Using Clay Mineralogy to Analyze Sediment Sources, Kronebreen and Kongsvegen Glaciers, Svalbard, Norway

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Abstract

Svalbard is a Norwegian island archipelago located at 79°N whose glaciers are highly susceptible to climate fluctuations. Glaciers located in Svalbard sit between warm water from the south and cold polar water from the north. This position increases their sensitivity to climate fluctuations. Due to amplified and continuous climatic warming at high latitudes, the glaciers of Svalbard are prime subjects for understanding not only glacial dynamics, but also the effects of contemporary climate change. Tidewater glaciers are dynamic systems, with ice retreating and glacial and subglacial streams continuously shifting. An understanding the current spatial distribution of sediment sources will aid in interpreting sediment core data. From this we can infer former climactic and environmental conditions. Kongsfjorden is a 15 km long fjord located in northwest Svalbard, with the glaciers of Kronebreen and Kongsvegen forming the head of the fjord. There are two main sediment sources that discharge sediment rich water into the fjord: a subglacial stream that forms an upwelling plume at the calving margin, and a glacial stream that forms a prograding delta complex from the southern margin of Kongsvegen glacier. This project aims to characterize these sediment sources based on the clay mineralogy found in the samples and to map their spatial distribution in the fjord. Sediment from the sediment sources was collected using water samples and vacuum filtering the water in order to catch the sediment. Sediment from the fjord floor was collected using an Eckman box-corer attached to a wire and winch system. Twenty-nine samples were collected, dried, and sieved to separate the silt and clay fraction from the coarser sediment. Using X-ray diffraction, the clay mineralogy of the samples was found to be composed primarily of illite and chlorite. The 001 diffraction peak of chlorite is not visible in several samples. Chlorite is commonly found in metamorphic rocks, which are present as a bedrock source underneath Kronebreen glacier, but not Kongsvegen. The absence of the 001 chlorite peak could be due to sample preparation or a weaker concentration of chlorite in those samples. Overall, the sediment in front of the calving margin of the Kronebreen and Kongsvegen glacier complex is well mixed and the sediment distributed by the upwelling plume and Kongsvegen Delta are not differentiable in the box cores samples.

1 Introduction

The glaciers of western Spitsbergen, Svalbard are highly susceptible to climate fluctuations. They are located between the warmer West Spitsbergen Current that transports Atlantic water from the south and the colder Polar water that flows from the north (Hald et al., 2004). Due to amplified and continuous climatic warming at northern high latitudes (IPCC, 2007), the glaciers of Spitsbergen, Svalbard are prime subjects for understanding not only glacial dynamics, but also the effects of contemporary climate change. There are increasing concerns about the impact of anthropogenic climate change, particularly how a reduction in ice volume might affect sea levels, water resources, and natural hazards. Glaciers in the Svalbard area are examples of a polythermal glacial system located in the Arctic, which is analogous to many tidewater glaciers located in polar regions. Awareness and modeling of tidewater glacial systems is imperative to understanding the effects of a warming climate.

The purpose of this project is to understand and characterize the two point sources that contribute sediment to Kongsfjorden, at the termini of Kronebreen and Kongsvegen glaciers (Figure 1). The strength and relative input of the sediment sources can shift spatially and temporally, so a current understanding of the spatial distribution is essential in interpreting sediment core data. Sediment cores can be used to identify former locations of the sources as well as former climactic and environmental conditions.

The two point sources distributing sediment in the fjord are an upwelling plume and a delta. The sediment sources can be characterized by the clay mineralogy of fjord floor sediment samples collected proximal to the ice front. Any differences in the clay mineralogy of samples located in each source will be noted and can help to analyze the spatial distribution of material transported by these sources. The magnitude and direction of the sources could be delineated after characterizing the mineralogy of each source.

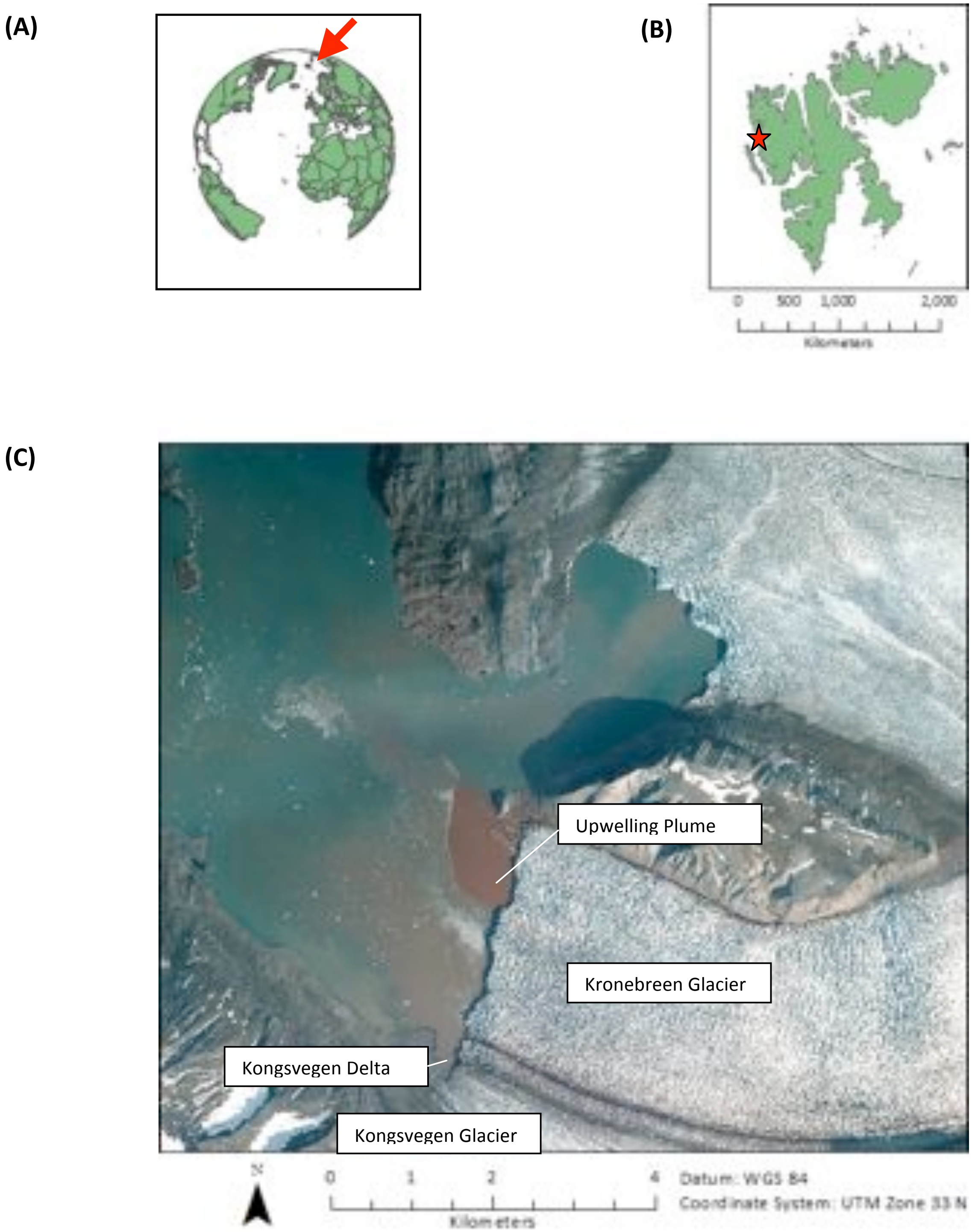

Figure 1. Location of study area. **(A)** Location of Svalbard on a global scale. **(B)** Map of the Svalbard archipelage. **(C)** Locations of study site within Kongsfjorden.

1.1 Geographic and Climatic Setting

Kongsfjorden is a fjord in western Spitsbergen, Svalbard, Norway (79◦N, 12◦E) (Figure 1). Many glaciers calve into Kongsfjorden, including Kronebreen (444 km^2) and Kongsvegen (163 km^2) at the fjord's head (Hagen and others, 2005). The North Atlantic current moderates Svalbard's temperatures, giving it up to 20 °C higher winter temperature than similar latitudes in continental Russia and Canada. This keeps the surrounding waters open and navigable most of the year (Hanssen-Bauer, 2002). The summer air temperature at sea level averages about 4-5 °C and in winter about -12 °C, and is commonly -20 °C in the west. On the south coast of Spitsbergen, the temperature is slightly higher than further north and west. Katabatic winds are usually strong in long fjords with direct access from inland ice (Harland, 1998).

Annual precipitation is low, with 10 mm/yr recorded on the east coast of Svalbard. On the west coast the average is about 300-400 mm/yr, most of which falls as fine snow or rain in the summer or autumn. The East Spitsbergen Current supplies a large quantity of pack ice to Svalbard's waters and fjords. This ice usually melts slowly in warming waters in the spring and summer (Harland, 1998). Freezing and thawing of water in the fjords, as well as iceberg calving, adds bay ice to the fjord.

1.2 Geologic Setting

Regional Bedrock Geology

Since the vegetation cover is so sparse and the glacially eroded landscape so fresh, there are large continuous sections of exposed bedrock. Geologic units in Svalbard range from Archean bedrock to Quaternary alluvium. Much of Svalbard has thick Paleozoic sedimentary units that were deposited when Svalbard was located near the equator. Kongsvegen is underlain by Middle and Upper Carboniferous and Permian fine-grained sandstone and Devonian sand/siltstones (Melvold and Hagen, 1998).

Colletthøgda is a large exposed mountain that divides Kronebreen into two calving margins. Colletthøgda has been identified as being composed of the Gipsdalen Group, which is a laterally-extensive depositional unit covering central and western Spitsbergen (Figure 2). It is composed of an upper dolostone member and a lower Kloten Breccia member. The dolostone is buff-colored, generally thick-bedded, blocky, and has a micritic or silty texture. The Kloten Breccia is contains various types of limestone and dolostone. Carbonates and evaporates are also present in Colletthøgda.

The Boggega Formation (Fm.), located on the southern margin of Kongsvegen glacier, is a Precambrian carbonate schist that forms the visible peaks that constrains Kongsvegen. The Signehamna Fm. forms the cliffs on the northern margin of the study site. These outcrops are primarily blocky and massive quartzite (Harland, 1998). All of the local bedrock formations contribute different mineral grains to the subglacial till. Future provenance studies could be used to determine the origin of a sediment sample to a specific bedrock formation.

The clay minerals that form in any particular environment depend on the nature of the parent rock, temperature, availability, and chemistry of the water, and time. The clay produced by normal weathering of common silicate rocks and subsequent transport tends to be fairly rich in smectite (Moore and Reynolds, 1997). Minerals assemblages expected to see in this study are clay minerals common in carbonate rocks such as kaolinite, montmorillonite, vermiculite, and chlorite. These clay minerals contain magnesium, as does the dolostone bedrock. Calcite and dolomite are dominant non-clay minerals in this area. Table 1 summarizes major clay minerals.

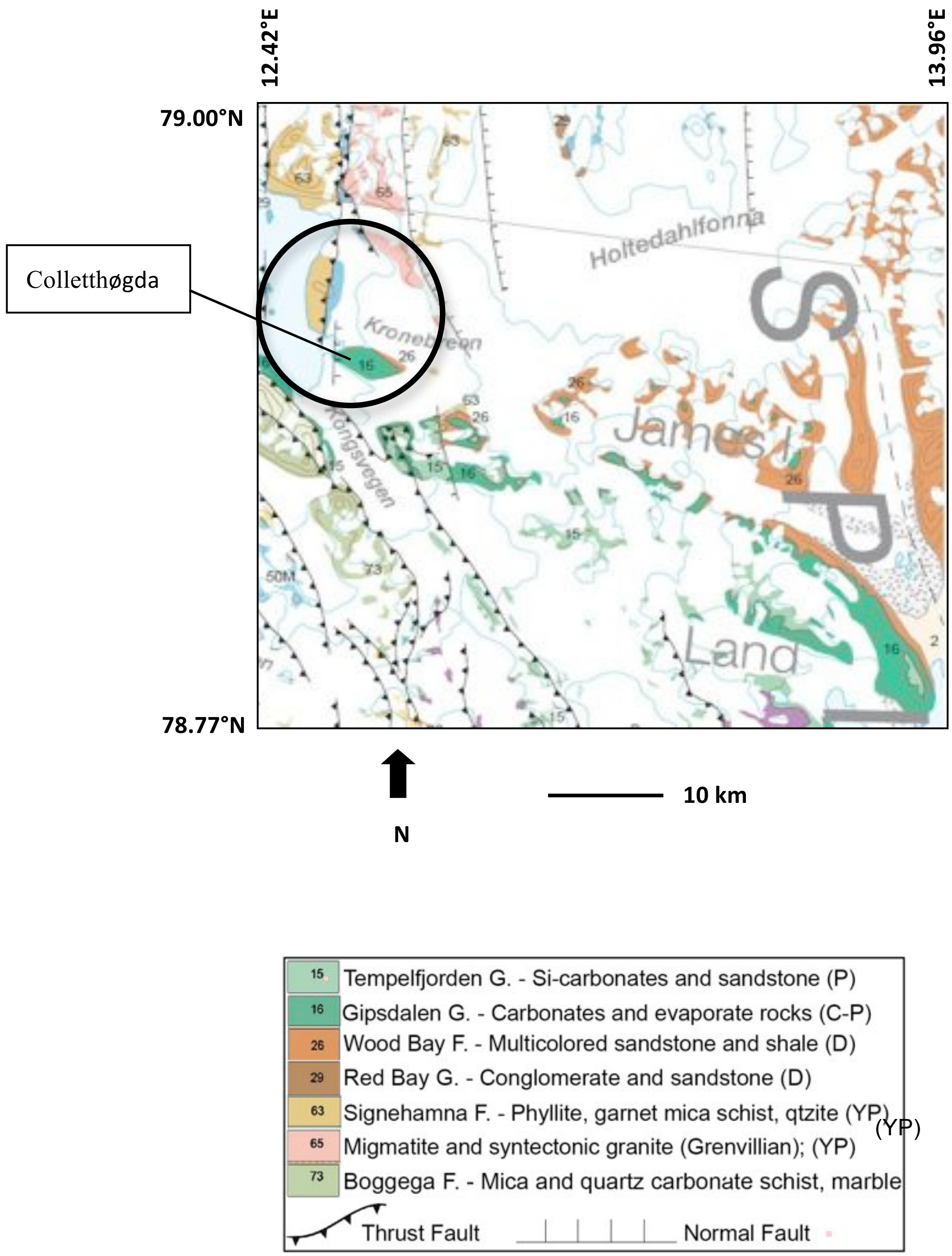

Figure 2. Geologic map of Kronebreen and Kongsvegen. The study area is indicated with a circle. Letters next to rock type age P=Permian, C=Carboniferous, D=Devonian, YP=Young Proterozoic (Hjelle and others, 1999).

Table 1. Major clay mineral groups (Poppe and others, 2001).

Group	Occurrence
Chlorite	Low-grade greenschist facies
Illite	Weathering of silicates (primarily feldspar), degradation of muscovite
Kaolinite	Hydrothermal alteration or weathering of feldspars under acid conditions
Smectite	Weathering of basic groups
Vermiculite	Alteration of micaceous minerals

Glacial History

The Kronebreen-Kongsvegen glacier complex in Svalbard reached its maximum Holocene extent during the Little Ice Age (Liestøl, 1988). Since then, the ice front has been in retreat, interrupted by short periods of advance due to surge events (Melvold and Hagen, 1998). Kronebreen last surged in 1869; at the end of the surge, the ice front extended about 10-11 km beyond its present-day position (Melvold and Hagen, 1998; Svendsen and others, 2002). The complex again advanced from 1936-1948 when Kongsvegen surged (Woodward and others, 2002). Once Kongsvegen returned to a quiescent state and its flow velocity decreased to its present-day value of 2-3 m/yr, the complex again started to retreat, reaching its current position in the mid-1980s (Melvold and Hagen, 1998). Kronebreen is now the dominant tidewater cliff and one of the fastest flowing glaciers (750 m/yr) in Svalbard (Hagen and others, 2005; Woodward and others, 2002).

Kongsfjorden has been the study site for many sedimentological and oceanographic studies. Ice rafted debris is an additional sediment source that will undoubtedly be present in this study. Benn and others (2007) discuss the dynamics of the calving occurring on the Kronebreen and Kongsvegen ice front. The glaciers calve at very high rates daily, and many of these enormous icebergs carry loads of glacial till and sediment. The sediment is either frozen in the ice or resting on an exterior surface of the iceberg. This ice rafted debris enters the water column as the iceberg melts and becomes part of the fjord floor sediment.

1.3 Sediment Sources

Two main sources discharge sediment from Kronebreen and Kongsvegen at the tidewater margin (Figure 1). The first is a subglacial stream located near the northern end of the glacial front. The freshwater is far more buoyant than the surrounding cold, saline water, and therefore the plume rises directly to the surface in front of the glacier (Figure 3) (Powell and Domack, 1995). This upwelling creates a plume of reddish brown sediment-rich water, approximately 750 m wide.   The plume is very visible from aerial photographs (Figure 1) and in the field. The position of the Upwelling Plume shifts daily, yet the location can usually be determined by spotting the thousands of Arctic Terns and other birds that feast on the krill paralyzed by the cold, fresh water brought up by the subglacial stream.

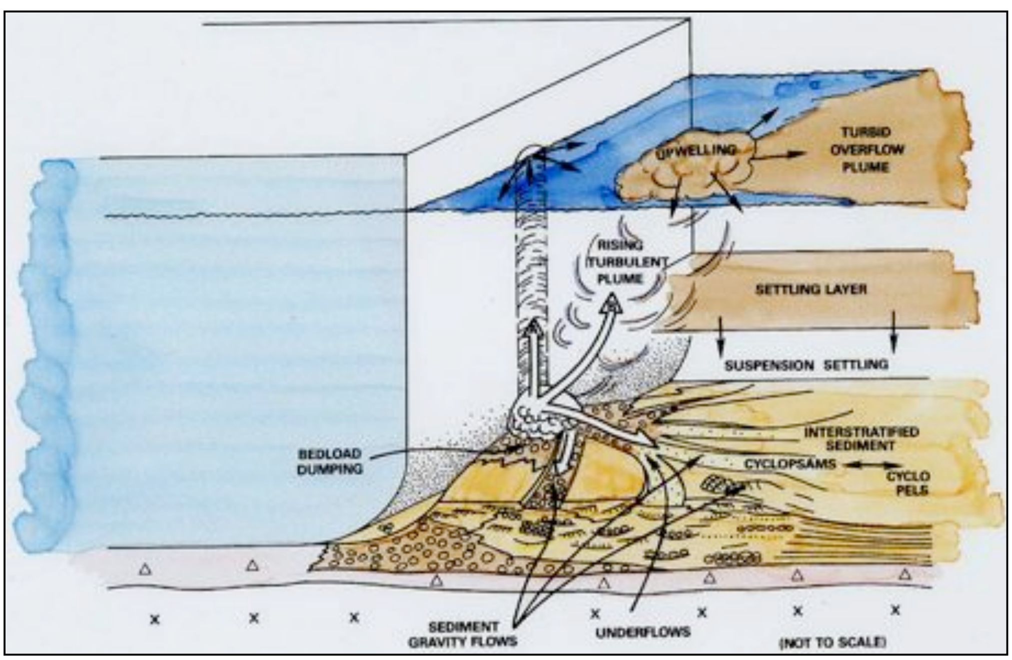

Figure 3. Glacial margin sedimentation processes (Powell and Dumack, 1995).

The second sediment source is an ice-marginal stream located on the south end of the glacial front. Its point of discharge in Kongsfjorden is between the ice of Kongsvegen and the southern valley walls. Unlike the Upwelling Plume, it is unlikely to change position over the timescale of this project. This sediment source originates as a subglacial stream on Kongsvegen, but changes into a glacial stream before entering Kongsfjorden. A delta has formed at its meeting point with the fjord. The delta has prograded since 2005 (Trusel and others, 2010), with high volumes of sand and gravel continuously being transported from the glacier into Kongsfjorden. The clay and fine particles from this ice-marginal stream disperse into Kongsvegen Delta. This creates a plume of dark brown sediment-rich water, approximately 1 km wide. This plume is also visible from aerial photographs (Figure 1) and in the field. The difference in density between fresh and salt water keeps the freshwater discharged from the glacier from mixing immediately with the saline fjord water. A plume boundary is easy to delineate, and it is easy to map the sources' temporal movement on a daily timescale.

Two additional sources contribute sediment to Kongsfjorden. A subglacial stream from the northern section of Kronebreen distributes a plume (approximately 500 m wide) of light brown sediment into Bearded Seal Bay. A glacial stream discharging from a glacier located on the south side of Kongsfjorden enters the fjord to the northwest of Kongsvegen Delta. Sediment from this stream creates a 500 m wide plume and the Southwest Delta of chocolate brown sediment. All four sources are visible on Figure 1, and their apparent strength and magnitude is apparent.

This project focuses on analyzing the sediment discharged from the Upwelling Plume and Kongsvegen Delta. Sediment is discharged from these sources at an average velocity of 8-10 m/s, and the length of their plumes are 1.2 km and 2 km, respectively. Sediment is being deposited quickly on the fjord floor, with sediment accumulation rates estimated to be greater than 1 m/yr (Kehrl, 2011). These sediment sources heavily influence the fjord floor morphology, and understanding their distribution will help analyze the temporal movement of these sources.

1.4 Clay Mineralogy

X-ray diffraction (XRD) has been used as a diagnostic tool to analyze the mineralogy of clay-size (< 2 μm) fjord sediments. Using sediment obtained with gravity cores, Bausch and others (1998) analyzed the assemblages of clay minerals of Jurassic marine black shales in Spitsbergen. Results showed that the presence or lack of kaolinite can indicate paleoclimate conditions. This distinguishing characteristic can help correlate samples found in Spitsbergen to rock units found in mainland Europe. Kaolinite forms only under acidic conditions thus its presence in marine shales could be a result of many processes. One hypothesis is that weathering and reworking on land of kaolinite-rich rocks, and subsequent transportation and deposition in the marine basin. Another hypothesis is that kaolinite could be produced on land under tropical/subtropical climatic conditions, and then transported and deposited in the marine basin (Bausch and others, 1998). Allen and others (2001) used XRD to analyze soils in Arctic Sweden to understand the landscape evolution of a recently deglaciated valley. Their results indicated a dominance of muscovite mica, which is representative of the muscovite schist bedrock in the region.

A high percentage of Svalbard is covered with glaciers, and bedrock geology can only be inferred from visible mountain peaks and valley walls. In addition to analyzing the sediment sources in Kongsfjorden, this study will provide insight to the mineral composition of the bedrock of Kronebreen and Kongsvegen glaciers. Information from this project could be useful in constructing a more complete geologic map of Svalbard and also in gaining greater insight into sediment provenance studies.

2 Methods

The distribution of sediment in the fjord from the two point sources can be analyzed by using box core samples. Once the clay mineralogy has been characterized using XRD, the spatial distribution of the sediment sources can be mapped. The data can also be compared to sediment core data to inform how the glaciers advanced and retreated in the past. Understanding the current sedimentary processes occurring at the ice-margin may help predict the distribution of sediment with increased glacial melting due to global warming.

2.1 Field Methods

All fieldwork was completed July 24-August 3, 2011. Although extensive efforts to collect samples according to the sampling plan and at a close but still safe distance from the calving margin were made, it was almost impossible due to the strong currents, wind conditions, and ice coverage in the work area. In order to analyze the mixing of sediment from the two sources, samples were collected in a grid-like formation in front the ice-margin. This would allow for a spatial analysis of composition of the sediment. A grid was superimposed on a satellite image of the study site, and three transect lines parallel to the ice face spaced approximately 500 m apart were drawn. Six samples spaced 500 m apart were taken along each transect line (Figure 4).

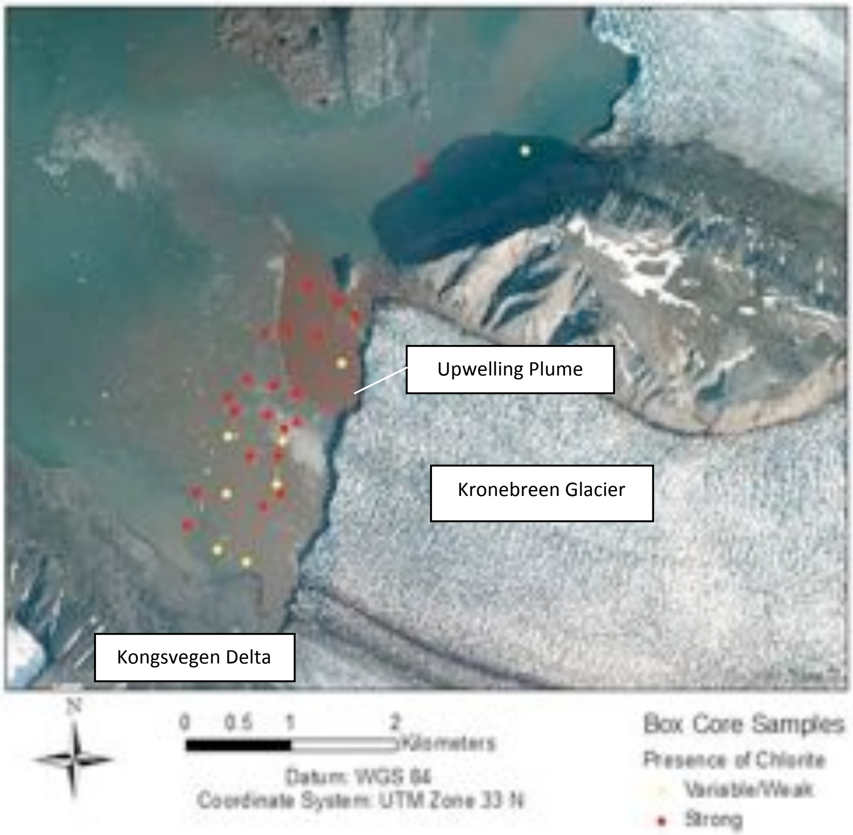

Figure 4. Aerial photograph of the study area. Dots indicate box core samples (Hjelle and others, 1999).

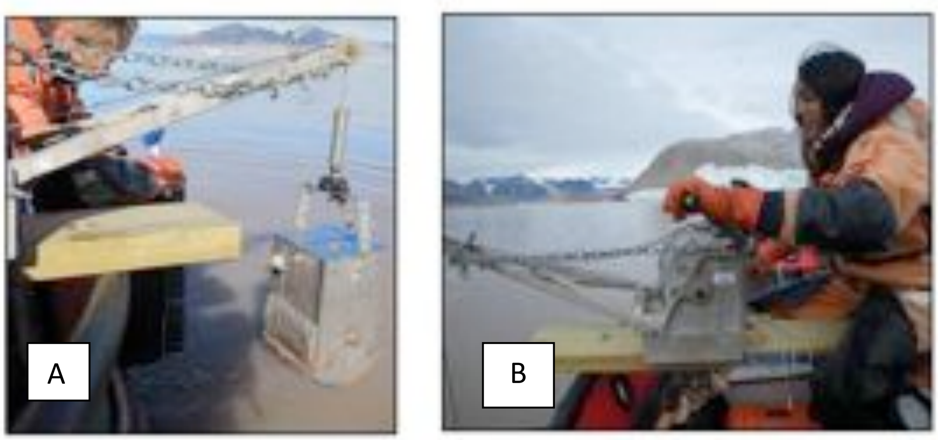

Figure 5. Field methods for collecting box core samples. **(A)** Box core suspended from winch over the side of a boat. **(B)** Team member using the winch to haul up a box core.

The b

winch system (Figure 5). Two different winches were used during field work, one using steel cable and the other using nylon cord. Weights were added to the box core in order to increase its descending speed to the fjord floor as well as to stabilize it against currents in the water column. The box-core was attached to a 200 m steel cable with a depth counter. The box core was lowered at a steady pace until the fjord floor was felt, then raised 5-10 m. Next the box-corer would free fall to the floor, and sink into the substrate. Lastly, a messenger was deployed in order to close the jaws of the box-corer and obtain the top-most sediment layer. Sediment was placed in Ziploc and Whirl-pack bags, labeled, and taken back to the lab. Box core sample data are presented in Table 2.

The purpose of using the Ekman box-corer was to grab a sample of the top layer of sediment being deposited into the fjord. Sample size varied between several cm^3 of sediment and m^3. Sample sizes depended on the texture of substrate. The presence of coarser material, such as gravel, caused the doors of the box core to jam and work inefficiently.

Table 2. Box core data

Sample name	Latitude °N	Longitude °E	Depth (m)	Collector*
2407ES01	78.8941	12.5196	17	L,M,R,Dk
2407ES02	78.8911	12.5114	85	L,M,R,Dk
2507ES03	78.8863	12.5032	63	L,M,R,Dk
2507ES04	78.8834	12.4985	81	L,M,R,Dk
2507ES05	78.8768	12.4908	81	L,M,R,Dk
2507ES15	78.8911	12.4881	87	J,Ro,G
2507ES16B	78.8874	12.4813	80	J,Ro,G
2607ES17	78.8857	12.4734	109	L,R,J
2607ES18	78.8777	12.4611	109	L,R,J
2607ES19	78.8750	12.4578	43	L,R,J
2607ES06	78.8721	12.4845	11	L,R,J
3007ES07	78.8930	12.5280	63	L,R,Dk
3007ES08	78.8889	12.5227	46	L,R,Dk
3007ES09	78.8839	12.5041	46	L,R,Dk
3007ES10	78.8787	12.4966	89	L,R,Dk
3007ES11	78.8845	12.4762	87	L,R,Dk
3007ES12	78.8810	12.4966	73	L,R,Dk
0108ES20	78.8823	12.4980	50	L,M,R,G
0108ES21	78.8779	12.4987	65	L,M,R,G
0108ES22	78.8824	12.4740	80	L,M,R,G
0108ES23	78.8844	12.4909	65	L,M,R,G
0108ES24	78.9055	12.5547	22	L,M,R,G
0308ES25	78.8953	12.5069	46	L,M,R,G
0308ES26	78.8915	12.4976	60	L,M,R,G
0308ES27	78.8869	12.4930	69	L,M,R,G
0308ES28	78.8809	12.4839	79	L,M,R,G
0308ES29	78.8778	12.4742	80	L,M,R,G
0308ES30	78.8731	12.4717	43	L,M,R,G
0308ES31	78.9072	12.6001	61	L,M,R,G

*L, Liz Ceperley; M, Mark Goldner; R, Rebecca Siegal; G, George Roth; Dk, Daksha Rajalopalon; J, Julie Brigham-Grette; Ro, Ross Powell; D, Darren MacGregor

2.1 Laboratory Methods

X-ray diffraction

Identification of the dominant minerals present in a sample can be determined by using qualitative techniques after analyzing each sample with X-ray diffraction. Samples were initially wet sieved through a #200 size standard sieve. This separates the clay and silt size fraction from coarser material. After drying at 50 ºC overnight, samples were ground with mortar and pestle to remove any clumps. Next they were top-loaded into a metal slide and packed randomly until a flat surface was achieved. The random packing of grains prevents any preferential orientations of clay minerals that might affect the results. Samples were X-rayed from 2 to 30º 2θ with Cu K-alpha radiation (40kV, 30 mA) using a step size of 0.05º 2θ and a counting time of 5 seconds per step on a Rigaku MiniFlex II X-Ray Diffractometer.

Sample 3007ES07 was used to evaluate the slide and sample preparation methods. An oriented-aggregate slide of sample 3007ES07 was created by vacuum filtering the clay and silt fraction of a sample. A glass slide was then pushed on the filter paper, and the sediment was transferred to the slide. This sample was then analyzed using X-ray diffraction three times: once as a powder slide, once as an oriented aggregate slide, and once after heating to 550°C for 1 hour (Figure 6). The sample was heated in order to confirm the presence of chlorite. The powder and the oriented slides produces comparable spectra, therefore it was concluded that the powder slides are sufficient for analysis.

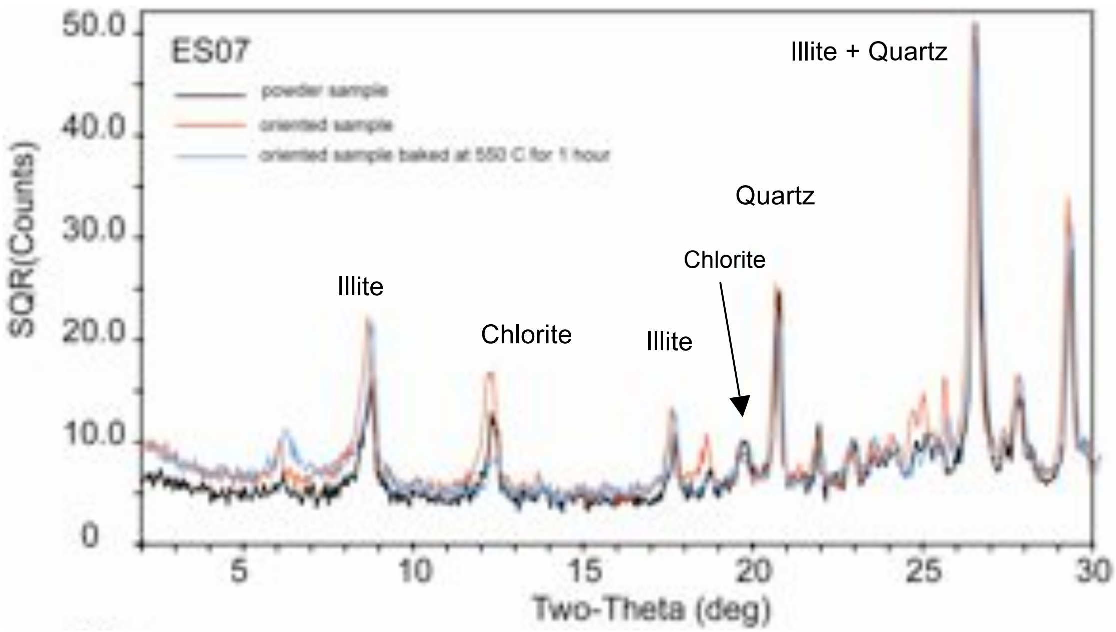

Figure 6. X-ray diffraction spectra for box core sample ES07.

Identification of clay minerals can be accomplished by careful consideration of peaks positions and intensities, which are compared to published values. Comparing complete 00*l* diffraction patterns of major clay mineral groups to the diffraction pattern of the samples allows the presence or absence of major mineral groups to be known. Minerals were identified following guidelines explained by Moore and Reynolds (1997). Minerals produce X-ray diffraction peaks when an X-ray beam diffracts off of a crystal face. The d-spacing between the peaks are known and established for each mineral using Bragg's Law. The spacing between the peaks produced on the spectra is what characterizes each mineral and helps the identification processes. The width and intensity of a peak depends on properties of the mineral and the angle at which the X-ray hits a cleavage plane of the crystal. Peaks identified from X-ray diffraction are given labels 001, 002, 003, etc., based on their order of occurrence from the starting angle of measurement.

3 Results

After collection in the field, all samples were dried and prepared for X-ray diffraction analysis. Observation and results from the field can support results obtained from X-ray diffraction. Characterizing the mineralogy of the box core samples will allow differences between the mineralogy of the Upwelling Plume and Kongsvegen Delta to be visible.

3.1 Field Results and Observations

The sediment-rich plumes created by the Upwelling Plume and Kongsvegen Delta are visibly different in color. The Upwelling Plume is more chocolate brown with red hues, while Kongsvegen Delta is darker brown and more grey. This is consistent in the box core samples, with a sample taken from the directly in the plume of Kongsvegen Delta being darker than a sample taken from a location in the Upwelling Plume (Figure 7). The sorting of the samples are also very different, and can be observed after the samples were dried. Sample 2607ES06, located in Kongsvegen Delta is much more poorly sorted, containing sediment ranging from clay to gravel size. Sample 3007ES07, located in the Upwelling Plume, is moderately sorted, and contains sediment ranging from clay to coarse sand.

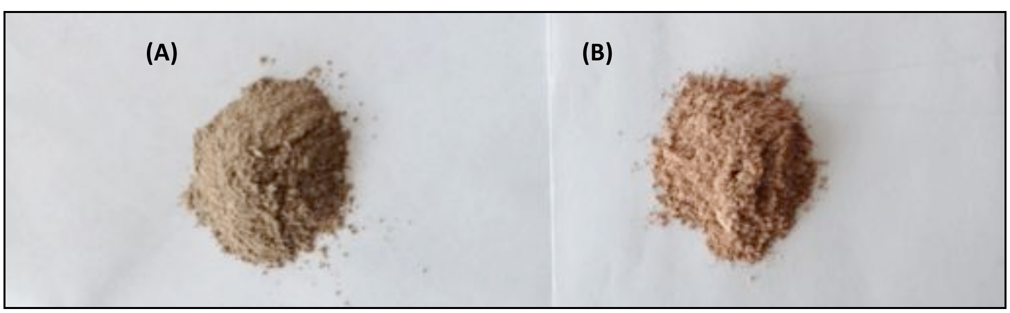

Figure 7. Observed color differences between samples from Kongsvegen Delta **(A)** and Upwelling Plume **(B).**

3.2 X-Ray Diffraction Results

All samples were analyzed using X-ray diffraction from 2 to 30º 2θ with Cu K-alpha radiation (40kV, 30 mA) using a step size of 0.05º 2θ and a counting time of 5 seconds per step. All samples show the presence of clay and silt-size mineral grains. Chlorite and illite are the dominant clay minerals and quartz, dolomite, microcline, and orthoclase are the dominant non-clay minerals. Differences in the clay mineralogy of the samples are the focus of this study, but it can be recognized that the samples have a diverse mineralogy composed of a variety of minerals. Further separation of the clay and silt size particles would help isolate the clay minerals.

Illite

All samples show the presence of illite. The 001, 002, and 003 peak spacing matches to the values published in the literature. Peaks are spaced at 8.7° 2θ, 17.7° 2θ, and 26.8° 2θ are consistent throughout the samples. The 003 peak has a much higher intensity than the 001 and 002 peaks due to its superposition with quartz. Figure 8 is the XRD spectra of samples ES12 and ES06. These samples were chosen to show due to their representative mineral compositions.

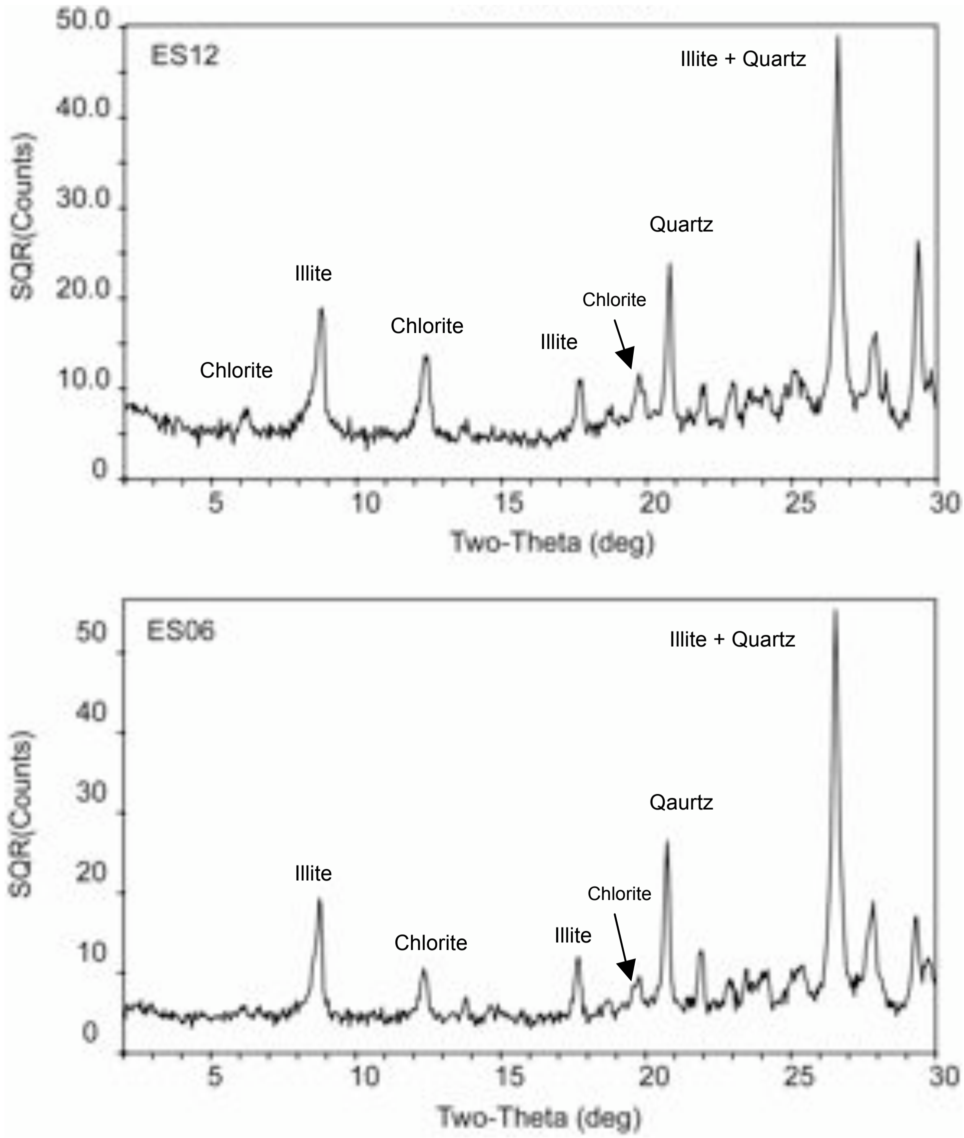

Figure 8. X-ray diffraction spectra for samples **(A)** ES 12 and **(B)** ES06.

Chlorite

Chlorite and kaolinite have very different structure and geologic occurrences, but they are often discussed together because they require a deeper X-ray diffraction analysis to differentiate them in a sediment mixture (Moore and Reynolds, 1997). Initially, chlorite and kaolinite were recognized by the 002 peak of kaolinite at 24.9° 2θ, and chlorite's 004 reflection at ~25.1° 2θ. Two separate, yet small, peaks are visible at these positions. Chlorite was identified by peaks at

6.2 and 18.8° 2θ. Since weak reflections were present at 12.5 and 25° 2θ, the sample could contain only chlorite, only kaolinite, or a mixture of the two. The sample was then heated to 550°C for 1 hour. This causes the dehydroxylation of the hydroxide sheet in chlorite and the diffraction pattern of chlorite will shift and the 002, 003, and 004 peaks to decrease in resolution. These changes will indicate the presence of chlorite. The 002, 003, and 004 peaks did decrease in resolution, yet the 001 peak did not shift. When heated to 550°C, kaolinite becomes amorphous to X-ray and its diffraction pattern disappears (Moore and Reynolds, 1997). A higher resolution scan would be necessary to precisely identify kaolinite in the samples, but the presence of chlorite is confirmed. Figure 6 shows the different spectra for the powder slide, the oriented sample, and the baked oriented sample. The differences in the spectra confirmed the presence of chlorite and eliminated the need to create oriented samples for every analysis. The XRD spectra from all other analyzed samples are in Appendix 1.

The lack of the first, 001, peak for chlorite in Figure 8B can be observed. At 6.2° 2θ in Figure 8A there is the noticeable 001 peak for chlorite, but it is absent, or undistinguishable, in sample ES06.

4 Discussion

Kronebreen and Kongsvegen glaciers form a calving margin at the head of Kongsfjorden. Two distinct plumes of sediment-rich water are visible from aerial photos and field work conducted proximal to the ice-front. The plumes differ in morphology; one is an upwelling plume formed by a subglacial stream located in the center of Kronebreen, and the other is a prograding delta formed by a glacial stream located on the southern margin of Kongsvegen. Twenty-nine box core samples were collected within 1 km of the ice front in order to characterize the clay mineralogy of the sediment sources and analyze the spatial distribution of the sources within fjord proximal to the calving margin of Kronebreen and Kongsvegen ice front. Sediment distributed proximal to the ice front appears to be well mixed and have similar compositions. Box cores collected in each sediment source show a consistent mineralogical composition and the sediment sources are not differentiable from one another using based on clay mineralogy.

The clay minerals present in the samples are illite and chlorite. Matching peaks visible on the XRD spectra to published peak positions and spacing for each respective mineral can identify both minerals. The 001 chlorite peak is not as apparent or strong in several samples (Figures 4, 8 and 9). This could be a product of a variety of reasons. The dry-packing sample preparation can influence the strength of a mineral peak visible in X-ray diffraction analysis, as the sediment is randomly oriented. Therefore, X-rays could be diffracting an oblique angle of a mineral's cleavage plane in the samples where the intensity is weaker. Figure 9 is an overlay of samples ES06 and ES07. ES06 is a sample from the Kongsvegen Delta and ES07 is from the Upwelling Plume. The spectra for these two samples are very similar, except for the 001 peak for chlorite, at 6.2° 2θ, where the peak in sample ES06 is less apparent. A weaker 001 peak was noted in 8 of the box core samples (Figure 4). This occurrence could have a significant meaning for the clay mineralogy of the sediment collected in front of the Upwelling Plume and Kongsvegen Delta, or it could be a result of the methodology used to produce the powder slides for X-ray diffraction.

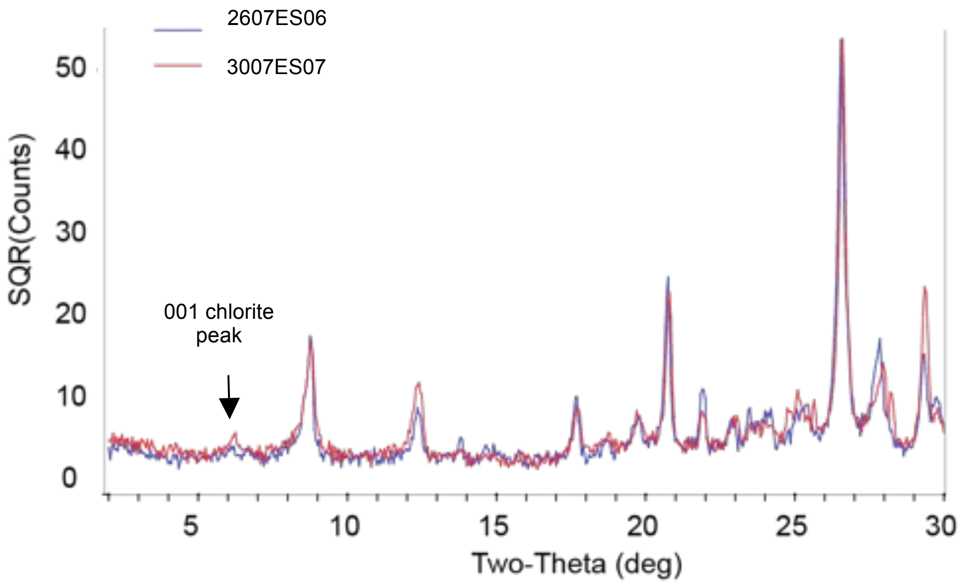

Figure 9. Overlaid spectra of box core samples 2607ES06 and 3007ES07. The 001 peak of chlorite is not as strong in sample 3007ES06.

The strong presence of illite reflects the common occurrence of this mineral. Illite is a common clay mineral found in many rock types as a product of digenesis and weathering of a bedrock source. Illite can from in weathering in hydrothermal and metamorphic environments. It can also form from smectite in deep burial diagenetic conditions. The illite found in these samples could represent authigenic or detrietal minerals from the bedrock that underlies Kronebreen and Kongsvegen glaciers.

5 Future Studies

The box core, water, and iceberg samples can be used in future studies to examine many aspects associated with glacial marginal processes, fjord sedimentation, and spatial analysis of sediment deposition and mixing. The water samples from the sediment sources can be extremely useful in characterizing each sediment source and understanding sediment distribution. One recommendation would be to make slides immediately after vacuum filtering the water, as sand-size particles are present in the top of the water column near the sediment source. These coarse particles make it difficult to remove the sediment from the filter paper after the sediment had completely dried on the filter paper.

Grain size analysis of the box core samples would be useful in quantitatively determining the clay fraction present in each sample. Since this project uses X-ray diffraction to identify clay minerals, knowing the grain size distribution of each sample can strengthen the identification of different minerals. For example, the proportion of non-clay to clay minerals in a box core sample could differ between sediment sources. Therefore, determining this ratio and how it varies could be useful in provenance and transport studies. Grain size analysis can also further the understanding of sediment settling and deposition from an upwelling plume or delta. Generally, the samples should show a finer distribution farther away from the sediment source as heavier and coarser particles settle out faster. The delta environment should contain coarser particles than the upwelling plume, as the glacial stream can support a heavy bedload. The box cores samples are biased towards delta data, as it is not safe to sample directly at the mouth of the upwelling plume. The presence of fining-up sequences visible in gravity cores taken radial from the delta would confirm the presence of the Kongsvegen Delta over time.

Several analytical techniques can be used with the box core samples in order to analyze the distribution of the sediment from the Upwelling Plume and from Kongsvegen Delta. Measuring the magnetic susceptibility of the samples would be useful in helping to find any major differences in bedrock source between the two sediment sources. The current magnetic susceptibility of sediment being deposited from the two sediment sources could be compared to magnetic susceptibility of sediment preserved in gravity cores from similar locations. Comparing two datasets would aid in determining the spatial movement of the Upwelling Plume and Kongsvegen Delta over time.

Determining the quantitative mineralogy of the box core samples would be useful in understanding how the sediment sources mix and distribute sediment within the fjord. This can be obtained by using RockJock methodology outlined by Eberl (2003). RockJock is a computer program that estimates the percent mineral weights in a sample by comparing known X-ray diffraction peaks of corundum with the sediment samples' peaks. This is achieved by mixing corundum with each sample according to a specified ratio. A recommendation would be to first characterize the mineralogy of the sediment sources using the water samples, and then second to see how the water sample compositions are represented in the box cores across the ice-front. These techniques would yield a more detailed spatial analysis of the distribution of sediment from the sources. RockJock identifies both clay and silt-size minerals, so this technique can be really useful in understanding the bedrock composition as well.

X-Ray Fluorescence (XRF) is an additional analytical technique that can be used to analyze elemental differences between box cores. Comparing specific elemental ratios between box core samples could yield information about the bedrock and the source of the sediment. Additionally, XRF data would represent the modern elemental levels in the sediment, and could easily be compared to XRF data from gravity cores taken in the same area. Comparing the preserved and current elemental ratio for a given sample could aid in understanding the spatial variation of the sediment source over time. For example, the location of the subglacial stream that produces the Upwelling Plume could shift over time and carry sediment from a variety of bedrock sources.

Iceberg samples represent subglacial till and would be very useful in understanding the bedrock geology of Kronebreen and Kongsvegen glaciers. It is difficult to identify an exact location where the iceberg calved on the ice front the glacier complex, and hence which part of the glacier it represents. But, the characterizing the clay mineralogy and grain size distribution of the iceberg samples would aid in understanding tidewater glacial sedimentation processes.

X-ray diffraction can be used as a diagnostic tool to find major mineralogical differences between samples collected in a variety of settings and environments. It can be used to understand bedrock composition under a glacial by analyzing sediment carried in a glacial stream if the bedrock is unknown or variable. Box core and water samples were collected from the two additional sediment sources mentioned in the section 1.3, Bearded Seal Bay and the glacial stream located to the west of Kongsvegen Delta. Incorporating X-ray diffraction analysis of these sediment sources with data from the Upwelling Plume and Kongsvegen Delta can be a possibility for future studies as well.

6 Conclusions

Deposition of sediment from a tidewater glacier is complex and incorporates a variety of processes. The head of Kongsfjorden in west central Svalbard is an ideal setting to study sediment deposition as sediment is continually being deposited in the fjord due to the rapidly retreating Kronebreen and Kongsvegen glacier complex. Through analysis of the clay mineralogy of box core samples collected proximal to the ice-font it can be suggested that the fjord is well mixed and the sediment being currently deposited contains homogeneous clay mineral compositions. The distribution of box core samples that show a weaker 001 peak of chlorite does not seem to reflect a geographic trend. It could be suggested that this occurrence was produced by the powder slide preparation due to the lack of a geographic trend. Identifying low-angle non-clay minerals would help to identify the 001 peak of chlorite, as the 001 peak should be present on all XRD spectra for these samples, yet it is hard to distinguish on eight spectra from box cores samples (Figure 4).

The box core samples represent a well-mixed calving-margin, where the two main sediment sources are not distinguishable. Results from this study suggest that gravity cores from this area would lack fine laminations representing seasonal depositions; instead the sediment cores would show a well-mixed glacial margin with broad changes in sedimentation present. Comparing this study with gravity cores data would be valuable in order to understand the recent history of sediment deposition in this location and understand the spatial distribution as well as temporal variation of the Upwelling Plume and Kongsvegen Delta.

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Appendix A.

X-ray diffraction spectra of all box core samples, as presented in Table 2.