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A general description of cryoconite and its expected characteristics and origin at the glacier Nigardsbreen, Norway

A research proposal

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Abstract

Dark dust accumulates on the surfaces of glaciers ablation zones where it aggregates and forms cryoconite. Inorganic content, often silicate minerals, and organic matter, including wind-blown pollen and plant fragments as well as microbes which contributes to the cryoconite's own ecosystem, compose the aggregates. Due to its dark color cryoconite absorbs solar radiation better than the surrounding ice and produces heat energy. The increased temperature creates depressions in the ice, filling them with meltwater, and forms cryoconite holes with the sediment at the bottom of the depression. Currently, there are different opinions about the way cryoconite influences glaciers. It does reduce the albedo and contributes to the meltwater production, but there still is debate ideas if cryoconite affects the mass balance of the glaciers or not. The observed ages of cryoconite ranges from modern to ancient which depends on where the dated carbon originates from.

For this study, cryoconite samples have been collected from the glacier Nigardsbreen in Norway. One of the samples was decided to be radiocarbon dated and was sent to the University of Lund, Sweden, and attained an age varying between 5045 to 4830 cal. yr BP. This study includes a proposal of how to evaluate the composition and the provenance of the sampled cryoconite, both the mineralogical and the organic part. Silicate minerals and microbial life may also be the dominant compounds in cryoconite originating from Nigardsbreen, as for other analyzed samples all around the world. The study will also place the date into a glacier historical and mass-balance context.

Keywords: Cryoconite, cryoconite holes, glacial dust, Nigardsbreen, Southwestern Norway

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1. Introduction

Nigardsbreen is part of the larger ice cap Jostedalsbreen and is one of the greatest outlet glaciers at the ice cap (Østrem, Liestøl, & Wold, 1976). It was first mentioned in historical documents in 1735 due to a large ice advance that damaged valuable land. Jostedalsbreen covers an area of 487 km^2 where Nigardsbreen represents almost 10% of the ice cap with its 48 km^2 (Diodato, Støren, Bellocchi, & Nesje, 2013).

Cryoconite means ice (cryo) dust (conite) and can be found on the glacial ablation zones worldwide. This dark-colored dust transports by wind and deposits on the glacier's surface. Cryoconite is composed of inorganic and organic matter which together reduces the surface albedo of the glacier and creates depressions in the ice, filling them with water. These depressions are termed cryoconite holes (fig. 1). (Takeuchi, 2002; Xu, Simpson, Eyles, & Simpson, 2010). Albedo is a measurement of the total solar radiation reflection a material provides. Snow and ice usually have a high albedo due to its light color while cryoconite, with its dark color, has a low reflectance, i.e. a high absorption. The cryoconite holes, containing the inorganic (mainly minerals) and organic dust, are known for having microbial activity in the form of e.g. bacteria, fungi, diatoms and green algae (Xu et al., 2010). This dust is not only composed of minerals, organic matter and microorganism, but radioactive isotopes and heavy metals also contribute to the content of cryoconite, both anthropogenic and natural (Baccolo et al., 2017; Baccolo et al., 2020; Lokas, Zaborska, Kolicka, Roycki, & Zawierucha, 2016).

In this study, I want to describe cryoconite in a general manner. I will also propose a method for future lab work with cryoconite samples collected at Nigardsbreen in September 2019 during a field excursion to Norway. A hypothesis of what I believe the Nigardsbreen cryoconite samples are composed of and its provenance, considering the knowledge about cryoconite stated in this study, Norway's glacial history and the environment surrounding Nigardsbreen, will also be stated. The research questions pointed out in this study are: (1) what is cryoconite composed of? (2) How does it accumulate on the glaciers surface and how does the transportation work? (3) What is its origin? (4) What is the general age? (5) In what way does it influence glacier melting?

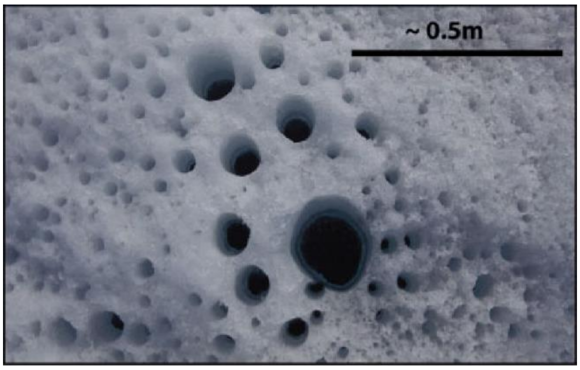

Figure 1. Figure from Cook et al. (2016) that shows developed cryoconite holes.

Even though there are a great number of studies targeting cryoconite, there is a lack of knowledge concerning how it influences light absorption and meltwater production on glaciers. Also, more knowledge about the microbial activity and its ecology are important and how this influences the glaciers (Cong et al., 2018; Takeuchi, 2002; Xu et al., 2010). Takeuchi (2002) and Xu et al. (2010) discuss the possible significant role humic substances in cryoconite might have on accelerating melt processes occurring in glaciers due to the reduction of albedo it contributes to. Cryoconite could possibly have a large active role in the shrinkage of glaciers which is worth focusing on and develop more knowledge about. Cryoconite may also have played a significant role in the early stages of Earth's history during Snowball Earth. Hoffman et al. (2017) discuss the possible influence cryoconite had during the Cryogenian (720-635 Ma) as a temporal microbial habitat that may have been an important part for the survival of the early life.

2. Geographical distribution

Cryoconite, at both low and high latitudes and in the northern and southern hemisphere (fig. 2A), have been analyzed. Any analyses about the cryoconite in the mainland Norway have not yet been published, which makes an analysis of the Nigardsbreen cryoconite even more interesting.

Norway's ice cap Jostedalsbreen and its outlet glacier Nigardsbreen (fig. 2B, C) is located north

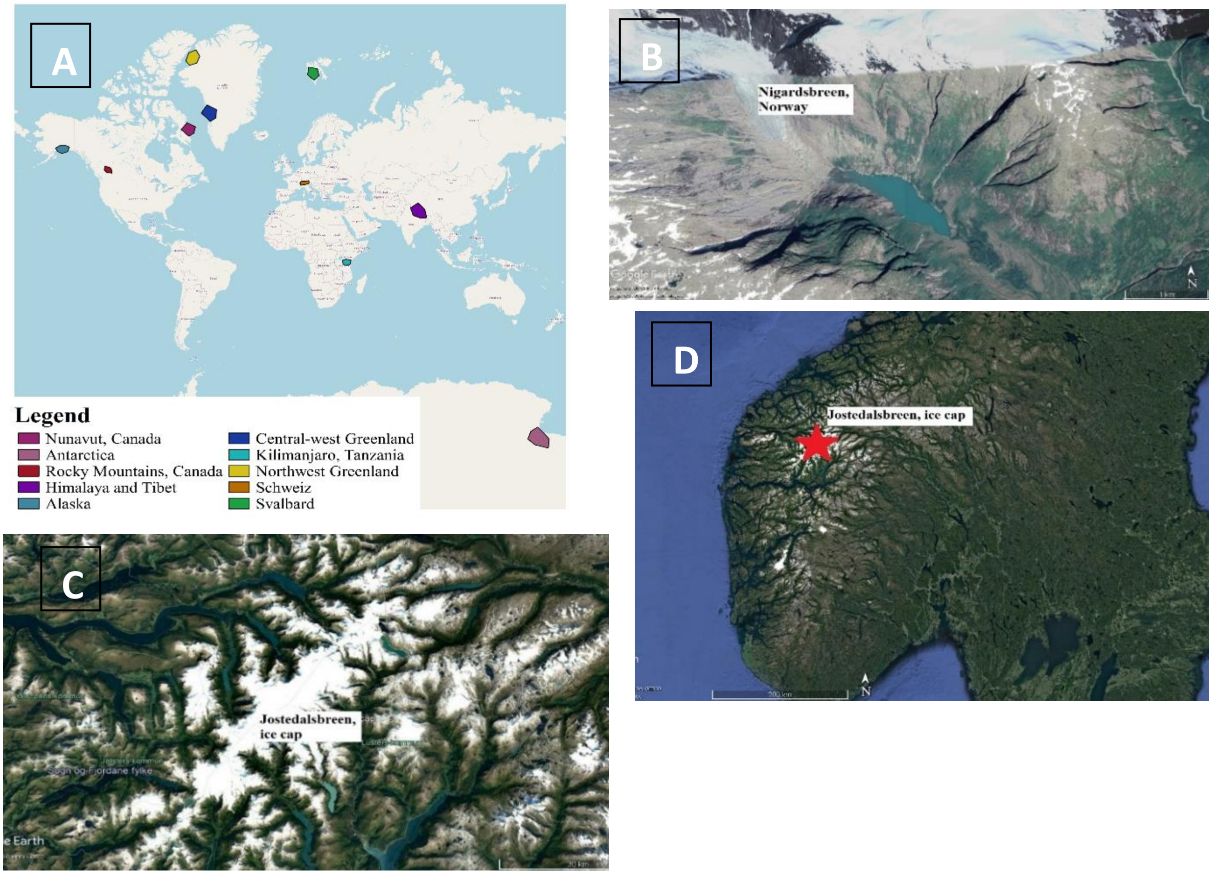

Figure 2. ***A***. *Map showing earlier studies and sampling locations of cryoconite. Glaciers in Antarctica: Canada Glacier (McMurdo Dry Valleys). Canada: Athabasca Glacier (Rocky Mountains), Greenshield Glacier, and Sverdrup (Nunavut), Greenland: Eqip Sermia (Central-West Greenland), Qaanaaq Glacier, Qaqortaq Glacier, Tugto Glacier, Bowdoin Glacier, Sun Glacier, and Scarlet Heart Glacier (northwest Greenland). Alaska: Spencer Glacier and Matanuska Glacier. Himalaya: Yala Glacier, AX010 Glacier, and Rikha Samba. Tibet: Meikuang Glacier, Gozha Glacier, Xiao Dongkemadi, Glacier, Urumqi no. 1 Glacier, Laohugou Glacier, Palong no. 4 Glacier, and Baishui no. 1 Glacier. Svalbard: Austre Brøggerbreen, and Hans Glacier. Tanzania: Kilimanaro's Northern ice field. Schweiz: Morteratsch Glacier.* ***B***. *Satellite picture of the outlet glacier Nigardsbreen from Google Earth.* ***C***. *Satellite picture of Jostedalsbreen ice cap from Google Earth.* ***D***. *Overview picture of Jostedalsbreen ice cap from Google Earth.*

of Sognefjorden at the southwestern part of Norway (fig. 2D).

3. Characteristics of Nigardsbreen and the environment surrounding the glacier

Close to the southwestern part of Jostedalsbreen ice cap, the glacier Flatebreen's glacial history during Holocene has been analyzed by Nesje et al. (2001). Three large glacial expansion episodes are shown in the sedimentary succession that were reconstructed from lacustrine sediment cores from the proglacial lake Jarbuvatnet, about 1,4 km in front of the present-day ice margin of Flatebreen Glacier. The first major expansion, Erdalen Event, ceased around 10200 cal. yr BP (fig. 3). The end moraines from this event extends about 1 km beyond the moraines formed by the 'Little Ice Age'. A second expansion occurred about 2000 years later (8200 cal. yr BP) and was named Finse Event (fig. 3) (Nesje et al., 2001). The third expansion took place around 4000 cal. yr BP and has lasted to the present for the time of the study (fig. 3). This third advance also included the 'Little Ice Age', with its peak around 200-300 cal. yr BP (fig. 3). The moraines formed by the 'Little Ice Age' extends as far as 890 m beyond the 2001 ice margin of Flatebreen glacier (Nesje et al., 2001). The current Nigardsbreen margin is 4,5 km behind the 'Little Ice Age' moraines (measured from Google Earth). The age determination of the 'Little Ice Age' is partly based on historical evidence, lichenometry (dating lichens), and moraine stratigraphy (Nesje et al., 2001).

Andreassen, Elvehøy and Kjøllmoen (2020) studied changes in mass balance, area, length, and surface elevations at glaciers in the mainland Norway. The timeline reaches from the 1960s-2018. For 131 analyzed glaciers, between the 1960s and the 2010s, a glacial area coverage of 817 km^2 (1960s) had decreased in size to 734 km^2 (2010s), a reduction of 10%. Glaciers in Norway have continuously advanced and retreated throughout the history. Since the early 1900s, when the beginning of glacial measurements started, the glaciers are now at a minimum stage for the time of the study. During the 1990s, an advance for many glaciers took place but ended in the beginning of 2000s. Some individual years during 2000s did favor the advance of glaciers, but in a general manner retreat has dominated the glacial conditions since the last 20 years. For the ice-margin, the general retreat velocity from the 1960s is 12 m a^{-1} (meter per year). Between 1982-2000, the weather favored many glaciers and the general retreat became slower with an ice-margin retreat velocity of 2 m a^{-1}. This changed abruptly between 2000-2018, when glaciers began to retreat faster with a velocity of 20 m a^{-1}. Between 2017-2018, many glaciers had their maximum change with a velocity of 33 m a^{-1} (Andreassen et al., 2020). Jostedalsbreens ice cap, where Nigardsbreen serves as one of the outlet glaciers, has an average mass balance change of -0,39 m w.e. a^{-1} (unit measuring mass balance in meter per year) between years 1960-2018, where Nigardsbreen had an average surface elevation change of -2,2 m between 1964-2013 (Andreassen et al., 2020).

The mass balance of glaciers, especially located in southern Norway (such as Nigardsbreen), are influenced by the North Atlantic Oscillation (NAO). When the pressure is greater at the Azores than over Iceland, a positive NAO-index occurs which brings strong westerly winds and a great amount of snow accumulation to Norway’s southern glaciers (Andreassen et al., 2020). However, the Arctic Oscillation (AO) also correlates with Norway’s glacier mass balance record (Andreassen et al., and references therein, 2020). A positive AO-index correlates with a strong Northern Hemisphere (NH) polar vortex, and a negative AO-index is associated with a weaker polar vortex (Ripesi, Ciciulla, Maimone, & Pelino, 2012), which in turn may weaken the NH jet streams that provide warm south westerly winds (Marshak., 2015). When the NH polar vortex weakens, i.e. a negative AO-index, the climate could become colder due to a higher contribution of northeastern cold winds.

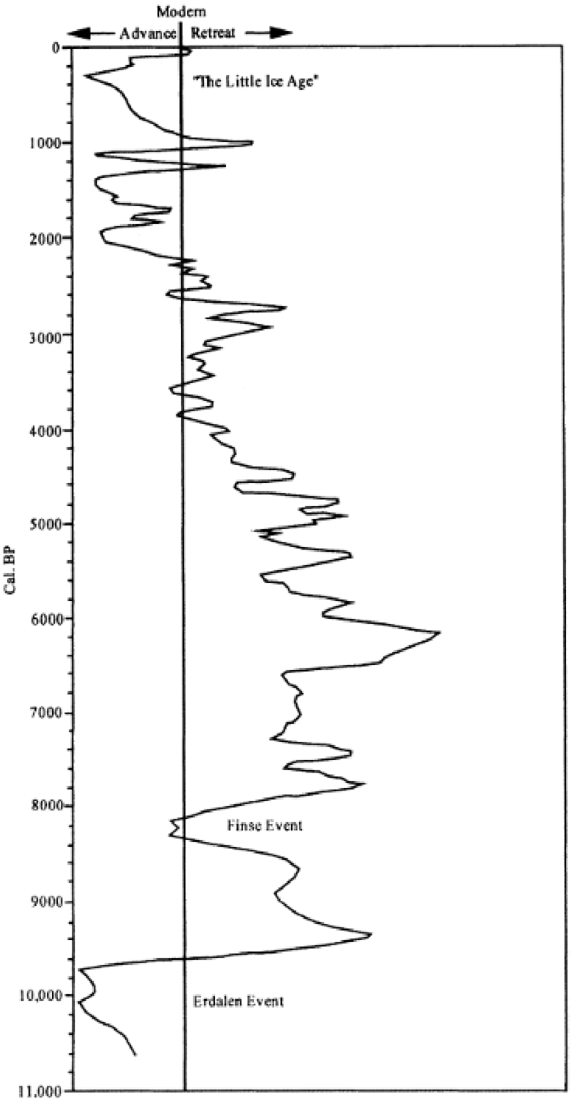

Figure 3. Figure from Nesje et al. (2001) showing the glacial changes at Jostedalsbreen during Holocene. The three expansions at ~10000 cal. yr BP (Erdalen event), ~8000 cal. yr BP (Finse Event), and ~4000 cal. yr BP to present are shown in the figure as advance peaks. Also, the ‘Little Ice Age’ is being pointed out with its maximum advance at 300 cal. yr BP.

The surrounding bedrock at Nigardsbreen is a monzonite/quartz monzonite and a dioritic to a granitic gneiss (Norges Geologiske Undersøkelse, 2019). These rock types are composed of silicate minerals such as feldspars and quartz. In front of Nigardsbreen and Nigardsbrevatnet (the lake, fig. 4), glacial features are to be seen, e.g. end moraines and eskers. The surrounding vegetation consists of mosses, lichens, grass, and smaller trees (fig. 4).

4. Cryoconite, a general description

4.1 Composition

Cryoconite has a complex composition with minerals, organic material, microorganisms, anthropogenic and natural radioactive elements, and heavy metals. These will each be explained under this section.

4.1.1 Inorganic content

The types of inorganic matter are discussed here, and its provenance will be discussed later. The inorganic components may in some cryoconite samples be the dominant part in the composition. Bøggild, Brandt, Brown & Warren (2010) observed that a cryoconite sample from northeast Greenland contained almost 95 % mineralogical content and 5 % of biological matter. This amount changes between individual glaciers where e.g. another analysis at northwest Greenland, showed an organic matter content of 13-20 % (Bøggild et al., and references therein, 2010), whereas other glaciers' cryoconite could possibly contain a larger amount of organic matter than the inorganic material.

Nagatsuka, Takeuchi, Uetake, and Shimada (2014) studied the mineral composition in cryoconite from six different glaciers (Qaanaaq, Qaqortaq, Tugto, Bowdoin, Sun, and Scarlet Heart) at the Northwestern Greenland (fig. 2A) where silicate minerals were most abundant. At Qaanaaq Glacier, cryoconite samples were collected from five diverse elevations on the ablation zone. The minerals quartz, feldspars, hornblende, and the clay minerals illite and kaolinite were detected, along with chlorite which was only recognized at three of the five elevations. For the Qaanaaq Glacier, the mineral analysis showed the highest amount of quartz (31-36 %) and plagioclase (16-29 %) and the lowest amount of chlorite (0-4%). Quartz together with plagioclase dominated the mineral composition and the amount of orthoclase feldspar, hornblende, kaolinite, and illite are rather similar for all the five different elevations at the Qaanaaq Glacier. These minerals showed a small variation of mineral content for the glacier (fig. 5).

Figure 4. The surrounding environment of Nigardsbreen. The glacier is seen in the middle of the picture as a white-blue feature. Notice the vegetation (smaller plants and trees).

At the other five glaciers, the mineral content varied, where some did not show any peaks for illite and chlorite while another did not contain hornblende (fig. 6). This represents a strong variation in mineral composition for the individual glaciers. Quartz is abundant, but the amount differs for each glacier. Plagioclase content varies notably from being the most abundant mineral in glacier Bowdoin to having one of the lowest amounts in Qaqortaq Glacier.

Sanna & Romeo (2018) also analyzed the mineralogy in cryoconite from Eqip Sermia Glacier in Central-West Greenland (fig. 2A), which also showed a high content of silicate minerals and some rare oxides. The average grain size was between 10–50 mm which corresponds with medium to coarse gravel, but grain sizes ranging from a few micrometers to around 100 mm for the largest sizes, were also found. Sanna & Romeo (2018) also determined that the grains were angular flat shapes with sharp edges where each grain was composed of a single crystal of either quartz, feldspars, amphibole, or oxides. Bøggild et al. (2010) analyzed grain sizes in cryoconite from northeast Greenland (fig. 7), which were significantly smaller with a medium size of 2-63 µm (fine, medium, and coarse silt) and 63-200 µm (fine sand). The most common grain size for 'Stake 12, 8 and 5' (the cryoconite on Holocene ice) were 20-63 µm (coarse silt). Clay and larger sand-sized grains were also detected.

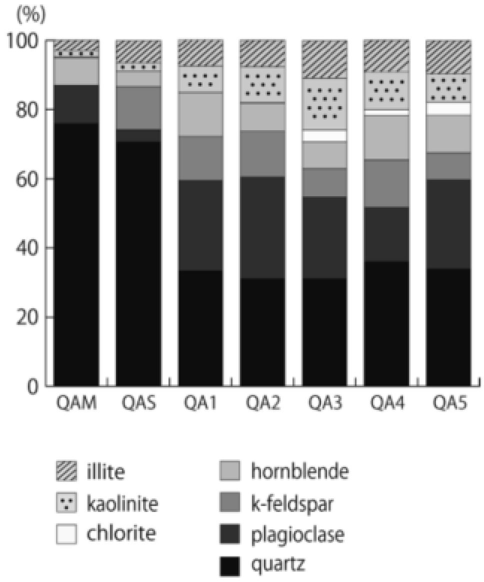

Figure 5. Diagram from Nagatsuka et al. (2014) showing the mineral composition at the Qaanaaq Glacier, northwest Greenland, where QAM and QAS represents mineral content from the nearby moraine and soil, respectively. QA1-QA5 represents the composition of the five different elevations.

Iron oxides have been found by Cong et al. (2018) in cryoconite at glaciers on the Tibetan Plateau (Urumqi no. 1, Laohugou, Xiao Dongkemadi, Palong no. 4, and Baishui no. 1) (fig. 2A). The iron oxides originated from the minerals hematite (Fe_2O_3) and goethite ($FeO(OH)$). The sampled cryoconite, at the Tibetan Plateau, contained between 81-98% goethite of the total amount of iron oxides, which can be explained by the favorable cold and moist environment for the formation of this mineral. Hematite, on the other hand, is favored by warm and dry conditions.

Apart from iron, other heavy metals have also been found in cryoconite. Baccolo et al. (2017) discuss that the heavy elements hafnium (Hf), thorium (Th), uranium (U), tungsten (W), tantalum (Ta), and gold (Au) are more abundant in the cryoconite at the Morteratsch Glacier in the Swiss Alps (fig. 2A), than in the surrounding moraine. E.g. Au has a higher concentration in the cryoconite by a factor of 6,5 compared to the moraine, and in comparison to the upper continental crust (UCC) cryoconite has an 8,5 times higher concentration of Au. The much higher concentration of heavy elements in cryoconite is believed to arise due to flowing superficial meltwater which removes the lighter mineral fractions, and an enrichment occurs for the heavier minerals where trace elements are to be found (Baccolo et al., 2017). Łokas et al. (2016) found the heavy metals copper (Cu), lead (Pb), zinc (Zn), iron (Fe), manganese (Mn), and cadmium (Cd) in cryoconite at Hans Glacier in Svalbard (fig. 2A) and concluded that the concentration of these metals is higher in the cryoconite than in the UCC and the local rocks. Due to this discovery, Łokas et al. (2016)

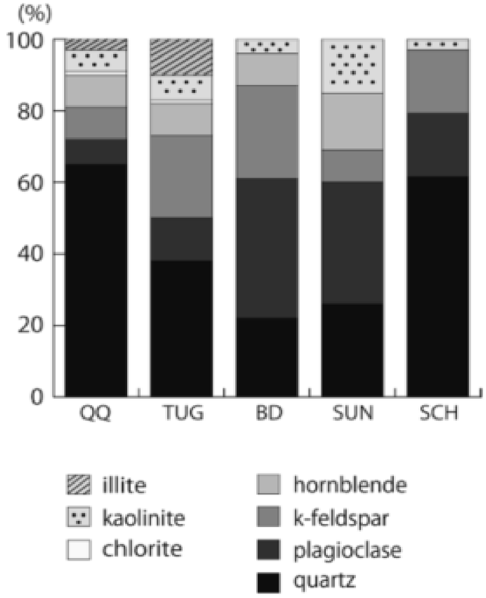

Figure 6. Diagram from Nagatsuka et al. (2014) showing the five other glaciers mineral composition at the northwest Greenland. QQ, TUG, BD, SUN, and SCH represents Qaqortaq, Tugto, Bowdoin, Sun, and Scarlet Heart, respectively.

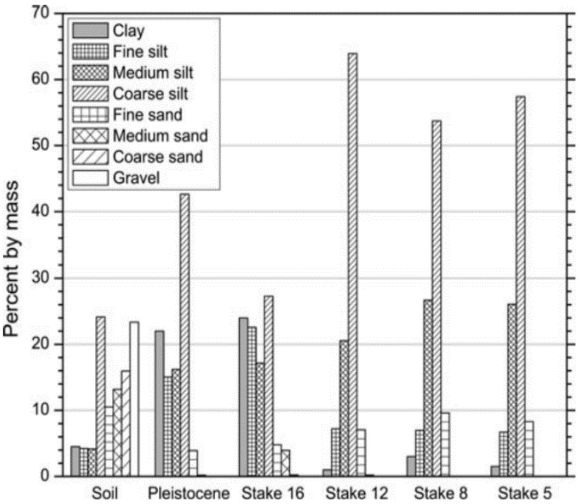

Figure 7. Graph from Bøggild et al. (2010) showing the grain size distribution by percent by mass of cryoconite from a glacier in the northeast Greenland and soil from the nearby tundra. Both 'Pleistocene' and 'Stake 16' were sampled from the Pleistocene ice of the glacier and 'Stake 12, 8, and 5' were sampled on the Holocene ice.

concluded that the heavy metals do not only have a natural origin but also a high contribution of heavy metals from anthropogenic activities.

Radioactive isotopes have also been detected at glaciers in the Swiss Alps and Svalbard (Baccolo et al., 2017; Łokas et al., 2016). Comparable to heavy metals, radionuclides can have an anthropogenic or natural origin as well. Łokas et al. (2016) analyzed the natural radionuclide ^{210}Pb and the anthropogenic radionuclides ^{238,239,240}Pu, ^{137}Cs, and ^{90}Sr at Hans Glacier in Svalbard (fig. 2A). The environment is surrounded by peatlands and mosses which showed a lower concentration of ^{210}Pb-, ^{238,239,240}Pu-, and ^{137}Cs-activity compared with the concentration in cryoconite.

4.1.2 Organic content

The other dominant part of cryoconite composition is organic matter, which can be even the basis for a complex and unique ecosystem. There is a general lack of knowledge about this sub-area due to its complexity and what it contributes to.

Xu et al. (2010) analyzed cryoconite sample from the Athabasca Glacier in the Canadian Rocky Mountains (fig. 2A) where n-alkanes, n-alkanols, fatty acids, wax esters, and sterols were recognized and analyzed. Each of these compounds are a clue to the provenance of the organic matter.

A large amount of mid chain n-alkanes were observed, which speak for an input of mosses and lichens (non-vascular plants), but Xu et el. (2010) also recognized a smaller contribution of long chain n-alkanols, n-fatty acids, and wax esters that represents higher order plants. However, an absence of vanillyl (V), syringyl (S), and cinnamyl (C) lignin derived phenols, which are associated with non-woody and woody tissues (that contributes to the strength and stability in the cell walls in trees), demonstrates a small amount of vascular plants in the cryoconite sample. Several articles also indicate that pollen contributes to the organic content of cryoconite (Margesin, Spröer, Schumann, & Schinner, 2003; Margesin, Zacke, & Schinner, 2002; Takeuchi, Matsuda, sakai, & Fujita, 2005), but any standard palynology analyses on cryoconite pollen are not commonly made. Glacial environment with its below 0°C temperature, are expected to preserve pollen protoplasm (i.e. cytoplasm for eukaryotic cells, the living part of a cell) and its DNA. Pollen protoplasm is not a common preserved characteristic found in pollen from lacustrine sediment or from peatland, which makes glacial pollen beneficial for DNA analyses (Nakazawa, Suyama, Imura & Motoyama, 2018).

A high content of phospholipid fatty acid (PLFA) was also detected in the Athabasca cryoconite (Xu et al., 2010). PLFA is strongly associated with microbial life where it can be found as components in cell membrane from microorganisms. After death, PLFA quickly breaks down and serves as biomarkers for the viable microbial life that compose the cryoconite (McCrimmon, Bizimis, Holland, & Ziolkowski, 2018). Some of the organism sources that PLFA originates from, at the Athabasca Glacier are algae, fungi, and bacteria (Xu et al., 2010).

Xu et al. (2010) also observed a high value of alkyl/O-alkyl ratio (2,16) in the cryoconite sample. Alkyl/O-alkyl ratio is used to provide a value for the degradation of organic matter. This value was compared to several soil sample ratios from grasslands, forests, and mixed soil from grassland and forest in Alberta, Canada. The ratio varies from 0,39-0,79 which is significantly lower than the ratio in cryoconite (Xu et al., and references therein, 2010). The cryoconite sample has a higher ratio than terrestrial soil which indicates that some of the organic content in cryoconite is derived by microbial activities instead of plants as in the terrestrial soil (Xu et al., 2010). A high alkyl/O-alkyl ratio is consistent with an absence of lignin and high concentrations of PLFA which all illustrate a widespread microbial activity that, together with large amounts of mosses and lichens, constitutes the organic content of the analyzed cryoconite.

McCrimmon et al. (2018) analyzed δ^{13}C and C/N ratio of cryoconite sample from southern Alaska (Spencer Glacier and Matanuska Glacier, fig. 2A) for determination of the carbon's origin. A δ^{13}C value of -26,3‰ ± 0,9‰ indicates that the carbon could originate from sources of microbial activities, C_3 vegetation (plants that have three carbon atoms in the base molecule during photosynthesis), but also fossil sources from oil or organic carbon in sedimentary rocks. It is hard to determine the origin of carbon with the value of δ^{13}C alone but along with analyzed C/N ratio, the carbon can be determined to have a microbial or land-plant origin. For the primary carbon, a C/N ratio between 5:1 to 15:1 indicates a microbial, algal, and soil origin and eliminates the possibility of a land-plant organic matter derived carbon. McCrimmon et al. (2018) obtained a C/N ratio 9,5-13,6. Takeuchi (2002) also analyzed the C/N ratio of cryoconite from glaciers at the Himalaya (Yala, AX010, and Rikha Samba Glacier), Tibet (Meikuang, Gozha, and Xiao Dongkemadi Glacier), Canada (Greenshield Glacier and Sverdrup Glacier), and Svalbard (Austre Brøggerbreen) (fig. 2A), and obtained a similar result (9,0-14,2) as McCrimmon et al. (2018). The C/N ratio therefore implies that some of the organic carbon is not blown in land-plant material.

The microbial life in cryoconite can be affected by the mineralogical content due to incorporation of nutrients from mineral particles, especially clay minerals (Nagatsuka et al., 2014). This could therefore have a significant role of the microbial production. In turn, because microbial activity affects the light absorption due to its dark color, the clay-sized particles mineralogy also affects the reducing albedo of glacial surfaces and is therefore an important feature. Furthermore, a higher clay content may provide a larger microbial community (Nagatsuka et al., 2014).

Xu et al. (2010) analyzed the substance levoglucosan, which works as a biomarker that indicates biomass burning. Only a small input of this substance was found in the Athabasca cryoconite, but it indicates that not only natural vegetation and microbial life are viable in cryoconite holes but also biomarkers from anthropogenic sources or indicators for wildfires in the surrounding forests.

4.2 Accumulation processes and transportation in the glacier

Powdery sediment carried by the wind, accumulates on the surfaces of glaciers all over the world. Cryoconite is commonly found on the glacier’s ablation zone (Cook, Edwards, Takeuchi, & Irvine-Fynn, 2016; Hoffman et al., 2017) (fig. 8), but dust can accumulate all over the surface of a glacier. In time, blown in dust deposited on the accumulation zone will travel towards the ablation zone due to glacier dynamics (Benn & Evans, 2010; Hoffman et al., 2017). Deposited dust on the accumulation zone will sooner or later become buried by accumulating snow. As time goes by, snow will transform to ice, by compaction, recrystallization, and refreezing of meltwater. The sediment will in turn become incorporated into the ice. A glacier’s size will change due to the variation in the ablation and accumulation rates leading to advance or retreat of the ice margin depending on the balance (fig. 9) (Benn & Evans, 2010). A larger mass at the accumulation zone provides a movement of glacial ice towards the ablation zone. The incorporated dust and other sediment will get englacially transported until it reaches the ablation zone. The sediment, that once was blown in dust deposited on the accumulation zone, accumulates on the surface of the ablation zone and appears to be stuck in the ice at the margin of the ice crystals, which was observed on Nigardsbreen (fig. 10). The ice crystals with the incorporated dust melts and the supraglacial meltwater moves the sediment particles and transport them, forming aggregates in pockets. Due to the dark color a decrease of the surface albedo appears (more absorption of solar radiation) which increases the temperature in and around the cryoconite. The increased temperature

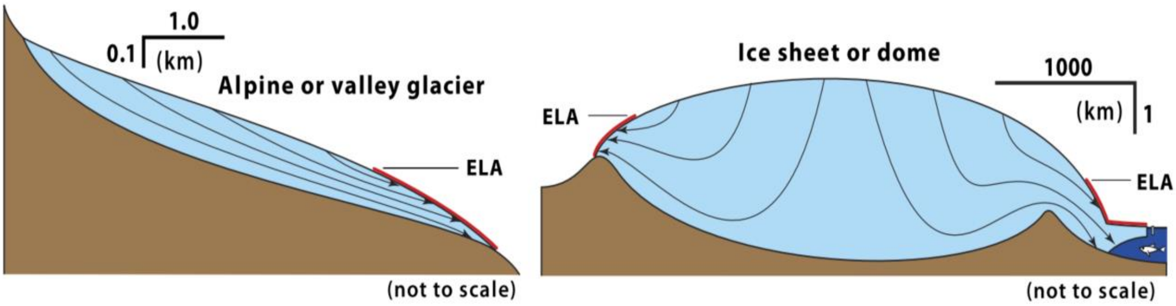

Figure 8. Modified figure from Hoffman et al. (2017). Red line displays where cryoconite accumulates for an alpine/valley glacier and for an ice sheet/dome. ELA stands for equilibrium line altitude.

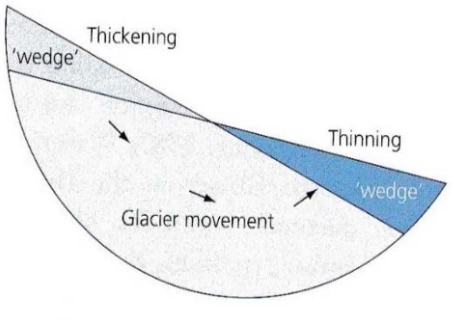

Figure 9. Modified figure from Benn & Evans (and references therein., 2010) showing the wedge concept about glacial balance. The white wedge, where thickening occurs due to accumulation, pushes the glacial ice mass towards the ablation zone (blue wedge), where thinning occurs as a result of melting.

melts the surrounding ice and creates depressions where the cryoconite accumulates in so-called cryoconite holes (fig. 11) (Cook et al., 2016; Xu et al., 2010). From observations I made on the glacier Nigardsbreen, rapid surface melting near the margin caused melting of the holes, which left the accumulated cryoconite on the ice surface, without any holes (fig. 12).

If no such rapid melt process occurs, the depressions are formed as cylinders (fig. 11) and have an average horizontal and vertical dimension of <10 cm, but huge holes have also been discovered with a depth of 5 m and a diameter of 30 m (Fountain, Tranter, Nylen, Lewis, & Mueller, 2004). The depth of cryoconite holes reaches its maximum in the late summers when it reaches the steady-state depth. This limit is attained when the total melting rate of the glaciers surface equals the rate of the downward melting occurring at the bottom of the cryoconite hole. This is due to solar radiation which has a hard time to be absorbed by the sediment because of its difficulty to reach the cryoconite as a result of hole deepening (Fountain et al., 2004). In the summers (ablation periods), high melt rate occurs which produces meltwater in the cryoconite holes. When the winter begins, (accumulation period) the melt water freezes and forms an ice lid on top of the cryoconite hole (fig. 10) (Fountain et al., 2004).

Cryoconite is present at both temperate and polar glaciers, but well-developed cryoconite holes filled with meltwater are more common on temperate glaciers (Fountain et al., 2004).

Figure 10. Sediment trapped in the ice at the edges of ice crystals. A thumb appearing on the left side of the picture, acting as a scale. Ice crystals are 1-3 cm in size. Picture taken by Mark Johnson at Nigardsbreen, Norway.

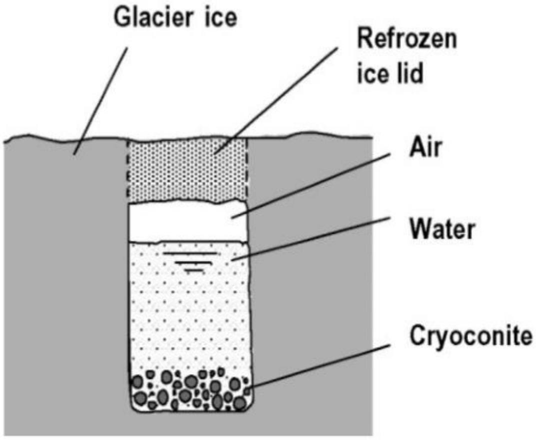

Figure 11. Figure from Fountain et al. (2004). A cross sectional, vertical cryoconite hole is displayed with its cryoconite sediment at the bottom of the cylinder, filled with water and with a refrozen ice-lid on top of it due to colder climate. If it would have been warmer, the ice-lid would melt.

4.3 Provenance of cryoconite

4.3.1 Inorganic content

Nagatsuka et al. (2014) analyzed the mineralogical content in cryoconite at six glaciers in northwest Greenland (fig. 2A). Three main sources are the most common origin for the mineralogical material found in cryoconite which are (1) origin from the local areas geology by weathering of the rocks, (2) melting ice produce outcropping of glacial debris that was basally derived or (3) from a long distance origin, e.g. sand grains from deserts, as windblown mineral particles that deposited on the glacier surfaces (Bøggild et al., 2010; Nagatsuka et al., and references therein, 2014). Bøggild et al. (2010) analyzed cryoconite samples from glaciers in

Figure 12. Image of me collecting cryoconite. The average surface melting could possibly have been rapid and melted the cryoconite holes walls and left the accumulated cryoconite on the surface. Picture taken by Mark Johnson.

northeast Greenland and discuss the diverse provenance with respect to grain sizes. In one of the analyzed samples of cryoconite, collected from a part of a glacier from Pleistocene age, they found a large amount of clay-sized minerals (>20%) (fig. 7). This is believed to originate from a long distance and does not have a local source due to differences in mineralogy between the clay and local soil samples, and also an absence of the clay minerals in cryoconite closer to the ice margin. On the other hand, the coarser sediment grains Bøggild et al. (2010) analyzed, such as silt and sand, are believed to originate from short distances and therefore local sources.

At the Qaanaaq glacier in the Northwestern Greenland (fig. 2A), five samples of cryoconite were collected at different elevations. The analyzed mineralogy did not differ significantly between the different elevations, instead it was surprisingly similar, which indicates that the minerals were derived from one specific source, probably from the local area (1) (Nagatsuka et al., 2014). However, at site QA3, clay-sized minerals were more common compared to the other locations. Nagatsuka et al. (2014) therefore discuss the possible source of the clay minerals at QA3 to be (2) or (3).

The local areas' geology and redistribution of sediment by coastal, glacial, and fluvial processes have the strongest influence on the locally derived mineral sources found in cryoconite (Nagatsuka et al., 2014). Nagatsuka et al. (2014) compared the cryoconite at Tugto Glacier with that at Bowdoin Glacier and Scarlet Heart Glacier, which have different mineralogical composition. Tugto Glacier has more clay minerals of illite and kaolinite, and Bowdoin Glacier and Scarlet Heart Glacier are composed of less abundant clay minerals of only kaolinite even though all three glaciers are situated on the same geological unit.

Sanna & Romeo (2018) analyzed cryoconite grain sizes at Eqip Sermia Glacier in Central-West Greenland (fig. 2A) that resulted in an average grain size of 10-50 mm (medium to coarse gravel). This size cannot originate from blown in mineral dust, i.e. (1) or (3), therefore these mineral grains must originate from basally derived debris that later outcrops at the surface of the ablation zone, (2).

Heavy metals in cryoconite may originate from the local geology, as natural heavy metals, but also as an anthropogenic source from the combustion of fossil fuel and from mining activity, from where particles are transported as aerosols. The heavy metals Zn, Cu, and Pb are mainly carried and deposited by precipitation (Łokas et al., 2016). For heavy metals in cryoconite found at the Hans Glacier in Svalbard (fig. 2A), the prominent source is from industries in Russia and Europe, transported atmospherically (Łokas et al., 2016).

Łokas et al. (2016) also discuss the provenance of natural (^{210}Pb) and anthropogenic (^{238,239,240}Pu, ^{137}Cs, ^{90}Sr) radionuclides. Interestingly, there is a strong difference in the level of radioactivity in cryoconite compared to the surrounding peatland and soil, but the knowledge is still poor for this subject, and it is not fully known why the concentration of radionuclides are particularly high in cryoconite. The primary source for anthropogenic radionuclides, however, is believed to originate from atmospheric fallout from both local and global nuclear tests and from failures at nuclear reactors such as Chernobyl. The natural radionuclide ^{210}Pb bonds with aerosol particles and travels via the atmosphere and deposits on glacier surfaces (Łokas et al., 2016).

4.3.2 Organic content

As described in section 4.1.2, the organic content studied by Xu et al. (2010) on the Athabasca glacier (fig. 2A) was determined to primarily originate from microbial activities and mosses and lichens (non-vascular plants), and not from higher order plants due to small contributing evidence and an absence of lignin phenols, which acts as biomarkers for vascular plants. The observed absence of lignin phenols, along with a high amount of PLFA and a high alkyl/O-alkyl ratio, are evidence for microbially derived organic matter (Xu et al., 2010). Signs for lower order plants (mosses and lichens) were also found due to the similarities the local tundra soils have with the detected mosses and lichens, e.g. observed n-fatty acids, n-alkanols etc. which were found in both the cryoconite and tundra soils at the Athabasca Glacier, Canadian Rocky Mountains (Xu et al., 2010). The observed organic matter in cryoconite at the Athabasca Glacier is therefore a mixture of blown in mosses and lichens and in-placed produced microbial organic material, together with small proportions of higher order plants.

McCrimmon et al. (2018) analyzed the carbon isotope δ^{13}C and the C/N ratio of cryoconite from southern Alaska (fig. 2A) and obtained, similar to Xu et al. (2020), a result that provided microbially derived carbon. Even Takeuchi (2002) observed a C/N ratio of cryoconite from glaciers at the Himalaya, Tibet, Canada, and Svalbard (fig. 2A), that concluded a high amount of carbon from microorganisms.

McCrimmon et al. (2018) collected and analyzed 12 cryoconite samples from southern Alaska and observed that the carbon found in cryoconite can be divided into two subgroups: (1) microbial communities that uses modern carbon from the atmosphere which are surrounded by (2) aged carbon that likely originates from rocks. This will be discussed more under section 4.4 Age.

Even though a higher microbial content was observed in the Athabasca Glacier, plant derived organic matter, both low order plants such as mosses and lichens, and higher order plants, were recognized. Mosses and lichens do contribute to the organic matter relatively much, but the higher order plants were only found in small proportions (Xu et al., 2010). The organic matter in cryoconite therefore has a wide range of provenances, both microbially and terrestrially derived material.

4.4 Age

A few age determinations have been made on cryoconite where the results indicate a wide range of ages. Noell, Abbey, Anderson, and Ponce (2014) radiocarbon dated cryoconite samples from Kilimanjaro's northern ice field (fig. 2A) that resulted in a modern age (after the 1950s). According to Noell et al. (2014), cryoconite microbial activity can manipulate the age of cryoconite by erasing the older carbon. The microbes are sometimes able to incorporate modern CO_2 with the older cryoconite carbon, which then makes the cryoconite appear younger than it is.

McCrimmon et al. (2018) collected 12 cryoconite samples from southern Alaska (fig. 2A) and extracted the subsample total lipid extract (TLE) from each of the 12 cryoconite bulk samples. From the TLE samples, subsamples of PLFA were extracted. The PLFA only composed a small portion of the total TLE sample. PLFA acts as compounds for cell membranes whereas TLE can contain alkanes, levoglucosan, black carbon compounds etc. The solvent extractable subsamples (TLE and PLFA) together with the cryoconite bulk samples were ^{14}C analyzed, where the solvent extractable compounds represent <10 % of the total cryoconite bulk organic matter. An obtained Δ^{14}C value of -1000 < 0 ‰ tells that the sample is depleted in ^{14}C and therefore has an age ranging from 100 to 50000 years old. A Δ^{14}C value of 0 < ~+20 ‰ express an enrichment in ^{14}C and provides a modern age of the sample (McCrimmon et al., 2018). McCrimmon et al. (2018) obtained a Δ^{14}C value ranging from 22 to 48 ‰ for the PLFA (with two odd depleted Δ^{14}C values of -63 and -234 ‰), in general an enrichment in ^{14}C which implies that the carbon was recently in equilibrium with the atmosphere and therefore shows a modern age. For the TLE only two Δ^{14}C values were obtained, -30 and -162 ‰. The age of the TLE must therefore be older than the PLFA and therefore its carbon may not originate from the same source. Finally, the cryoconite bulk organic carbon (the extractable and the non-extractable carbon together) obtained a $\Delta^{14}C$ value between -839 to -92 ‰, where some of the 12 samples shows a depletion in ^{14}C and all of them indicates an older age than in the PLFA and TLE. The cryoconite bulk organic carbon therefore shows a combined age due to a mixture of both the modern extractable and ancient non-extractable carbon.

Due to the large difference in radiocarbon analysis ranging from modern to ancient ages, McCrimmon et al. (2018) concluded that most of the cryoconite carbon is not being used by microorganisms, instead the microbial life in cryoconite use young carbon, fixed by atmospheric CO_2 through photosynthesis or by consuming recently fixed modern carbon, therefore obtaining a modern age. The rest of the cryoconite bulk organic carbon, was more depleted in modern carbon and showed ages ranging from 14680 ± 40 to 770 ± 25 ^{14}C age BP. McCrimmon et al. (2018) discuss the possible sources for the aged non-extractable carbon. Due to the surrounding environment at the Matanuska and Spencer glaciers in southern Alaska, where the cryoconite was sampled, McCrimmon et al. (2018) argue that the most trustworthy source would be from rocks such as shale. McCrimmon et al. (2018) also discuss other possible sources such as soil organic matter which has traveled with the wind and accumulated on the surface. But the authors conclude that this scenario is unlikely to happen due to that many samples were depleted in ^{14}C ($\Delta^{14}C_{bulk}$ -839 to -92 ‰) for the cryoconite bulk organic carbon, which would not be the case for terrestrial soil. Also, sources as combusted fossil fuels were discussed but not likely to be the origin of the aged carbon. McCrimmon et al. (2018) mention that if the aged carbon would have originated from fossil fuel, the solvent extractable TLE carbon should be more depleted in ^{14}C ($\Delta^{14}C_{TLE}$ ~-700 ‰) than it was The last discussed possible source for the aged carbon may come from other organic carbon sources, such as plants, that once in time deposited as modern carbon on the surface of the glacier's accumulation zone. As time went by, it aged and became older carbon. If this is the case, the oldest samples would be expected to be found at the margin of the glacier at the ablation zone, which was not investigated by McCrimmon et al. (2018).

The large difference in age between different sources of carbon, suggests that microbes preferentially use young carbon and not the aged carbon surrounding them. This, in turn, reflects that most of the carbon in cryoconite will not be decomposed by microorganisms.

The result of radiocarbon dating analysis of samples from Nigardsbreen provided by Lund's University, is discussed in the appendix.

5. Cryoconites influence on glaciers

5.1 Albedo, light absorption, and meltwater production

When cryoconite aggregates, a reduction in the albedo on the surface of the glacier appears. A change in surface albedo may affect the climate and mass balance of glaciers, therefore measurements of the albedo are important for climate-modeling analysis (Takeuchi, 2002). This occurs as a result of a higher light absorption in cryoconite, which has a dark color, compared to the surrounding ice which almost reflects all the incoming solar radiation. The cryoconite becomes heated as a result of this process and melts the ice, forming depressions (Takeuchi, 2002; Tedesco, Foreman, Anton, Steiner, & Schwartzman, 2013).

Takeuchi (2002) analyzed cryoconite samples from glaciers in the Himalaya, Tibet, Canada, and Svalbard (fig. 2A). Cryoconite from the Canada, Svalbard, and the Himalaya showed a low spectral light reflectance (high light absorption) compared to the samples in Tibet which had a higher reflectance. The spectral reflectance of the mineralogy of all three glaciers cryoconite were analyzed and did not show a significant difference among the samples. Thus, Takeuchi (2002) argues that minerals have a low influence in the process of light absorption. However, the Tibet cryoconite had a lower content of organic matter compared to the two other locations, indicating that biological substances have a large influence on cryoconites optical characteristics. Tedesco et al. (2013) also suggests that the organic material affects the reflectance in a wider range than minerals do.

However, Cong et al. analyzed iron oxides in cryoconite and concluded that, at a wavelength of 450 nm, goethite, together with organic matter, were the most dominant substances that absorbed solar radiation. For a longer wavelength, 600 nm, goethite was more insignificant (fig. 13). Organic matter is by far the substance that has the largest impact but different minerals, such as goethite, may also influence the light absorption to a rather great extent (Cong et al., 2018; Takeuchi, 2002). The microbial activity in cryoconite may also contribute to the melting processes creating cryoconite holes due to its metabolic activities which produce heat energy (Fountain et al., 2004; Takeuchi, 2002; Tedesco et al., 2013). Furthermore, field experiments have shown that cryoconite holes are about 10% shallower with dead microorganisms that constitute the organic matter instead of living organisms (Fountain et al., and references therein, 2004).

Although much implies that cryoconite holes affect the albedo and therefore the mass balance of glaciers, Fountain et al. (2004) do not fully agree. Fountain et al. (2004) discuss that the cryoconite hole coverage is low. It is estimated that 4-6% of the ice surface, at ablation zones, is covered with these holes at glaciers in the McMurdo Dry Valleys, Antarctica (fig. 2A). Fountain et al. (2004) continues arguing that of that coverage, the albedo reduced from 0,65 (for the ice surface) to 0,5 (for the cryoconite hole surface), which represents an average albedo decrease over the glacial surface of 3%. Fountain et al. (2004) argues that other factors contribute to the reduction of the albedo to a larger extent than cryoconite holes do, such as wind intensity and precipitation.

Nonetheless, cryoconite holes do contribute to melt. Fountain et al. (2004) observed only small portions of meltwater on the surface of glaciers in Antarctica, which has its explanation in the form of subsurface water systems composed of frozen cryoconite holes which are interconnected. These subsurface water systems are located only some tens of cm below the glaciers surface, which depends on the depth of the holes. Fountain et al. (2004) used a proxy for observing the water level by continuously measuring the depth to the thin, frozen ice-lid at the surface of the hole water that will reform as the water level changes. One half of the cryoconite holes on glaciers in Antarctica are estimated to be hydrologically connected. The interconnected cryoconite holes are important for creating meltwater. Fountain et al. (2004) evaluated that the holes contributes with, at least, 13% of the total runoff from the Canada Glacier, Antarctica. The passageways are believed to be enlarged by the heated water from solar radiation and the change in water level depends on ice melt within the holes and lateral flux of water, traveling through the holes (Fountain et al., 2004).

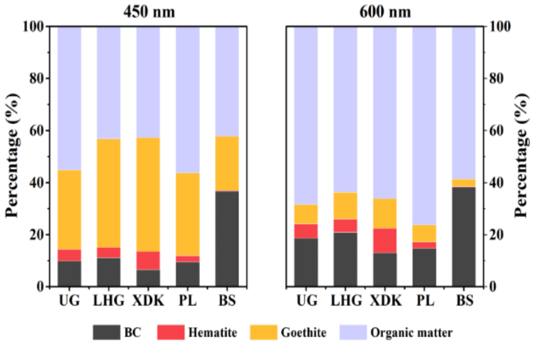

Figure 13. Figure from Cong et al. (2018). Samples collected from the Tibetan Plateau. The graphs display total light absorption at wavelength 450 nm and 600 nm where each color represents substances absorbing solar radiation (black carbon, hematite, goethite, and organic matter). UG = Urumqi no. 1 Glacier, LHG = Laohugou, XDK = Xiaodongkemadi, PL = Palong no.4, BS = Baishui no. 1 Glacier.

5.2 Snowball Earth

Cryoconite may also have influenced early life on Earth by providing habitat for fungi, algae, and bacteria to populate during Snowball Earth episodes, where they may have played a critical role in the survival of life. The glacial episodes of Snowball Earth, where ice covered the whole surface of the Earth, have characterized the Neoproterozoic era (1000-541 Ma) and early Paleoproterozoic era (2,5-1,6 Ga) (Hoffman et al., 2017). There is evidence of several Snowball Earths throughout time and one of these appeared during the Cryogenian (720-635 Ma), a period within Neoproterozoic era. During the period, ice spread out in all directions due to gravitation and covered both landmasses and the oceans. At the equator, which represented the ablation zone, windblown volcanic, detrital (mechanical, weathered mineral grains), and cosmic dust accumulated and may have aggregated and formed something similar to cryoconite.

Hoffman et al. (and references therein, 2017) discuss that cryoconite holes and their microbial activity, seen on modern glaciers, also existed during the Snowball Earth. If that was the case, these aggregates may have provided an environment for microorganisms to populate in the unfavorable climate which prevailed during this period. Life on Earth could possibly have survived the difficult climate as a result of cryoconite-like aggregates, in anticipation of a warmer environment. Hoffman et al. (2017) discuss that during Cryogenian and its glaciations algae and heterotrophs (e.g. fungi) did survive but also, at the same time, evolved. Cryoconite could possibly have played a large role for the survival of life and also the evolution of it.

6. Analytical methods

In this section, analytical methods of earlier studies that have been used to determine composition and characteristics of cryoconite is presented. The goal here is to be able to select which analyses will be appropriate for the study of the Nigardsbreen cryoconite.

6.1 Separation of organic content and mineralogical content

To determine how much organic content and mineralogical content cryoconite is composed of, Tedesco et al. (2013), Takeuchi (2002) and Foreman et al. (2007) all used the same procedure, namely combustion of the organic material. The cryoconite is weighed before and after the combustion to get a percentage of the loosing material, i.e. the organic content.

6.2 Grain-size analysis and mineralogy identification

Scanning electron microscopy (SEM) is by far the most common method when determining the grain sizes but it can also be used for the mineralogy identification. Sanna & Romeo (2018) used SEM as a verifier for the optical microscopy which they used for identifying the minerals. Tedesco et al. (2013) and Foreman et al. (2007) also used the SEM for analyzation of grain sizes and mineralogy, respectively.

X-ray diffraction (XRD) analysis is also commonly used for identifying minerology (Nagatsuka et al., 2014; Sanna & Romeo, 2018; Tedesco et al., 2013), often the mineralogy of the clay particles. Optical microscopy can, for both XRD and SEM, be used when determining mineralogy and grain sizes, but the method is not widely used. Tedesco et al. (2013) verified the mineralogy with XRD after a produced mineral assay with a mineral liberation analyzer (MLA), which is an alternative method to XRD.

6.3 Organic content analysis

Xu et al. (2010) explains how biomarker analysis works, which focuses on determining what kind of organic content cryoconite is composed of and what sources it has. This method includes sonication, alkaline copper (II) oxide oxidation method (CuO-method) and a method extracting phospholipid fatty acids (PLFA). Sonication is a process done before the CuO-method where solvent compounds become extracted by sound energy and dichloromethane and methanol. The solvent extractable compounds are necessary for the CuO-method which primarily works to extract V-, S-, and C-lignin derived phenols associated with non-woody and woody tissues. (Xu et al., 2010; Kögel & Bochter, 1985). Extracting PLFA is done by evaluating the total lipid content chemically, which includes neutral lipids, glycolipids, and polar lipids.

Xu et al. (2010) used a gas chromatography-mass spectrometry (GC-MS) for analyzation of the solvent extracts, CuO oxidation products and the PLFA. GC-MS is useful in many different sub-disciplines within science. Its primary function, in this case, was to identify substances in the biomarkers which were compared with reference standards found in mass spectral library databases and published mass spectra.

Nuclear magnetic resonance (NMR) spectroscopy determines the molecule structure of samples and is optimal for biomolecules and tissue samples due to its non-invasive character (Lehmann, 2018). Xu et al. (2010) performed two different NMR analyses, solid state, and solution state. Solid state analysis provided results of alkyl carbon, O-alkyl carbon, aromatic and phenolic carbon, and carboxyl and carbonyl carbon. The solution state produced results of peptides, aliphatic compounds, carbohydrates, and peptidoglycan. The idea with NMR analysis was to determine the amount of cryoconite that was from terrestrial organic matter, as plants, and how much of it that originates from microbial activities.

6.3.1 Carbon, nitrogen, and their stable isotopes ^{13}C and ^{15}N analysis

For analyzing the bulk organic carbon and nitrogen, McCrimmon et al. (2018) determined it via an Elemental Analysis (EA) at the University of Georgia, USA. For measuring the stable isotope ^{13}C for carbon, an Isotope Ratio Mass Spectrometer (IRMS) was used. This instrument is also able to analyze carbon, nitrogen and ^{15}N. Analyzing ^{13}C content and thereafter provide a δ^{13}C value will tell something about the provenance of the carbon. The C/N ratio also gives a hint of where the carbon originates from. A C/N ratio between 5:1 to 15:1 indicates that the primarily carbon source originates from algae, microbial and soil organic matter (McCrimmon et al., 2018).

6.4 Radiocarbon dating

Noell et al. (2014) radiocarbon dated glacial dust at Kilimanjaro's northern ice field (fig. 2A) at different locations including supraglacial sediments found in cryoconite holes, dust layers at the bottom of the glacier, soil samples and sediment from an ablation zone. The dating was performed by Beta Analytic in Miami. McCrimmon et al. (2018) also radiocarbon dated cryoconite from glaciers at southern Alaska (fig. 2A). Samples were prepared and sent off to the University of Georgia, USA, where an accelerator mass spectrometry (AMS) was used.

6.5 Light absorption analysis

Takeuchi (2002) measured the spectral light reflectance to evaluate the optical characteristics of cryoconite at glaciers in Himalaya, Tibet, Canada, and Svalbard (fig 2A). The reflected irradiance (power received by a surface per unit area) of prepared cryoconite samples was measured by a spectrometer in wavelengths from 400 to 950 nm. The calculation of the total spectral reflectance was done by calculating the difference between the reflected irradiance of cryoconite and the irradiance of a white reference plate. For determination of spectral reflectance of minerals, the same procedure as above can be used after removing the organic content by heated hydrogen peroxide (Takeuchi, 2002). Spectral reflectance was measured for cryoconite, containing both organic and mineralogical material, and for just mineral particles in cryoconite in order to display the organic contents role in light absorption.

6.6 Iron oxide analysis

Iron oxides in cryoconite has been detected by Cong et al. (2018). They used inductively coupled plasma mass spectrometry (ICP-MS) on prepared samples for the elemental analysis which showed results of iron and other elements.

To extract the iron oxides from the total iron, cryoconite samples were prepared by the citrate-bicarbonate-dithionite (CBD) method and later determined by a spectrophotometer to measure the iron mass in the form of dissolved iron oxides. Subtracting the total iron mass and the iron oxide mass provide the mass of iron that is still in a structural form (Cong et al., 2018).

$$Fe_{(struc)} = Fe_{(tot)} - Fe_{(ox)} \tag{1}$$

The extraction between goethite and hematite was performed by a diffuse reflectance spectroscopy (DRS). The more commonly used XRD did not qualify for this analysis due to a low abundance of iron in the cryoconite. To obtain a wt% of goethite and hematite as the iron oxides contain, a reference sample of hematite was measured (due to its intense red color) and used as a variable for a percentage of reflectance in the red color band, 630-700nm. This variable was later used in a transfer function for calculating the hematite content in the sample. Goethite content can be calculated after established values of hematite and the total iron oxide content.

6.7 Radioactivity analysis

Baccolo et al. (2020) measured treated cryoconite samples with gamma-spectrometry for analyzation of anthropogenic and natural radionuclides. These nuclides were ^{137}Cs, ^{241}Am, ^{207}Bi and ^{40}K along with ^{238}U and ^{232}Th decay chain nuclides. Direct measurements of ^{238}U and ^{232}Th was not made but estimated from the total content of U and Th. In an earlier study, Baccolo et al. (2017), used the same instrument for analyzation of radionuclides but also an alpha spectrometer for analyzing $^{239+240}$Pu and ^{238}Pu. Łokas et al. (2016) measured radionuclides with gamma- (for ^{137}Cs and ^{210}Pb) beta- (for ^{90}Sr) and alpha-spectrometry (for $^{239+240}$Pu and ^{238}Pu).

6.8 Heavy metals analysis

Łokas et al. (2016) prepared cryoconite samples and used an atomic absorption spectrometer (AAS) for the analyzation of the heavy metals including Cu, Pb, Zn, Fe, and Mn. An ICP-MS was used to analyze Cd and stable isotopic ratios of Pb. Baccolo et al. (2020), and the earlier publication Baccolo et al. (2017), estimated U and Th content and elemental material, respectively, through Instrumental Neutron Activation Analysis (INAA).

7. Proposed analysis of cryoconite at Nigardsbreen, Norway

At the Earth Science Center, University of Gothenburg, some of the instruments and analyzations, described in section 6, could be used in a future project for analyzing the sampled cryoconite at Nigardsbreen. A proposed method of what to analyze, and its related research question, are described below.

7.1 Combustion of organic material

This method is inspired by Foreman et al. (2007), Takeuchi (2002) and Tedesco et al. (2013) for determination of the percentage of organic and mineralogical content in cryoconite.

A specific amount of cryoconite is weighed before and after drying it to obtain the water content. The next step is combustion of the organic material, for this purpose a percentage of the organic and mineralogical material, respectively, can be calculated.

Research question: How large is the proportion of organic and mineralogical content for the cryoconite at Nigardsbreen?

7.2 Scanning electron microscopy (SEM) for grain size and shape analysis

Analyzation by SEM for grain size and shape analyses is inspired by Tedesco et al. (2013). The SEM at the University of Gothenburg is a Hitachi S-3400N SEM, coupled with an Oxford EDX spectrometer and one wavelength-dispersive crystal spectrometer.

Next, the sample is prepared by combustion, in order to only analyze the mineralogical material. SEM analysis works for organic as well as inorganic matter, it could therefore be interesting to use the instrument on a sample with organic matter, but perhaps it is more handy to combust the sample for a grain size and shape analysis hence all the "uninteresting" material will not confuse the analysis.

Research question: What grain size and shape are common in the mineral fractions for cryoconite at Nigardsbreen?

7.3 X-ray diffraction (XRD) for mineralogy identification

XRD analyzation is inspired by Nagatsuka et al. (2014), Sanna & Romeo (2018) and Tedesco et al. (2013) for identification of the clay mineral content. The XRD at the university is a Siemens D5005.

The combusted sample (see section 7.1) must be pulverized with an agate mortar, in order to analyze the mineral fractions in the XRD. Nagatsuka et al. (2014) performed the scans for XRD at 2° to 40° (2θ), which are the angles for analyzing the minerals of interests, in this case the silicate minerals.

Research question: What clay minerals are common for the cryoconite at Nigardsbreen?

7.4 Nuclear magnetic resonance (NMR) for organic content identification

For determining whether the organic content in cryoconite originated from terrestrial sources or microbial activities, Xu et al. (2010) used NMR which allows analysis of organic matters composition overall and gives detailed structural information about the compounds.

Swedish NMR Centre at the University of Gothenburg provides NMR analysis.

Research question: Where does the organic material originate from? What organic compounds does the cryoconite contain?

7.5 Isotope ratio mass spectrometer (IRMS) for analyzing carbon, nitrogen, ^{13}C, and ^{15}N

Inspired by McCrimmon et al. (2018), carbon, nitrogen, and their stable isotopes ^{13}C and ^{15}N can be measured with an IRMS. The instrument model at the University of Gothenburg is a Sercon 20-22 IRMS (Secont Ltd., Crewe, England), coupled to an elemental analyzer (Europa ERA-GSL).

For preparing the analysis, all samples should include an equal amount packed in tin capsules and be weighed. For CN analysis, the samples should ideally contain >100 µg N but not more than 2000 µg C.

Research question: What amount of the respective molecules and isotopes are present in the cryoconite and how does this influence the organic matter? Where does the organic matter originate from?

7.6 Radiocarbon dating at the University of Lund, Sweden

Earlier studies have determined cryoconites age by radiocarbon dating (McCrimmon et al., 2018; Noell et al., 2014). One sample, about 50 ml, have been sent to the University of Lund for radiocarbon dating. The results arrived on 05/08/2020 and will be briefly discussed in the appendix.

Research question: What is the general age of the sampled cryoconite at Nigardsbreen? What does the age indicate?

7.7 Elemental analysis with Inductively coupled plasma mass spectrometry (ICP-MS)

Cong et al. (2018) analyzed iron oxide in cryoconite samples with an ICP-MS. The spectrometer also manages to analyze heavy metals, a function which Łokas et al. (2016) used. The model that the University of Gothenburg has is a Quadrupole ICP-MS (Agilent 8800QQQ) coupled to a New Wave NWR 213 laser ablation system. With this instrument, possible iron oxides and other heavy metals can be found.

Research question: Does the cryoconite contain iron oxides and/or other heavy metals?

7.8 Pollen analysis at the University of Stockholm, Sweden

Another more uncommon analysis on cryoconite, namely pollen analysis, could be made. Seppä (2007) describes the palynology method on how to analyze pollen in sediments and also the identification of observed pollen grains. Since terrestrial plants have been recognized in cryoconite samples from e.g. the Athabasca Glacier in Canada (fig. 2A) (Xu et al., 2010), pollen should also constitute the organic matter of cryoconite. Some samples could therefore be sent to the University of Stockholm, Sweden, for pollen analysis.

Research question: Does the cryoconite contain pollen? If so, what type of pollen grains are present in the cryoconite sample?

8. Hypothesis of the characteristics and origin of cryoconite at Nigardsbreen

As Bøggild et al. (2010) observed, the dominant part of the cryoconite consisted of minerals, which may be the case with the Nigardsbreen cryoconite as well. However, the very dark color of the sampled cryoconite (fig. 14) may indicate a high organic content which possibly dominates the cryoconite. The grain sizes that were observed during the collection, were fine grained, perhaps between the range of sizes sand and clay. Due to the high silicate bearing bedrock surrounding Nigardsbreen, the mineralogical part is expected to include minerals such as quartz, plagioclase, orthoclase feldspar, amphibole, and perhaps some clay minerals (kaolinite, illite, and chlorite). Norway has a diverse geology and it is likely that weathering of other bedrock types, further away from Nigardsbreen, may influence the mineralogical content in the cryoconite. Schists contain carbon, among other elements, and if it becomes weathered the schist powder may possibly influx the glacier's cryoconite and therefore contribute with carbon. As for heavy metals, an interesting feature was observed when a sample for radiocarbon dating was prepared. A red-brown stain, possibly iron precipitation, was visible in a couple of the plastic bags containing the collected samples (fig. 14). Cong et al. (2018) detected a relatively high amount of iron oxides in cryoconite samples from the Tibetan Plateau. This indicates that, together with other authors' observations of heavy metals in cryoconite, iron and other heavy metals are rather common and not at all unusual. Radioactivity is also not an uncommon feature observed in cryoconite. A large amount of the radionuclides is anthropogenic, originating from old nuclear test and nuclear power plant accidents. Due to the location of Nigardsbreen, not particularly isolated from human activities, radionuclides may contribute to the composition of the cryoconite.

Figure 14. One of the collected samples of cryoconite at Nigardsbreen. The red-brown stain in the bag (left side) together with its subsample in the plastic tube (right side) which was sent to the University of Lund for radiocarbon dating. Picture taken by Mark Johnson.

The collected cryoconite samples have a dark color which probably indicates a high amount of organic material (fig. 14). As Xu et al. (2010) point out, a high alkyl/O-alkyl ratio along with high amounts of PLFA and an absence of lignin phenols, indicates that the organic matter is microbially derived and does not primarily originate from plants. McCrimmon et al. (2018) and Takeuchi (2002) also concluded that much of the carbon originated from microbes. With this information, I hypothesize that the organic matter in the Nigardsbreen cryoconite originates from microorganisms and lower order plants, such as mosses and lichens, however it is likely that pollen is present as well. Xu et al. (2010) did also found evidence for small inputs of higher order plants, which may be available in the cryoconite due to the vegetation surrounding Nigardsbreen (fig. 4).

Cryoconite at Nigardsbreen is exposed to the atmosphere which implies that weathering of the sediment may happen and will perhaps not stay on the glacial surface for long. Also, the glacier surface is always exposed to wind which carries dust that deposits on the surface which may provide new particles to the cryoconite. Noell et al. (2014) radiocarbon dated cryoconite and obtained a modern age whereas McCrimmon et al. (2018) radiocarbon dating resulted in a modern age of the microbial lipids carbon (PLFA) and an ancient age, a couple of thousand years old on average, of the cryoconite bulk organic carbon. The age of Nigardsbreen cryoconite could match the result from Noell et al. (2014) and be modern, which does not seem to be out of the question considering the climate and the exposure to the atmosphere. On the other hand, as McCrimmon et al. (2018) point out, carbon could be divided in two main categories with younger carbon from microbes and older carbon most likely from rocks. Therefore, an older age on the cryoconite sample may also be obtained. Discussion about the obtained result from the radiocarbon dating at the University of Lund is found in the appendix.

Due to the glacial history and the ongoing shrinkage of glaciers in Norway (Andreassen et al., 2020), highly active ablation zones are expected, where the cryoconite is to be found. Cryoconite may therefore be a feature that will not disappear in the upcoming years, it may rather become more common. At Nigardsbreen, cryoconite with developed holes and meltwater was found but also aggregates without cryoconite holes were encountered (fig. 12).

No obvious subsurface water systems where recognized during the walk on Nigardsbreen, but that does not mean that they do not exist. This feature of cryoconite affecting glaciers was not considered and a hypothesis could therefore not be stated.

Cryoconite affects glaciers worldwide, but the question is to what extent does it influence glaciers and how? Some authors suggest that cryoconite covers an area too small to be able to influence the mass balance of glaciers (Fountain et al., 2004), while other authors do believe that cryoconite likely affects its mass balance (Nagatsuka et al., 2014; Takeuchi, 2002). Due to this knowledge gap this question will remain unanswered. The mass balance of Nigardsbreen may or may not be affected by cryoconite.

9. Conclusion

The mineralogical part of cryoconite, often silicate minerals, especially originates from the local area but could have a provenance from aeolian long distance sources and older basally derived mineralogical content that becomes exposed due to ice melting. Heavy metals and radioactive isotopes, both anthropogenic and natural, may also be found in cryoconite. The organic content provides unique ecosystems with microbial life such as fungi, bacteria, and green algae. The organic matter is primarily derived from microbial life and lower order plants (mosses and lichens). Minor evidence for higher order plants have also been observed. The analyzed general ages of cryoconite has a very wide spectrum, ranging from modern ages to tens of thousands of years old. This may be explained by different origins of carbon e.g. microbial bonded carbon which has recently been in equilibrium with the atmosphere, and aged carbon which may originate from sedimentary rocks or organic matter that aged in situ.

Dust accumulates on the surface of glacier's ablation zones and forms dark aggregates, named cryoconite. This in turn absorbs the solar radiation, reduces the albedo, and heats up the underlying ice, creating cryoconite holes. These holes may later interconnect, due to the melting of the ice, and form subsurface water systems which contributes to the total meltwater runoff from glaciers. The reduced albedo may also have a larger influence on glacier's mass balance, which in turn is an important contribution to the climate.

At Nigardsbreen, the surrounding bedrock is mostly composed of silicate minerals. The vegetation includes smaller plants and trees (fig. 4). The composition of cryoconite may be strongly influenced by the local area, for both the inorganic and the organic part. Microbial activity together with mosses and lichens may, as for many other glaciers, compose the organic content in cryoconite. Proposed analyses for future lab work on the proportion of mineralogical and organic material, mineralogical and organic composition, provenance of the composition, elemental composition, age determination, and pollen analysis have been stated in this study.

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12. Appendix

12.1 Radiocarbon dated cryoconite from Nigardsbreen

The result of the radiocarbon dating for the cryoconite sample that was sent to the University of Lund, Sweden, arrived 05/08/2020. The result ranges from 5045 to 4830 cal. yr BP with a probability of 95,4 % (fig. 15), a significantly older age than I hypothesized. At the y-axis in the diagram (fig. 15) the radiocarbon determination is displayed with the red graph which shows the concentration of radiocarbon, expressed in BP. The blue graph is for calibrating the years. It is often done with tree rings that have the same proportions of radiocarbon as the material that becomes radiocarbon dated, in this case the cryoconite. The calibrated years are displayed at the x-axis in the black graph, which suggests a calibrated age range with a probability of 95,4 % and 68,2 %.

Noell et al. (2014) obtained a modern age while McCrimmon et al. (2018) achieved a modern age for the microbially used carbon and an ancient age for the rest of the cryoconite bulk carbon. My radiocarbon result is best matched with the obtained age McCrimmon et al. (2018) observed. Considering that the samples at Nigardsbreen have not yet been analyzed, it is difficult to predict where the carbon likely originates from. McCrimmon et al. (2018) discuss possible sources and conclude that the aged carbon has a rock source, e.g. shale. Shales are not the most common rock type in Norway, but schists are a more familiar one, which weathers and may constitute the mineralogical content and provide the cryoconite with aged carbon. Combusted fossil fuel or organic modern carbon that has deposited on the glacier and aged in situ, e.g. mosses and lichens, may be two other potential carbon sources for cryoconite from Nigardsbreen. However, as McCrimmon et al. (2018) discuss, the cryoconite sample should be more depleted if the carbon originates from combustion of fossil fuel, which is not the case for the Nigardsbreen cryoconite.

About 5000 cal. yr BP, Jostedalsbreen ice cap retreated and started to advance again at 4000 cal. yr BP (fig. 3) (Nesje et al., 2001). According to the radiocarbon dating, the carbon is older than when the ice cap started to advance. If the analyzed carbon originates from an organic carbon source (e.g. plants) that has aged in situ on Nigardsbreen, the organic matter would have deposited around 1000 yr before the advance took

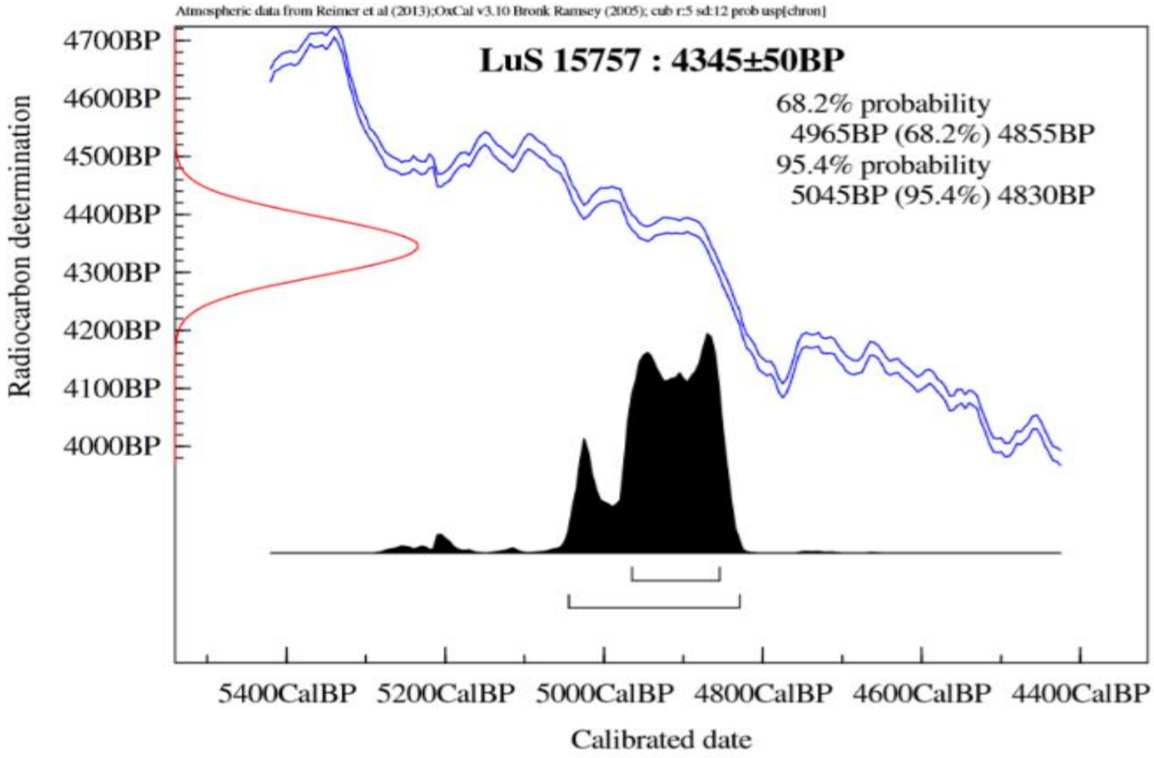

Figure 15. Graph, from the University of Lund, displays the radiocarbon dating and calibration of the cryoconite sample.

place. Material in general should have an easier time to get incorporated with the glacial ice when a glacier advance appears due to the higher accumulation rate. However, even though the ice cap retreated at ~5000 cal. yr BP, snow accumulation at the accumulation zone highly likely still happened and could therefore incorporate the blown in dust. If the carbon originates from organic matter deposited on the accumulation zone around 5000 cal. yr BP, a pollen analysis would be interesting to make. The possibly observed pollen may therefore provide a record of mid-Holocene regional vegetation.

Only one sample of the collected cryoconite at Nigardsbreen was radiocarbon dated. A couple of more age analyses is needed to be surer about the obtained age. Also, new resampled cryoconite would be preferred before sending new samples for radiocarbon dating. If a resampling of cryoconite takes place, GPS-points at each sampling location and the elevation would be obtained.