	50–100		24	16.9	12.8	10.1	3	2.8	3.5	3.5	7.5	8.2	2	2	4.2
28a	0–5	1.7	4.8	6.8	8	6.3	10.1	6	3.9	7.5	16.2	18.1	5.6	5	4.3
28b	5–50	2.3	13.7	10.3	8.1	7.2	6.8	9.4	11.6	4.3	8.2	10.1	4	4	3.4
28c	50–100	9.1	14.9	8.6	7.4	7.2	5.9	3.5	4	4.7	10.8	13.1	5.2	5.6	4.3
28d	100–150	6.4	16.2	10.2	9.1	8.7	6.4	15.6	5.9	2.1	5.6	7.6	3	3.2	3.2
28d	150–200	13.7	18.1	11.5	9.6	6.3	5	1.1	4.5	3.3	8.9	11.4	3.3	3.3	5.7
28e	0–10	7.5	10	7.1	5.9	5.6	5.1	2.9	3.5	3.5	10.6	20.7	9.4	8.2	4.4
28f	0–10	7	11.1	9.2	8	6.7	6.6	14.4	25.5	11.5					4.3
28g	0–10						5.5	7	3.5	14	43	20	7		3

Table 1 – *continued.*

Number of sample	Depth (cm)	Granulometric composition (mm)													Content CaCO$_3$ (% by volume)
		>12.0	12.0–4	4.0–2	2.0–1	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.1	0.1–0.05	0.05–0.02	0.02–0.006	0.006–0.002	<0.002	
Profile 5 (fluvioglacial outwash plain deposits 29–33; frontal moraine 34–36)															
29a	0–5				3.5	10	19.5	24	9	17	9	8			8.3
29b	5–10					9	14	36	12	18	7	1	2	1	9.8
29c	10–20					4.2	3.1	17.2	9.5	22	32	9	3		8.1
29d	20–40	7.6	5.8	3.1	1.8	1.7	2.1	2.8	1.9	13.2	31.4	21.2	3.7	3.7	6.6
29e	40–65					6.8	7.2	3	7	28	35	9	4		6.9
30a	10–30								6	8	33	43	6	4	4.5
30b	30–90						2	31.3	19.7	24	13	6	2	2	7.5
30c	90–100								3	10	48	32	7		6.6
31a	5–10						3	5.5	7.5	22	44	14	4		9.2
31b	10–80		18.3	20.6	23.8	15.1	17.3	2.9	2						11.7
31c	80–90					4.7	7.7	17.4	13.2	26	22	9			6.4
31d	90–120		9.4	9.8	19.5	28	26	6	0.2	1.1					9.6
31e	120–150				6.1	3.1	3.2	9.1	4.5	17	32	19	6		9.1
32a	0–10							5	9	31	43	10	2		7.8
32b	10–160					9.5	29.5	33.2	8.8	14	5				8.9
33a	0–10								3	10	53	28	3	3	6.8
34a	0–50		13.7	10.8	10.1	6.2	13	9.4	3.2	7	10.1	11.1	5.4		6.2
34b	50–100		17.9	11	8.8	5.2	9.2	4.2	3	4.3	10.5	14.5	5.7	5.7	8.9
34c	100–150	4.1	13.3	7.3	6.2	3.6	6.3	4.9	1.2	4.2	12.7	24.3	7.5	5.3	7.7
35a	0–20		14.3	13.2	11.5	6.4	10.3	6.1	1.1	7.4	12.3	11.9	3.3	2.2	7
35b	20–60	16.9	16	13.5	9.5	7.9	5.9	1.3	0.6	5.4	8.5	10.3	2.5	1.7	6
36a	0–50	7.5	20.9	13.3	9.8	8.2	6.8	6.5	2.7	3.2	7.6	8.9	2.7	1.9	5.2
36b	50–100								5	13	31	31	11	9	0
36c	100–150	4.4	7.9	6.7	5.6	4.2	3.7	4.1	1	1.9	19.3	28.1	7.5	5.6	2
Profile 6 (fluvioglacial outwash plain deposits 37–39)															
37a	5–10		27.3	19	17.2	17.8	11.3	3.7	0.6	3.1					8.9
37b	10–50		24.2	21.3	20.1	12.3	14.9	3.6	0.2	3.4					9.9
38a	0–5	4.7	23.9	16.4	10.6	7.2	6.1	3.2	0.8	3.7	8.4	10.6	2.2	2.2	5.1
38b	5–10	1.6	22.7	18.1	18	14.8	9.3	3.3	0.5	11.7					2
38c	10–50		17.4	21.1	20	17.8	13.4	3.9	1	5.4					4.8
39a	0–10	6	27.6	20	18.4	13.2	7.5	2.4	0.5	4.4					7.4
39b	10–60	12.2	27	20.1	16	11.3	6.7	2.7	0.8	3.2					7.9
Profile 7 (fluvioglacial outwash plain deposits 40–42, frontal moraine 43)															
40a	20–30	2.4	37.3	14.5	12.6	11.7	11.1	5.5	1.2	3.7					9.5
41a	0–5			12	10	5.7	8	3.7	0.6	9	27	21	3		8.2
41b	140–150		11.4	20.7	32.9	31.3	3.2	0.5							9.2
42a	0–5		5.3	5.6	5.3	4.8	5.3	3.4	0.8	6.7	26.8	29.3	6.7		5.9
42b	45–55		32	22.5	18.5	9.9	12.4	3	1.7						5.9
42c	95–105		8.8	5.6	7.1	8.9	13.4	6.8	28.8	20.6					9
43a	30–40	1.7	28.3	14.5	9	8.9	5.2	3.6	1.4	2.8	7	9.7	7.9		28.6

Table 2

Granulometric composition (% by weight) and content of CaCO$_3$ (% by volume) of samples from the Elisebreen marginal zone (Fig 2B), deepness (1–10 cm)

Number of sample	Granulometric composition (mm)													Content CaCO$_3$ (% by volume)
	>12.0	12.0–4	4.0–2	2.0–1	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.1	0.1–0.05	0.05–0.02	0.02–0.006	0.006–0.002	<0.002	
Profile 1 (fluvioglacial outwash plain deposits 1–8)														
1		3.1	1.4	3	10.6	30.7	30.3	5.5	7.3	4.8	2.2	1.1		16.7
2				0.8	10.1	33.5	24.1	5.5	11	9	6			19.7
3				0.9	5.2	29.6	37	8.3	10	2	7			16.5
4					1	16.9	39.2	12.9	18	6	6			16.5
5					1.1	4.6	39.9	14.4	25	9	6			11.1
6	12.4	25	10.8	7.7	9.5	12.5	11.4	4.7	6					26.6
7	2.2	2.8	1.7	1.8	1.4	7.8	27.6	14.2	24.3	12.6	3.6			15.5
8		2.2	6.3	7.6	9.2	21.5	25.4	7.1	15	5.7				22.5
Profile 2 (frontal moraine 9–10, lacustrine deposits 11–13)														
9	6.8	4.2	13.3	21.8	31.6	16.4	2.4	0.9	2.6					30.2
10		6	7.7	9.4	6.3	11.4	5.2	1.8	5.6	7.1	38.1	1.4		29
11								1	1	17	52	20	9	28.6
12					1.5	0.8	4.4	2.3	9	33	36	6	7	23.8
13					2.2	15.5	30.4	9.9	21	14	7			20.5
Profile 3 (lacustrine deposits 14, 20; basal moraine 15–19)														
14						0.4	1.6	3	19	27	45	4		23.8
15	0.9	3	0.6	0.6	0.9	4.4	18.6	0.1	2.8	17.7	34.8	8.5	7.1	20.5
16	8.6	14.2	8.8	7	6.4	4.9	4.3	1.4	4.9	6	25.8	5.5	2.2	22.5
17	2.7	15.4	9	7.8	6.4	5.3	4.7	1.8	4.7	8.2	22.3	9.4	2.3	19.7
18	12	27.5	12.2	8.3	6.8	6.5	4	1.2	2.7	3.6	6.3	3.3	5.6	18.1
19	3.5	23.9	10.1	9.6	8.5	9.9	6.1	1.3	4.9	7.6	6.2	2.7	5.7	18.1
20				1.6	4.5	18.1	25.7	9.1	20	12	9			15.1
Profile 4 (fluvioglacial outwash plain deposits 21, 24–25; basal moraine 22–23, 26–31)														
21		4.7	4.5	21.4	28.1	27.9	9.4	1.6	2.4					8.5
22	3.6	12.6	9.1	7.8	8.1	8	6.3	1.5	5.9	9.4	11.8	11.8	4.1	20.9
23				2.2	1	2.2	4.8	2.8	20	35	18	6	8	8.5
24		1.7	6.5	23.3	38.2	25	4.1	0.5	0.7					7.9
25		10.3	12.9	15.3	13.4	16.8	14.7	5.1	11.5					7.6
26				2	1		8.2	8.8	31	26	10	6	7	17.3
27				5.4	6.4	8.1	7.1	2	5	8	17	24	17	14.1
28				2.1	6.1	14.3	19	6.5	12	13	14	4	9	13.9
29			5.6	8	15.6	19	6	0.8	4	9	19	8	5	16.5
30		2.3	6.1	7.6	8.5	10.7	7.5	2.2	7.5	12.8	13.6	9.1	12.1	17.5
31				6.6	3.5	6.3	21.9	9.7	19	14	10	9		16.9

for analyses: basal, frontal and lateral moraine (lodgement till, flow till and meltout till), fluvioglacial deposits from inner and outer outwash plains and lake deposits of periodic/seasonal proglacial lakes. Icings patches covered some areas of basal moraine and inner outwash plains in the beginning of ablation season.

Granulometric composition and content of $CaCO_3$ of samples from the Werenskioldbreen marginal zone is presented in Table 1.

In the Elisebreen marginal zone, the samples of deposits were taken only in its inner part (between frontal and lateral moraines on the front of glacier; Fig. 2B). 31 samples were taken and analysed (Table 2). They represent similar types of deposits as from the Werenskioldbreen forefield.

Content of $CaCO_3$ in proglacial deposits of Spitsbergen glaciers varies significantly. Fluvioglacial deposits of the Werenskioldbreen marginal zone contain 7.2–10.2% of calcium carbonate. Samples taken close to icings patches were enriched in $CaCO_3$ (9.4–11.7%). After having collected the undisturbed sample taken from fluvioglacial sediment close to the edge of the Wiesława icing field (Fig 2A), a layer of the cryogenic $CaCO_3$ of 1.5 cm thick was noted (the sample is not indicated in Table 1). The content of calcium carbonate in this thin superficial layer of sediment reached 47%. Deposits in the proglacial area of Elisebreen have 7.6–11.8% of $CaCO_3$ and significantly higher content in the neighbourhood of icing fields (26.6–30.2%). In sandy aeolian sediments deposited on outwash plain of the Werenskioldbreen, the calcium carbonate volume fraction varies between 6.8 and 12.5%. Average content of $CaCO_3$ in the samples taken from basal moraine of the Werenskioldbreen is 4.8% but varies between 2.6 and 6.7%. Significantly higher admixture of $CaCO_3$ has been noted in basal moraine of the Elisebreen (15.1–22.5%) reaching 18% in average.

Interpretation

Estimation of mineral mass transfer in a glacier system. — Taking into account intensity of glacial processes within the medium size, land based polythermal glacier, an estimation of mineral mass flow, including $CaCO_3$, has been conducted. Functional model of such processes has been taken as a "flow chart" for quantitative estimations (Fig. 4).

Sliding on the bedrock is an important element of the movement of subpolar glaciers. The products of glacier sliding and abrasion have become a ground (basal) moraine the thickness of which (in respect of Werenskioldbreen) is between 0.3 to 1 m. It is assumed that about 70% of the volume of the bottom moraine has been composed of mineral matter (the remaining 30% is ice), and the thickness of the bottom moraine varies from *c*. 0.2 to 0.7 m (mean *c*. 0.4 m). Owing to the process of freezing of the ice to the bedrock the velocity of the basal sliding at the glacier front was reduced close to zero (Baranowski 1977). Basal sliding has been calculated to be of the order of 1 m yr^{-1} in the distance of 1 km upstream from the terminus (Jania 1988; Jania, personal comunication 2005). Therefore, the terminal part of the glacier ice has been enriched by basal moraine along shear planes within almost stagnant ice in such rate.
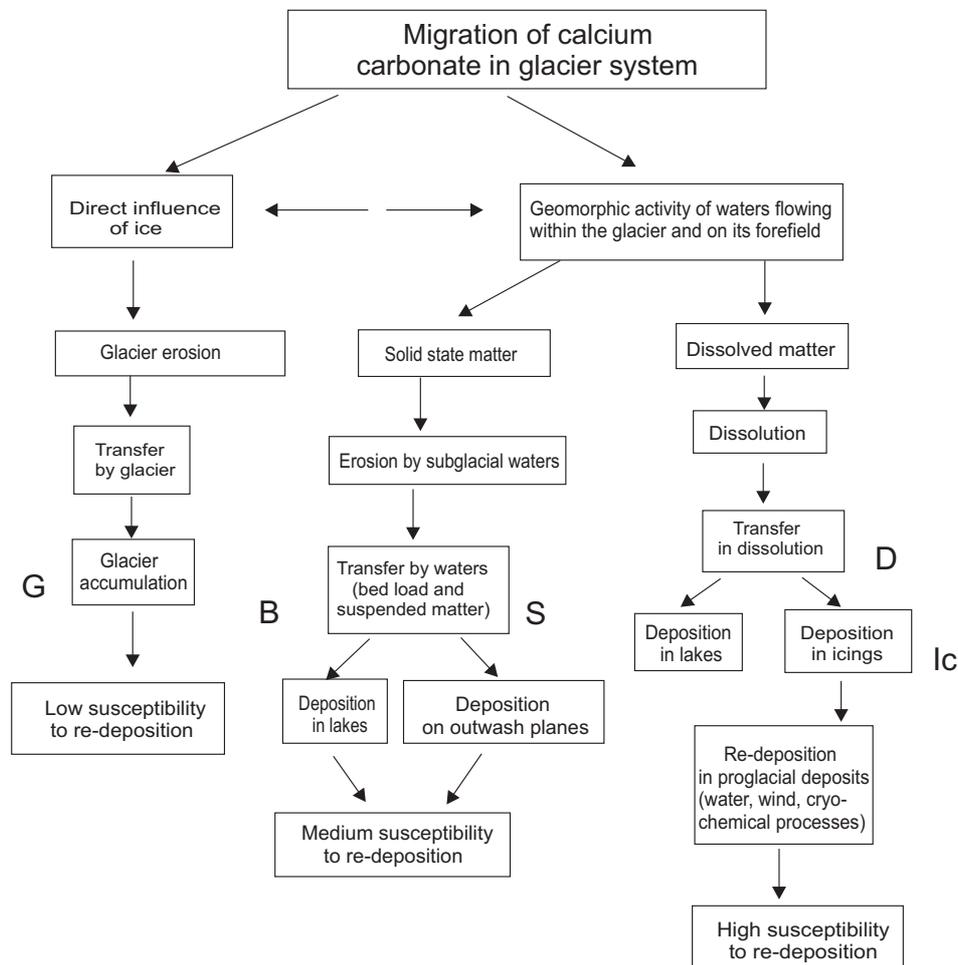
Fig. 4. Model of calcium carbonate migration in the glacier system. Some quantitative data for the Werenskioldbreen with estimated volume of contributed carbonates given in brackets are: G – glacial deposits: 22,000 m^{3}yr^{-1} (1,060 m^{3}yr^{-1}), B – bed load: 5,000 m^{3}yr^{-1} (900 m^{3}yr^{-1}), S – suspended matter: 14,900 m^{3}yr^{-1} (2,700 m^{3}yr^{-1}), D – dissolved matter: 1,140 m^{3}yr^{-1} (850 m^{3}yr^{-1}), Ic – calcite deposited in icing: from 3.7 to 18.5 m^{3}yr^{-1}.

The ground moraine has left the glacial system as a result of ablation and recession of the glacier front. Comparison of maps, aerial photos and surveys taken in various years confirms, that Werenskioldbreen is currently receding at the approximate rate of 25 m yr^{-1} (Bukowska-Jania and Jania 1988) and it is a process which has been continuing for several decades. Hence, each year a strip of land *c.* 25 m wide has been uncovered at the glacier front. The ground moraine forms almost the whole length of the glacier front (2.5 km) except for the subglacial outflows, with approximate length of these zones being *c.* 300 m. Assuming a mean thickness of 0.4 m, the volume of moraine sediment thus leaving the glacier may be estimated

at 22,500 m³ yr⁻¹. Analysis of the content of $CaCO_3$ in the ground moraine sediments of the Werenskioldbreen indicates that its representation is 4.8% (the corresponding value for the Elisebreen is about 18%). Accordingly, it is calculated that the amount of calcium carbonate leaving the Werenskioldbreen system due to glacial transport and frontal recession is *c.* 1080 m³ yr⁻¹.

Significant changes in the annual distribution of suspended matter transported in glacial rivers is typical of most glaciers. Meltwater streams contain little if any suspended load in winter (Pulina 1984), but it abruptly increases from several milligrams to several grams per litre at the beginning of the ablation period. These values are directly proportional to the water discharge, and normally the greatest value of the transported suspension load precedes the maximum flow (Drewry 1986).

The most extensive study of suspended load in rivers draining the Werenskioldbreen was carried out in the summer of 1986 (Krawczyk and Opołka-Gądek 1994). It showed that *c.* 40,250 tonnes of suspended material left the Werenskioldbreen basin in the period between 16 June and 14 September 1986. Complementary (but non-systematic) sampling conducted by the Author in 1998 and 1999 generally supported these estimates.

Mineralogical analysis of the suspension load samples taken from the glacial river of the Werenskioldbreen in the summers of 1986 and 1999 showed the mineral content which broadly reflects the complex geological structure of the glacier bed. The major components are the clay minerals: $(Mg_5Al)[AlSi_3O_{10}](OH)_8$, $Na[AlSi_3O_8]$, $Ca[Al_2Si_2O_8]$, $KAl_2[AlSi_3O_{10}](OH)_2$ and SiO_2. Calcite and dolomite ($CaCO_3$ and $CaMg[CO_3]_2$) were minor crustetments at 10% and 8% respectively.

If it is accepted that the mean content of calcite in the suspension load in the Werenskioldbreen glacial river is 10% and dolomite 8%, the data taken from Krawczyk and Opołka-Gądek (1994) suggest that 1,500 tonnes of calcite and 1,200 tonnes of dolomite leave the glacier basin annually.

However, it must be taken into account that significant amounts of sediments have been also observed along the river channel as a traction load. The measurement of amounts of the bed load material dragged along such a channel is of course very difficult, especially when water discharge is high. Nevertheless, detailed field measurements were carried out in the river outflow from the Nigarsbreen (S Norway) by Østrem in 1969, and, in respect of these data, proportions of suspended to bedload material might reasonably be considered as 3:1 (Drewry 1986).

Whether Østrem's results are applicable to all glacial rivers is highly speculative but the results of his experiments are the only way to try to resolve this problem. On the assumption that the total bed load matter in the Werenskioldbreen basin was of the order of 13,400 tonnes in 1986 (~5,000 m³ yr⁻¹) and in the knowledge that the traction load probably contained *c.*10% of calcite and 8% of dolomite, the total amount of removed material is *c.* 900 m³ $CaCO_3$ and $CaMg[CO_3]_2$ a year.

Certainly because mineralisation of glacial ice is insignificant (Pulina 1984; Paterson 1994), the processes of rock crushing, weathering and dissolution must have an all-important control on determining glacial meltwater chemistry.

Ablation water in summer is as much as 80–95% of the total meltwater flow but, beginning in September, the share of subglacial sources in the glacial river of the Werenskioldbreen increases, possibly representing the entire flow by the end of that month (Pulina 1990). The investigations of Pulina (1984, 1990) and Krawczyk and Opołka-Gądek (1994) enable us to estimate the amount of dissolved matter transported away from the Werenskiold Glacier in the various parts of the hydrological year. Krawczyk and Opołka-Gądek (1994) determined the amount of transported dissolved matter to be *c.* 3,033 tonnes per year when meltwater flows were active in the summer of 1986. Knowing, from chemical analysis, that the mean value of carbonate content during the year represents 75% of the total dissolved solids, it may be estimated that the amount of $CaCO_3$ transported out of the glacier system is of the order of 2,275 tonnes (~843 m^3 – assuming the density of calcite as 2.7 t m^{-3}).

Role of naled ice fields. — Clearly, the same processes, which are active during the formation and decay of icing, are also responsible for the supply of calcium carbonate to the deposits in the glacier forefield. Although the importance of cryochemical precipitation of calcium carbonate in the glacial environment is seldom discussed, notable exceptions are: Åkerman (1982), Pulina (1984, 1990), Hodgkins *et al.* (1997), Bukowska-Jania and Pulina (1999), the phenomenon of cryochemical precipitation of calcium carbonate in subglacial waters has been noted by Åkerman (1982), Pulina (1984, 1990), Gokhman and Khodakov (1985), Gokhman (1997), Bukowska-Jania and Pulina (1999). The investigations of Pulina (1984, 1990) and Krawczyk and Opołka-Gądek (1994) both indicate that winter subglacial waters are oversaturated in respect of the HCO_3^-. This easily dissociates and calcite precipitates in the naled ice fields. In this context, the author has observed encrustation of calcite on the surface of all seven icings located in the forefield of the Werenskiold Glacier (S Spitsbergen) and the Elise and the Waldemar Glaciers (NW Spitsbergen).

Filtration and drying the sediment revealed that the crystalline calcite content of the ice from the icing field of the Werenskioldbreen was *c.* 3.5–4 g per sample. The contents of cryogenic calcium carbonate in the studied naled ice field may therefore be estimated to be of the order 155 g m^{-3}. Gokhman and Khodakov (1985) obtained values of between 30 and 1000 g m^{-3}. Observations of the structure of naled ice suggest that cryogenic $CaCO_3$ probably occurs in only 30% of the ice mass. The remaining 70% consists of recrystallised snow and voids as recognised by the author during field observation and stated in literature (Grześ and Sobota 2000).

Naled ice fields, varying in area from 0.377 km^2 in 1999 to 0.5 km^2 in 1958 (Bukowska-Jania 2003; Bukowska-Jania and Szafraniec 2005), have formed in

the forefield of the Werenskioldbreen every year since observation began. Based on more than a dozen measurements over this period, it is concluded that the mean annual thickness of the naled ice is *c.* 1.5 m. Hence, the volume of the annual developments of naled ice has varied between 566,000 m^3 and 750,000 m^3. Pulina (1984) estimated the volume of the Werenskioldbreen naled ice in the summer of 1980 as *c.* 2900,000 m^3 and from this ~10 to 50 tonnes of pure calcite would appear to be precipitated in the forefield of the Werenskiold Glacier, each year. Certainly, it suggests that the cryogenic calcite deposited in naled ice fields represents several percent of the calcium carbonate which leaves the Werenskioldbreen glacial system as a bicarbonate solute.

Annual developments of the naled ice fields in the forefield of the Elisebreen cover areas ranging from 78,000 m^2 to 383,000 m^2 (Bukowska-Jania 2003). Extrapolation of the data from the Werenskioldbreen suggests that *c.* 1.3 to 6 tonnes of pure calcite may precipitate there every year.

Aerial photographs of the whole Svalbard archipelago show that fields of icing were present in the forefields of 217 glaciers in the summer of 1990. The total area of the icing patches was estimated as at least 12.3 km^2 (Bukowska Jania and Szafraniec 2005). Assuming that their mean thickness is 1.5 m, and that only 30% of the icings contained cryogenic calcium carbonate and that mean contents of $CaCO_3$ in each cubic metre was equal *c.* 150 g, it follows that at least 8,600 tonnes of cryogenic $CaCO_3$ were deposited on forefields of the glaciers in Svalbard during the winter of 1989/1990.

Structure of calcite crystals from naled ice. — The calcium carbonate crystals have been formed within the naled ice masses during the process of freezing of the subglacial water in winter. $CaCO_3$ has been moved out from the lattice of hexagonal columnar ice crystals towards their walls. Therefore, cryogenic calcium carbonate crystals have been formed between ice crystals and their hexagonal form mimics the ice crystal forms to which they were attached (see Fig. 5A). Cryogenic calcium carbonate appears to have a specific crystalline form (Fig. 5B). SEM images of calcite, which crystallised in naled ice, have revealed that calcite crystals in the size range 1–100 μm form flattened aggregates (Gałuskin and Bukowska-Jania 1999). Two generations of $CaCO_3$ crystals, corresponding to two phases of their formations, have been identified (Fig. 5B).

The first generation calcite forms from an oversaturated solution in a water film, which was several mm thick. Their growth was relatively fast at none-equilibrium crystallisation conditions of the solution around the growing crystal. This was apparently the cause of numerous defects of the crystal lattice. The second generation calcite crystallised in more stable conditions in a layer of water which was from several to more than a dozen centimetres thick, the water being less saturated. The orthorhomboedral calcite formed separate crystals or grew on the first generation calcite (Fig. 5B). The lattice of the second generation calcites has fewer defects than the first one.
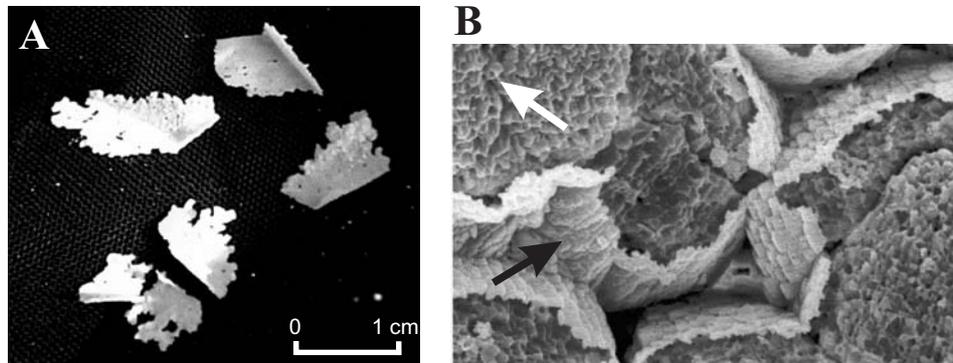
Fig. 5. **A**. Cryogenic calcite aggregates crystallised on the edges of columnar ice crystals in icing. **B**. Magnification of the cryochemical $CaCO_3$ crystals first and second generation by SEM. In the centre of each crystal, much more soluble, defected crystals of the first generation can be seen (darker) – the white arrow. On the edges there is the second generation of crystals (lighter) – the black arrow.
Photo by E. Gałuskin. Both samples from an icing field of the Werenskioldbreen.

Owing to their specific crystallographic forms (the first and the second generation of crystals), the cryogenic calcium carbonates are very sensitive to dissolution (due to numerous defects of its crystal lattice). Dry crystals are also easily re-mobilised by winds as aeolian sediment.

Conclusions

Calcium carbonate is well represented in fluvioglacial and moraine sediments and also aeolian deposits. Surprisingly perhaps it reaches from several to more than 20% even in those Spitsbergen glacial basins where the bedrock contains very little calcium carbonate (Bukowska-Jania 2003).

A theoretical model of $CaCO_3$ migration in glacier system (Fig. 4) shows the various paths and stages of mass transfer when applied to the Werenskioldbreen basin. Estimates show that the average volume of rock material eroded from the base of this glacier is *c.* 43,500 m³ yr⁻¹. Moraine, which is released due to melting of the glacier front, constitutes >50% of that amount; the suspended matter in proglacial rivers is *c.* 35%. The mobile bed load is difficult to estimate and seems to be at least 11% and dissolved material is usually less than 3% of the general volume of sediment transfer out from the glacier system. Within the Werenskioldbreen system, total volume of carbonates delivered by is ~6 000 m³ yr⁻¹ and its representation is as follows: $CaCO_3$ in the exposed (post-recession) layer of ground moraine *c.* 21%, carbonates transported as suspension in rivers >48%, carbonates in the bed load >16%, carbonates in solution *c.*15%.

Only the dissolved $CaCO_3$ can be deposited, due to cryochemical processes, in icing fields forming during winter time. The amount of cryochemically precipi-

tated pure calcite in the proglacial zone of the Werenskioldbreen during a winter period is estimated to be of the order of 10–50 t. This is not a large amount when compared with other path ways in the system but this $CaCO_3$ is concentrated on only relatively small parts of proglacial zones but not only those covered by the icing fields. This conclusion is supported by the results of analyses of the content of the $CaCO_3$ in samples from the outwash plain deposits (Tables 1, 2). In the case of the Werenskioldbreen, fluvioglacial deposits have a mean content of *c.* 9% (up to 47% in the vicinity of the naled ice) and 9,7 % (up to 30% in the vicinity of the naled ice) for the Elisebreen marginal zone respectively.

Calcium carbonate has migrated within glacier system by different ways. Its content in proglacial sediments varies widely and depends on many factors such as: the presence of source rocks underneath the glacier, the origin of particular types of sediments, the presence of icing fields and intensity of cryogenic processes and, last but not least, the type and intensity of post depositional processes with special emphasis put on dissolution, dessication and also deflation of $CaCO_3$ crystals. The glacial system is clearly much more effective for the mobilisation of calcium carbonate in the natural environment than a fluvial system in temperate climate zone. An important feature of the cryogenic calcium carbonate is its high susceptibility to re-deposition in comparison to $CaCO_3$ deposited by the direct glacier accumulation in moraines or by proglacial rivers.

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