doi: 10.3304/JMES.2018.008

Journal of Mediterranean Earth Sciences 10 (2018), 159-166

Journal of Mediterranean Earth Sciences

Mineralogy and geochemistry of cryoconite sediments in Eqip Sermia glacier (Central-West Greenland)

Laura Sanna [1], Alessio Romeo [2,*]

[1] *Istituto di Biometeorologia, Consiglio Nazionale delle Ricerche, Sassari, Italy*
[2] *La Venta Associazione Esplorazioni Geografiche, Treviso, Italy*
[*] *Corresponding author: speleokikers@tiscali.it*

ABSTRACT - The geochemical and mineralogical composition of cryoconite sediments on the Greenland Ice Sheet cap (Central-West Greenland) was investigated with the aim to characterize grain size, mineralogy and geochemistry of dark materials deposited on glacial surface. Cryoconite particles collected on the Eqip Sermia glacier have angular-faceted, sharp-edged shape of the fine grains with mean size of 10-50 mm. The X-ray diffraction analysis of these cryoconite sediments shows that they mainly contain three silicate minerals (quartz, amphibole and plagioclase) and rare oxides, with slight variation in modal composition. Also X-ray fluorescence geochemical exploration reveals a similar pattern among samples. Trace elements content normalized to the averaged upper continental crust indicates values close to 1, except for a depletion in barium and enrichment in chromium. This average composition resembles the mean of weathered rocks in the surrounding area, indicating that dark material deposition was probably dominated by input of local geological outcrops around the glacier.

Keywords: cryoconite; mineralogical composition; geochemical feature; Eqip Sermia glacier; Greenland.

1. INTRODUCTION

The Greenland Ice Sheet (GrIS) is the largest continuous ice body in the Northern hemisphere and the second one in the world (Takeuchi et al., 2014). As in the most arctic glaciers, the current climatic warming has extended its ablation zones (Fig. 1A), significantly affecting the mass balance and the flow of its glaciers (Koenig et al., 2016). Moreover, as it holds half metre sea level volume equivalent, its contribution to sea level rise has increased in the past decades due to the enhanced melting of its snow and ice surface (An et al., 2017). Amplified surface melting is not caused only by temperature rise, but also by reduction of surface albedo due to dark-coloured particles on the ice surface that absorb more solar radiation respect to the surrounding snow and glacier ice (Wientjes et al., 2011). In fact, a certain part of the glacial surface is dispersed by cryoconite holes, near-vertical tubes formed as consequence of melting induced by solar heating of dark debris (Cook et al., 2016) (Fig. 1 B,C). The term cryoconite was coined in the late 1800s by the two Greek words kryos and konis, meaning cold and dust, respectively (Tedesco et al., 2013). Mineral particles in cryoconites are transported from local or distant terrestrial surfaces by wind. The retreating ice exposes sediments in the pro-glacial area, making more material available for aeolian transportation. Cryoconite holes usually cover small area (less than 7%), however they may contribute to the glacial runoff on ablating ice surface, especially in the Middle-West Greenland (Fountain et al., 2008). Analyses of aggregate of dark minerals and organic matter on the glacial surface collected from dark region have revealed that certain mineral particles and algae can play an important role in ice melting (Takeuchi et al., 2014). Although cryoconite biology on Greenland glaciers has been previously studied (Stibal et al., 2015), only few information are available on abundance and mineralogical composition of these dark accumulations (Nagatsuka et al., 2014; Takeuchi et al., 2014; Wientjes and Oerlemans, 2010; Wientjes et al., 2011). Furthermore, knowledge of clastic material sources is still limited (Tepe and Bau, 2015). This paper aims to describe the geochemical and mineralogical composition of cryoconite sediments in the Eqip Sermia glacier, on the GrIS cap in Central Western Greenland, and compared it with samples collected in previous studies from other glaciers.

2. GEOLOGICAL SETTING

The study area is located close to Disko Bugt, in the central-western coast of Greenland, 30 km inland from the ice margin. This region represents the link between Greenland Ice Sheet and its largest ice-free expanse proglacial area (Fig.

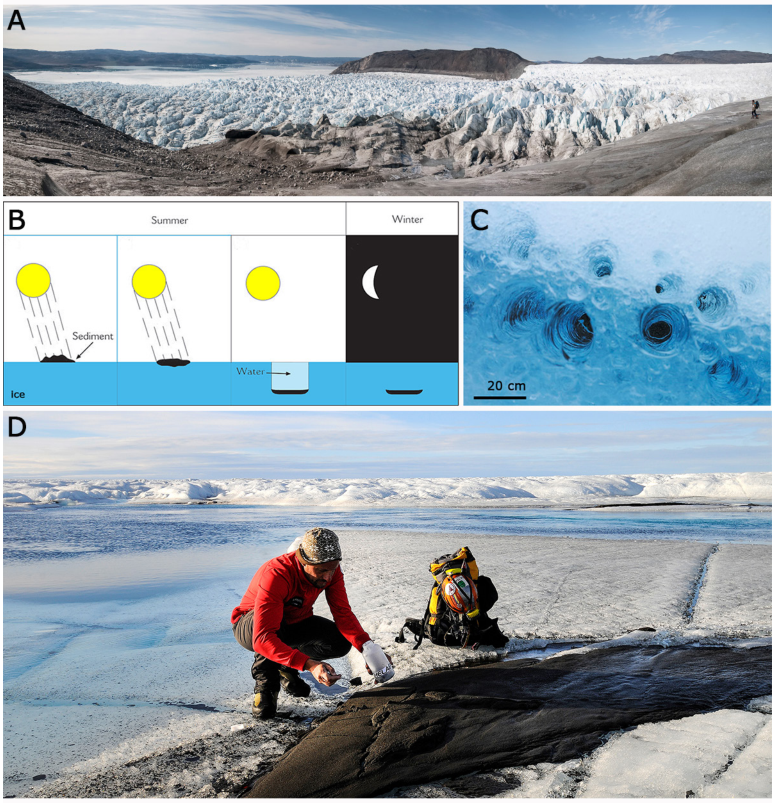

Fig. 1 - Overview of Eqip Sermia glacier (A), seasonal formation (B) and visual view (C) cryoconite holes, and dark sediments sampling (D) (Photos A. Romeo).

1A). It is hosted in Archaean supracrustal rocks about 2,800 Ma in age, divided by thrust in a lower volcanic unit and an upper sedimentary and volcanoclastic beds (Garde and Steenfelt, 1999). The lower volcanic unit comprises a basal pillowed greenstone sequence, an acid volcanic complex and an upper mafic igneous complex with a system of acid dykes (Fig. 2). This basement is in tectonic contact with Archaean migmatitic gneisses and variably foliated non-migmatitic granitoid rocks containing occasional layers of amphibolites. The Precambrian terrains are also unconformably overlain by early Proterozoic supracrustal rocks. The boundary area between the lower acid volcanic complex and the underlying pillowed greenstones shows extensively carbonitisation related to hydrothermal processes and it is locally affected by seritisation, chloritisation and pyritisation. The rocks succession is metamorphosed and the supracrustal sequence shows evidence of penetrative deformation episodes (Stendal et al., 1999).

3. MATERIALS AND METHODS

During GRAAL II expedition (Greenland Research Animal and Algae) organized by Spélé'Ice Association in summer 2010, samples of cryoconite sediments were collected on the Greenland Ice Sheet, in a region situated tens of kilometres from the glacial margin of the southern lobe of Eqip Sermia glacier (Fig. 2). Details of the location of the two sampling sites are reported in table 1.

The dark material of cryoconites was collected with a stainless steel scoop and stored in 1 L clean polyethylene plastic bottles (Fig. 1D).

The samples were analysed at the Chelab laboratory (Treviso, Italy). The cryoconites were dried at 40 °C for 4 days and sieved into grain size fractions. To qualitatively determine the mineralogical composition, each debris accumulation was studied using both optical microscopy and scanning electron microscopy (SEM) coupled with EDS. For these measurements, material was mounted on a stub and coated with carbon.

The bulk mineralogical composition of the whole samples was qualitatively analysed by X-Ray Diffraction (XRD), using a powder diffractometer with Cu-Ka radiation. The samples were powdered in advance with agate mortar. Abundance of major and a suite of trace elements were determined by EDXRF on pressed powder tablets.

4. RESULTS

The average grain size of the cryoconite sediments ranges around 10-50 mm, with minimum diameter of few micrometers and 100 mm for larger grains. Optical inspection using a light microscope revealed that most grains have rather angular flat shapes with sharp edges. Each grain consists of a single crystal, mainly quartz, feldspars, amphibole and some oxides. The SEM images confirm the angular-faceted, sharp-edged shape of the fine grains. Grain size and overall mineral grain shapes are comparable at the two sampling points.

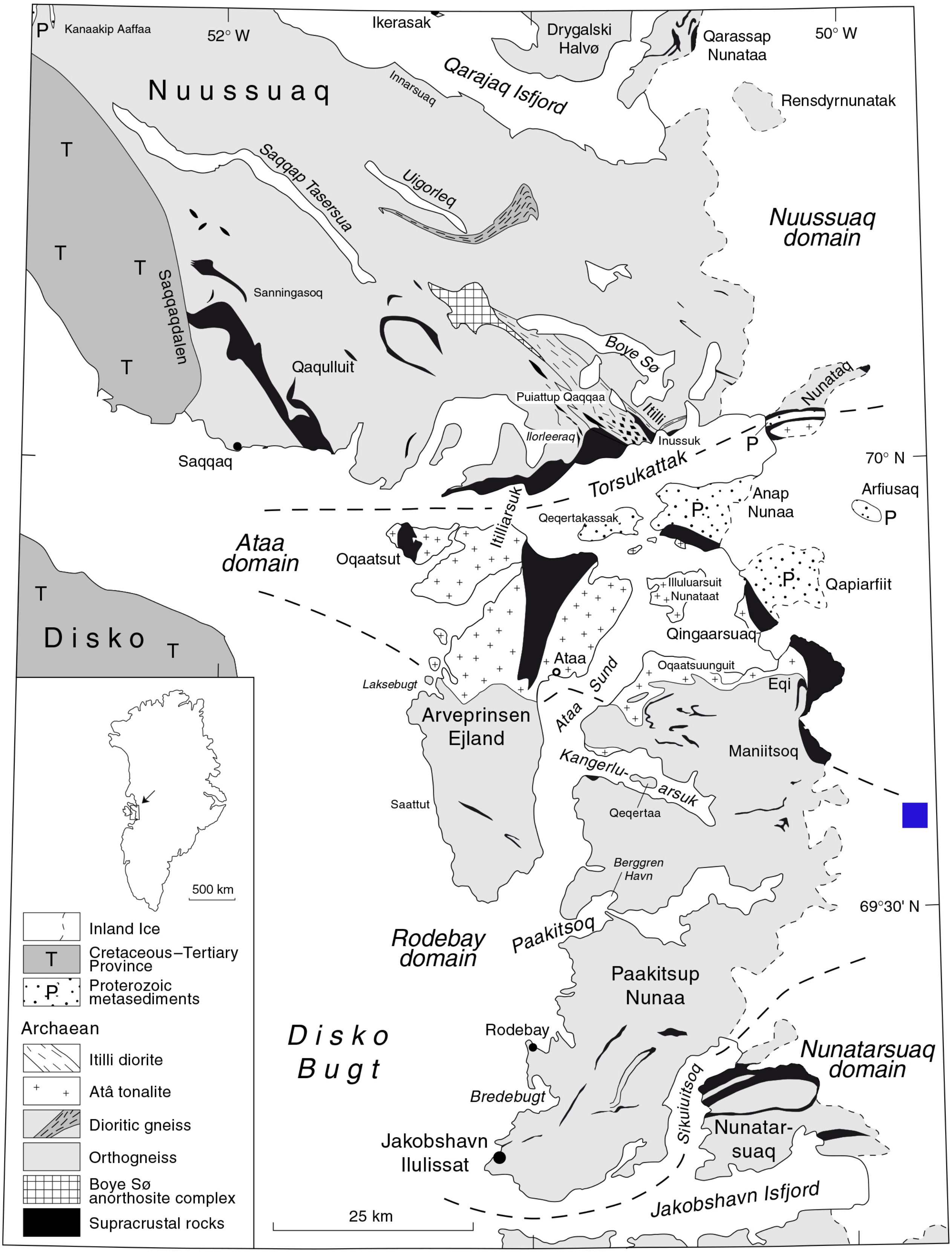

Fig. 2 - Geological sketch map of Eqip Sermia area (modified from Garde and Steenfelt, 1999). Blue square indicates the sampling area.

Sample	Latitude	Longitude	Elevation (m asl)	Date
CG1	69°34.993 N	49°47.274 W	863	03-09-2010
CG2	69°36.203 N	49°45.956 W	878	03-09-2010

Tab. 1 - Location of cryoconite sample sites on Eqip Sermia glacier (Central-West Greenland).

A dominant contribution of the silicate phases to the bulk dust mineralogy is in line with the results of the XRD spectra. The two sediments samples contain largely the same paragenesis, consisting of high abundance of quartz particles (60%) with almost the same proportion of plagioclase (albite) and hornblende (20%). Minor amounts of opaque oxides were also detected, but not relevant for table 2.

Figure 3 shows the modal mineral abundances for the two cryoconite samples from Eqip Sermia compared with other glaciers in northern Greenland. The later were substantially different from those on Eqip Sermia and also showed variation among them, with an important contribution of clay minerals (kaolinite, illite and chlorite). Conversely, no clay minerals were detected in Eqip Sermia samples. It is worth to note that the mineralogical composition of Eqip Sermia samples shows a larger percentage of amphibole (20%).

The samples from the two Eqip Sermia locations contain similar geochemical feature (Tab. 3). Among major elements only calcium shows a slight higher concentrations at CG2 than CG1 (Fig. 4). Iron content might be related to oxides. Trace elements pattern displays a relative slight enrichment for zirconium, antimony, arsenic, barium and lead in CG1 sample and for nickel, mercury and cupper in CG2 sample (Fig. 5).

In figure 6 cryoconite trace elements are normalized to the averaged upper continental crust with values close to 1 (Taylor and McLennan, 1995). Both CG1 and CG2 patterns show enrichment for chromium, antimony, titanium, vanadium and zirconium, and a depletion for barium and cadmium.

5. DISCUSSION

Dark material that reaches and accumulates on the ablation zone of the Greenland Ice Sheet can have two main sources: (1) recent enhanced deposition of dust or (2) accumulation through melting of outcropping ice that contains old dust layers. Some authors proposed that dark materials on the GrIS originated from East Asia and secondarily from North America or Sahara Desert (Tepe and Bau, 2015) while Wientjes et al. (2011) suggested a local sources in the western Greenland for cryoconite sediments. Dust causing cryoconite formation may thus originate from a period when more material settled in the accumulation zone of the ice sheet or it might have been deposited during cold periods, due to dry and windy conditions or, alternatively, it could be volcanic ash that was deposited on the ice. With the aim to discriminate the climate conditions during cryoconite formation, the changes in the mineralogy of atmospheric dust in the ice core has been investigated by Maggi (1997), spanning the time interval between the Eemian and the Last Glacial Maximum, and recognizing two distinct assemblages. One related to cold mid-high-latitude source areas consists mainly of quartz, illite, chlorite, micas and feldspars; and the other related to warm and humid low-latitude source areas consists mainly of kaolinite and iron oxides.

	quartz	plagioclase	hornblende	feldspar	chlorite	kaolinite	illite
CG1	60.0	20.0	20.0	0.0	0.0	0.0	0.0
CG2	60.0	20.0	20.0	0.0	0.0	0.0	0.0
QA1	33.4	26.1	12.7	12.7	0.0	7.6	7.6
QA2	31.1	29.4	8.0	13.1	0.4	10.3	7.7
QA3	31.1	23.6	7.8	8.2	3.3	15.0	10.9
QA4	36.0	15.6	12.8	13.8	1.7	10.9	9.2
QA5	33.9	25.8	10.9	7.8	3.7	8.1	9.7
QAS	70.9	3.5	4.4	12.4	0.0	2.5	6.5
QAM	75.9	11.0	7.9	0.0	0.3	1.9	3.0
QQ	64.6	9.5	8.9	6.7	0.9	6.1	3.4
TUG	37.8	23.0	9.0	11.9	0.9	7.5	10.0
BD	22.2	39.0	8.7	25.8	0.0	4.3	0.0
SUN	25.5	34.4	15.7	9.4	0.0	15.0	0.0
SCH	61.6	17.7	0.0	17.8	0.0	2.9	0.0

Tab. 2 - Modal composition of cryoconites from Eqip Sermia glacier in percent (%). The other Greenland dust samples are from Nagatsuka et al., 2014. (QA: Qaanaaq Glacier; QQ: Qaqortaq Glacier; TUG: Tugto Glacier; BD: Bowdoin Glacier; SUN: Sun Glacier; SCH: Scarlet Heart Glacier).

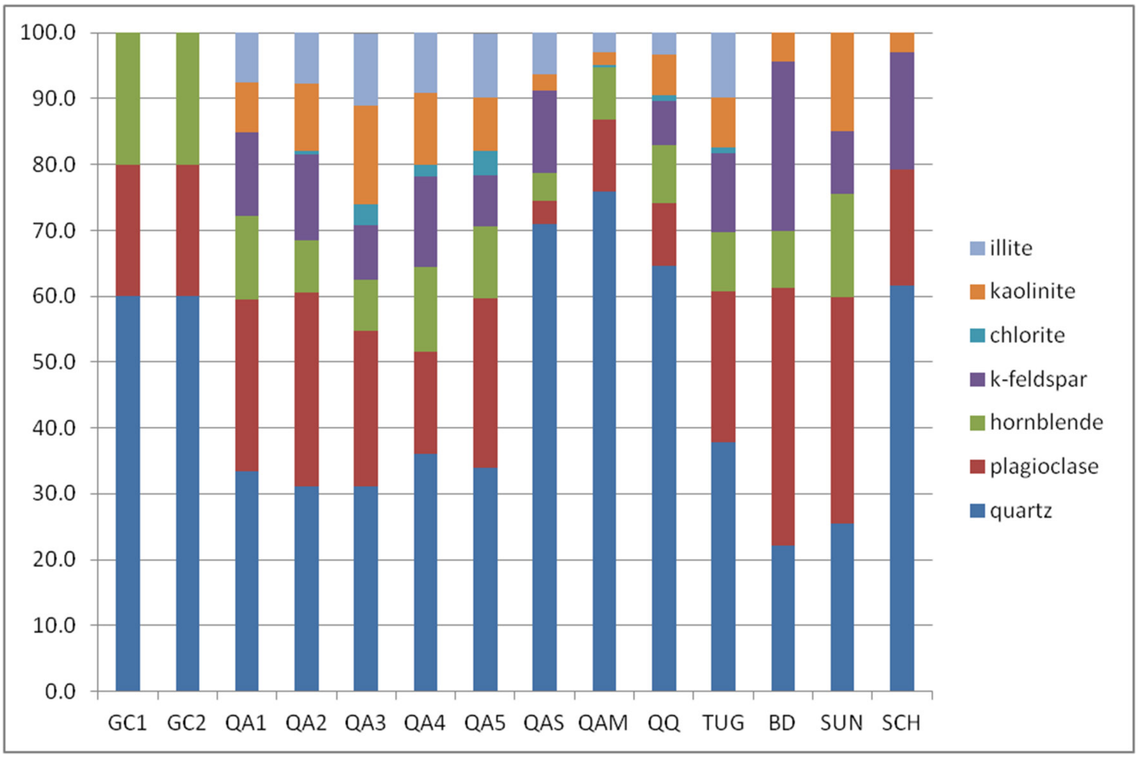

Fig. 3 - Modal mineral abundances for the two cryoconite samples from Eqip Sermia compared with other glaciers in northern Greenland. Data from Nagatsuka et al., 2014. (QA: Qaanaaq Glacier; QQ: Qaqortaq Glacier; TUG: Tugto Glacier; BD: Bowdoin Glacier; SUN: Sun Glacier; SCH: Scarlet Heart Glacier).

Element (wt %)	CG1	CG2	Element (ppm)	CG1	CG2
SiO_2	57.93	59.65	Ce	71	n.d.
TiO_2	0.75	0.73	Cl	166	159
Al_2O_3	14.41	14.77	Cr	118	117
Fe_2O_3	6.56	6.43	Sr	334	330
MnO	0.10	0.09	V	147	145
MgO	2.84	2.99	Zn	71	69
CaO	3.57	4.99	Zr	376	322
Na_2O	0.16	0.15	Sb	3.25	2.24
K_2O	1.76	1.81	As	1.6	n.d.
BaO	0.050	0.030	Ba	33.5	27.3
P_2O_5	0.171	0.180	B	3.75	3.84
SO_3	0.330	0.181	Cd	n.d.	0.176
			Co	8.58	8.10
			Hg	n.d.	0.130
			Ni	16.57	17.69
			Pb	19.1	12.06
			Cu	11.53	14.22
			Sn	n.d.	6.2

Tab. 3 - Geochemical composition for cryoconite sediments on the Eqip Sermia area (n.d.: no-detected).

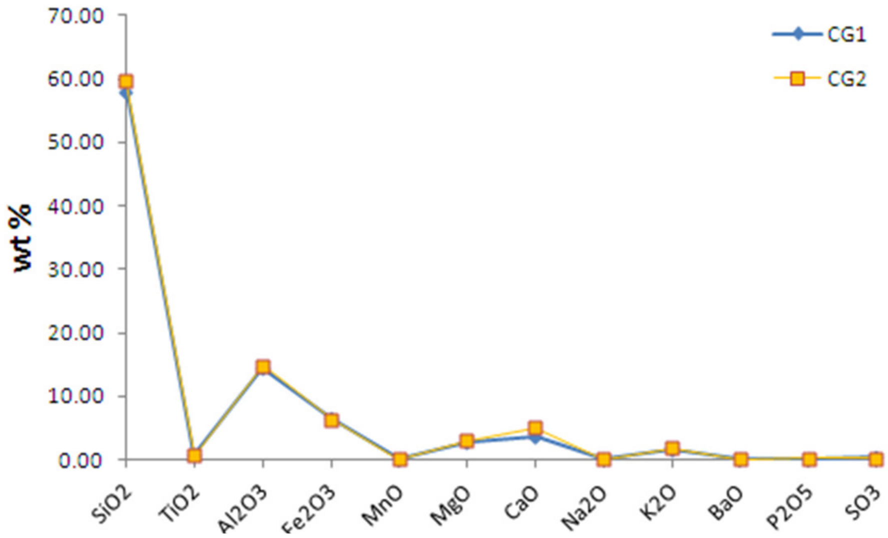

Fig. 4 - Geochemistry composition in major elements of cryoconite from Eqip Sermia glacier (weight %).

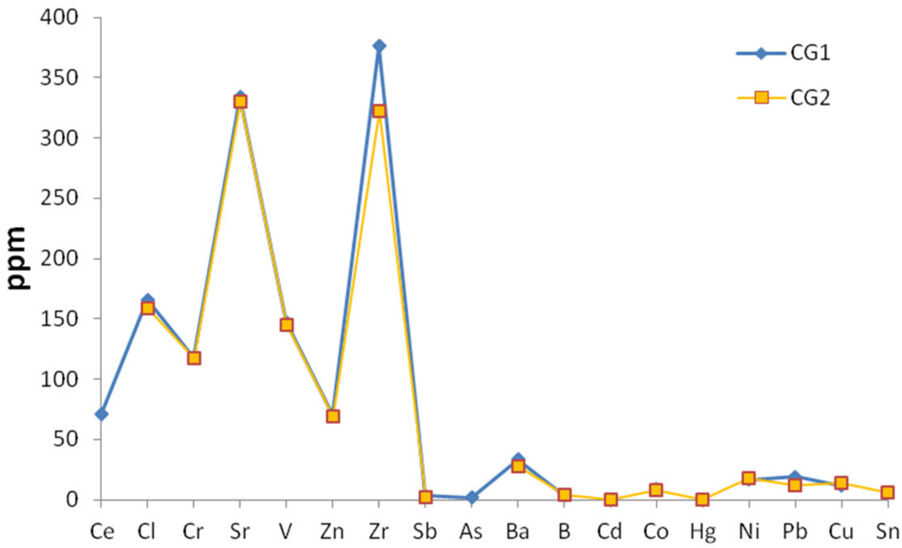

Fig. 5 - Minor elements of cryoconite from Eqip Sermia glacier (ppm).

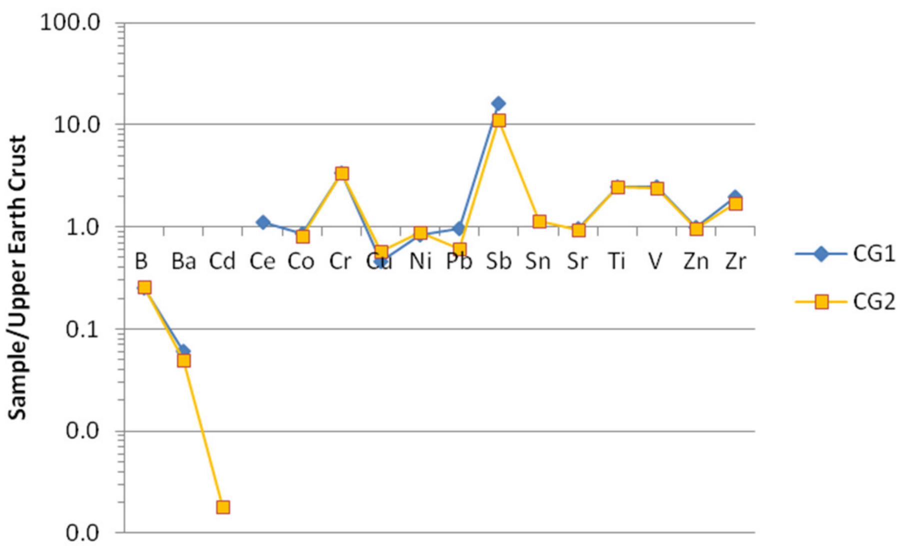

Fig. 6 - Trace elements pattern normalized to the upper continental crust for each Eqip Sermia cryoconite samples.

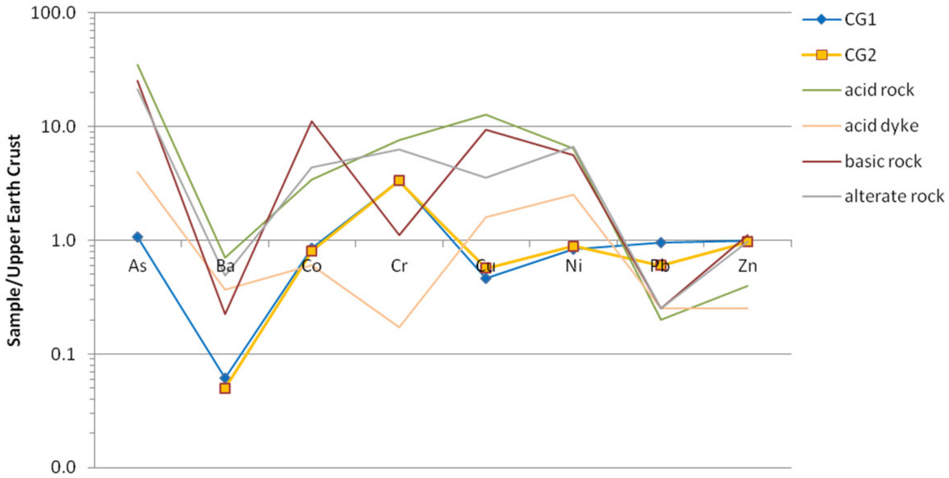

Fig. 7 - Eqip Sermia trace elements compared with rocks outcropping in the surrounding ice-free proglacial area. (Data for the surrounding bedrocks from Stendal et al., 1999).

In the Eqip Sermia cryoconites, the angular sharp-edged grains and the lack of rounded grains suggest that the shape of these mineral particles depend on the transport itself, independent of their origin. The mineralogical composition of Eqip Sermia samples is different from cryoconite of other Greenland glacial areas. It shows a larger percentage of amphibole (20%), respect to other Greenland glacier (between 4.4 to 15.7%) but comparable with basally derived debris at the margin of Russell glacier (Yde et al., 2010). This can be due to the possible higher influx of wind-blown material from the nearby bedrock. About the dust composition, the Eqip Sermia samples do not contain clay minerals (kaolinite, illite and chlorite) able to detect any assemblage that indicates the source area and climate condition during deposition. Besides, the high relative abundance of the quartz relative to amphibole and plagioclase is likely due to a higher degree of physical weathering. Moreover, the heavy metals such as antimony and chromium that have larger concentrations in the Eqip Sermia cryoconites might accumulate in melt water (Sanna and Romeo, 2016) due to uptake by microorganisms, which are abundant in these holes (Romeo et al., 2014). Furthermore, the trace elements patterns for the two samples reveal a source with a chemical composition similar to the upper continental crust. When plotting the ratio of Eqip Sermia trace elements with rocks outcropping in the surrounding ice-free expanse proglacial area (Fig. 7), cryoconite samples reveal close similarity with the mean concentrations for weathered rocks of the Eqip ablation zone (Stendal et al., 1999). As both the mineralogical composition and the trace element patterns do not show large variations, the dust from the two sites has mainly the same origin, indicating a local source probably the nearby weathered rocks.

6. CONCLUSIONS

The geochemical and mineralogical characteristics of cryoconites from Greenland Ice Sheet have been investigated in order to find out more about dark surface material deposited on glacial surface. Cryoconite samples were collected on the southern lobe of Eqip Sermia glacier (Central-Western Greenland). The both optical transmitted light and electron microscopy confirm the angular-faceted, sharp-edged shape of the fine grains (mean size 10-50 mm). The mineralogy consists of three silicate minerals (quartz, amphibole and plagioclase) with little variation in modal composition, and rare oxides. Geochemical analyses revealed that the elemental composition of the dark material is the same for both areas. The trace elements patterns for the two sites resemble the averaged upper continental crust, except for a depletion/enrichment of few elements. The relative abundance of some heavy metals might be explained by microbial activity. Based on these features the outcropping dust can be related to material originated from weathered rocks in the surrounding ablation zones. Comparison of the mineralogical composition of the dust with literature values confirms that the cryoconite sediments have a local origin. The lack of a typical mineralogical assemblage does not exclude the presence of other driven factors in cryoconite formation such as recent climate changes.

ACKNOWLEDGEMENTS - Special thanks to Spélé'Ice Association and La Venta Exploring Team for their essential contribution during the expedition and Chelab for its laboratory support.

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