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Sediment trap analysis in high-arctic lake Linnévatnet indicates a recent shift in the annual hydrological regime

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Sediment trap analysis in High-Arctic lake Linnévatnet indicates a recent shift in the annual hydrological regime.

An Honors Thesis

Presented to the Faculty of the Department of Geology, Bates College,
in partial fulfillment of the requirements for the Degree of Bachelor of Science

By

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Lewiston, Maine
March 28th, 2018

Abstract

The recent warming trend, which has been amplified in arctic regions, has caused a wide range of environmental impacts in the terrestrial and marine environments in the Svalbard archipelago. Warm temperatures in the late fall and winter season are associated with warm Atlantic water and associated warm air and corresponding storms that now commonly extend northward to Svalbard (Nilsen et al., 2016). The annual hydrological regime in the region has shifted accordingly, from a spring snowmelt-driven mode to one dominated by late “shoulder season” and occasional winter rain events (Nowak and Hodson, 2013; Schiefer et al., 2017). Monitoring of environmental processes and sedimentation in high-Arctic proglacial lake Linnévatnet since 2004 using sediment trap analysis, meteorological data, and time-lapse imagery has documented this regime shift.

Detailed analysis of grain size and geochemistry of sediment traps provides a reconstruction of distinctive annual and seasonal signatures, with compositional profiles indicative of provenance. Continuing the recent trend, the major accumulation of sediment in Linnévatnet in 6 of the last 7 years occurred in late summer and fall, when the active layer is at its greatest thickness and sediment is more easily mobilized. Sedimentation in the 2016-2017 hydrological year was the highest since monitoring began in 2003, attributed mainly to a major late season rainstorm event on October 14-15th, 2016. This storm produced flooding and extremely coarse-grained sediment transport from the main inlet river as well as triggered a major debris flow from the east valley wall which distributed a distinctive plume of calcium carbonate-rich sediment throughout the lake basin.

Acknowledgements

A special thank you to everyone who made this project possible, to the Bates Student Research Fund for allowing me to travel to Svalbard, to Steve Roof, Wes Farnsworth, Al Werner, and the team of UNIS faculty, staff, and AG-220 students for a successful field campaign, to Pete Dawson and Mike Rhodes at UMass Amherst for teaching and assisting me in the use of an ITRAX XRF scanner, and to Mike Retelle for being an ever-supportive professor and advisor.

Note to reader

Geographic features of the study location are referred to by their Norwegian names, hence Linnévatnet is Lake Linné, Linnédalen is the Linné Valley, Kapp Linné is Cape Linné, Linnébreen is the Linné Glacier, and Linnéelva is the Linné River.

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Chapter 1 Introduction

Purpose and Significance

The Arctic is warming faster than any other region on earth, as indicated by the most positive temperature anomalies in the last century, for both land masses and the ocean (Serreze and Barry, 2011), hence the concept of Arctic Amplification (Serreze and Francis, 2006a). Recent warming in the Arctic is strongly associated with feedback loops (Serreze and Francis, 2006b), where increases in greenhouse gas have caused losses of land and sea ice, which, in turn, decreases albedo and increases solar insolation absorbed, which continues the warming. Svalbard air temperature anomalies have been continuously positive since 2011, especially so in the winter months, which have been warmer and wetter (Nowak and Hodson, 2013) with decreased sea ice (Isaksen et al., 2016). Changes in arctic climate reflect a changing global climate, thus research of past and present Arctic climates is imperative in understanding present and future global climates.

Svalbard is an ideal location for arctic climate studies due to its location at the boundary of polar waters and warm North Atlantic waters, a century of meteorological records unique to the Arctic (Humlum et al., 2003), and existing infrastructure and accessibility. Combined with historical meteorological data, varved proglacial sediment is an ideal high-resolution proxy to quantify and understand changing Arctic hydrology. This proxy, alongside historical research and meteorological data, provides regionally amplified evidence of a globally changing climate.

Study Area

Location

The Svalbard Archipelago, located in the Barents Sea, encompasses the land masses from 74°N to 81°N latitude and from 10°E to 35°E longitude. The study area of Linnédalen is in western Spitsbergen, the largest island in the archipelago. Linnédalen is a glaciated catchment, adjacent to the cape, Kapp Linné, which defines the opening of Isfjorden to the Greenland Sea. Linnédalen is a 15-km long NNW-SSE oriented valley, containing the glacier Linnébreen and the proglacial lake Linnévatnet. The main inflow to Linnévatnet is Linnéelva, which also drains the lake to Isfjorden (Figure 1.1).

Figure 1.1: Map of the Svalbard Archipelago, inset showing study area of Linnédalen (toposvalbard.npolar.no)

Bedrock Geology and geography

The Svalbard Archipelago is located on the uplifted NW corner of the Barents Shelf Plate. The structural grain on Spitsbergen is dominantly NNW-SSE due to four similarly oriented episodes of tectonic deformation (Figure 1.2). Linnédalen, aligned along the dominant structural orientation, is located in the Western Spitsbergen Fold and Thrust Belt, uplifted during the Cretaceous and folded during the Eocene by transpressive forces (Dallman, 1999). Deformation is associated with Greenland making right-lateral contact with Svalbard. The westernmost formation in Linnédalen is the Heckla Hoak diamictite, consisting of steeply dipping highly metamorphosed Precambrian basement rocks. Linnédalen's western wall is comprised of steeply dipping argillaceous phyllite. The valley floor is composed of the Lower Carboniferous Orustdalen Formation, a quartzite containing coal and fossilized plants. The eastern wall of Linnédalen consists of Upper Carboniferous to Permian age limestone, dolostone, as well as evaporates such as gypsum and anhydrite (Dallman, 1999).

Linnévatnet, 4.7 km long by 1.3 km wide, sits at 12 meters above sea level and contains a deep main north basin and two shallow basins in the south. The more expansive north basin reaches a maximum depth of 35 m. The south basins are divided into east and west sub basins by a bathymetric ridge, with depths of 11m and 16 m, respectively (Snyder et al., 2000). The water column of Linnévatnet is subject to strong aeolian forced mixing, as the result of its location in a steeply walled valley. The lake basin as a whole is the result of glacial erosion, and the flatness and regularity of the north basin is explained by a high sediment supply of glacial silt (Bøyum and Kjensmo, 1978).

Linnébreen, at the southern head of the valley, is a small polythermal glacier located 5.5 km south of Linnévatnet. Retreat from the Little Ice Age moraine has exposed a 1.2 km long glacial fore-field consisting of siliclastic sediment that is incised by Linnéelva.

Figure 1.2: Bedrock Geological Map of Linnédalen (Dallman, 1999)

Glacial History of Linnédalen

Svalbard has experienced multiple periods of glaciation. During the Last Glacial Maximum, Linnédalen was covered by the Svalbard-Barents Ice Sheet, along with the rest of Svalbard (Ingólfsson and Landvik, 2013). Isostatic depression occurred, and following rapid deglaciation, Linnédalen became a fjord connected with Isfjorden, with relative sea level 65-75 m above modern sea level (Figure 1.3). Deglaciation of the valley occurred approximately 12,300 years B.P., as indicated by dated mollusks found above diamict in sediment cores taken from Linnévatnet. Following, isostatic rebound outpaced sea level (Ingólfsson, 2011). Cores taken from Linnévatnet contain lacustrine sediment atop marine sediment, indicative of an isolation basin, with the isolation contact dated to 9,600 years B.P. (Svendsen and Mangerud, 1997).

The sediment record indicates that Linnédalen was deglaciated from 10,000-4,400 years B.P., encompassing the period of the Holocene Thermal Maximum. Linnébreen reformed during the late Holocene Neoglacial and has existed at a variety of sizes since (Svendsen and Mangerud, 1997). The maximum postglacial extent occurred at the end of the Little Ice Age (LIA) in the late 19th century, marked by a prominent LIA moraine (Figure 1.4) (Reusché et al., 2014; Svendsen and Mangerud, 1997; Werner, 1993).

Figure 1.3: Variability in isostatic rebound in Svalbard as shown by relative sea level curves, study area highlighted in red, with a marine limit of 65-75 m (Forman et al., 2004).

Figure 1.4: 1936 south-facing oblique image of Linnédalen, Linnébreen still at LIA moraine (Norwegian Polar Institute)

Svalbard Climate and Environment

The climate of Svalbard is classified as Arctic maritime, due to its location at the boundary of arctic and temperate ocean currents and air masses in the Arctic North Atlantic, (Eckerstorfer and Christiansen, 2011). In the past century, Svalbard has been warming as seen in air temperature records (Førland et al., 1997) as well as the loss of glaciers and sea ice (Nuth et al., 2010). In the years 2001-2015, annual positive temperature anomalies were 1.7 to 2.5 °C warmer and the winter anomalies were 3.4 to 4.6 °C warmer, compared to the years 1981-2000 (Isaksen et al., 2016). Being a small land mass, the maritime arctic climate of Svalbard is highly thermoregulated by the West Spitsbergen Current, a warm branch of the North Atlantic Ocean (Førland et al., 1997). This maritime influence causes Svalbard to be more temperate than other land masses at similar northern latitudes, with rain and snow occurring in all seasons (Førland et al., 1997). The influence is strongest nearest fjord troughs like Isfjorden, where Linnédalen is located (Isaksen et al., 2016). The maritime influence, combined with the regional topography, creates a strong precipitation gradient, decreasing west to east across the archipelago (Førland et al., 1997; Humlum, 2002). A comparison of the precipitation records for Isfjord radio, located on Kapp Linné, to the Longyearbyen airport, located 50 km up Isfjorden, show that the coast receives significantly more precipitation than inland locations (Figure 1.5).

Figure 1.5: Comparative 30-year precipitation record for Longyearbyen Airport and Isfjord radio, located on Kapp Linné (Førland et al., 1997)

Arctic Hydrology

Arctic climates create unique hydrological systems due to seasonal hydrological loading and unloading of glaciers and permafrost interaction with runoff (Svendsen and Mangerud, 1997). A bare landscape atop permafrost has poor water retention abilities, creating high runoff and correspondingly high sedimentation during rain events. It is known that most northern rivers experience a nival flood hydrological regime, where the highest flow is in the spring, decreasing

through the summer to a winter standstill (Woo and McCann, 1994). During the winter, with the source river, lake cover, and glacier all frozen, fluvial action and corresponding sedimentation is generally negligible. The sedimentation during winter months is result of suspended sediment settling in predominantly undisturbed conditions (Zolitschka et al., 2015).

However, wintertime temperatures in Svalbard are highly variable and can range from well below to above freezing (Humlum, 2002), and in the last 10 years Nowak and Hodson (2013) found that the hydrology of Svalbard is changing, with warmer, wetter, and shorter winters. In addition, Frederiksen (2017) determined that since 2003, Linnévatnet ice cover duration has been decreasing. Shorter winters mean that the two shoulder seasons, spring and fall, are longer and have an increased effect of the hydrology of the system. With later onset of freezing condition in the fall season (Frederiksen, 2017), Svalbard has experienced increased precipitation as rain. Increased rain combined with a thawed late-summer active layer has led to extremely high sedimentation rates for these events (Retelle et al., 2017). While precipitation in the spring may fall as rain sooner than usual due to shorter winters, the active layer is frozen, preventing transport of sediment.

Proglacial Sedimentation

Sedimentation in a proglacial lake depends on many factors including proximity and type of glacier, delta formation and inflow mechanics, density relationships within the lake, modes of mixing, as well as provenance of sediment (Ashley et al., 1985). Annual sedimentation rates depend directly on quantities of catchment runoff, both from glaciers as well as precipitation events. Summer sedimentation, if undisturbed by large precipitation events, typically produces graded beds, while high-energy precipitation events tend to deliver sediment of a larger grain size. Cockburn and Lamoreaux (2008) state that late season rainstorms are the largest drivers of sedimentation change, and analyses of the largest grain sizes is the best proxy for looking at high intensity precipitation and sedimentation events. During the winter ice-locked months, the calm waters allow for the settling of finer sediments forming a thin “clay cap” atop the summer layer (Zolitschka et al., 2015). The seasonal variation in sediment input creates a distinctive annual sedimentation pattern or varve, making laminated arctic lake sediments an ideal proxy for hydrological studies (Ojala et al., 2012; Zolitschka et al., 2015).

Density and corresponding temperature stratification of the water column compared to the density of inflow will dictate how the inflow is dispersed. Grain size decreases proportional to distance from inflow, as larger particles settle first (Smith and Ashley, 1985). While proglacial lakes may be stratified during the summer, due to aeolian mixing Linnévatnet is not, thus it is classified as a cold monomictic lake (Bøyum and Kjensmo, 1978).

Linnévatnet Sedimentation

The distribution of sedimentation in Linnévatnet is highly influenced by the input and corresponding sediment delivery from Linnéelva. The sediment inflow is deflected in a right-hand manner by Coriolis deflection, hence the thickest accumulation occurs in the eastern sub-basin (Figure 1.6).

There are 4 distinct sediment sources for Linnévatnet. Historically, the major source of sediment is inflow from Linnéelva, draining a watershed of 27 km² which encompasses all three formations in the valley, with the glacially eroded coal bearing quartzite being the main source

on the valley floor (Snyder et al., 2000). Another source is the eastern carbonate alluvial fans which deliver sediment eroded from limestone and dolomite on the east valley wall. On the opposite valley wall are the western alluvial fans, which delivers sediment derived from phyllite. An additional sediment source is a meltwater stream flowing from the LIA cirque located SW of the lake. The stream delivers sediment dominated by the phyllite exposed on the western valley wall. Snyder et al. (2000) describe coarse grained laminae composed of phyllite rock fragments interbedded with the fine silty laminae in the west basin of Linnévatnet. In addition, soliflucted material of all sources is contributed around the lake basin by wave action.

Figure 1.6: Isopach map of sediment thickness in Linnévatnet (Svendsen and Mangerud, 1997)

Previous Work and Study Goals

Research throughout Linnédalen has been ongoing since 2003, led by Professor Retelle and colleagues. Student involvement was originally through a Research Experience for Undergraduates program funded by the U.S. National Science Foundation, but since 2016 has been supported by the University Center in Svalbard (UNIS) for a month-long summer research program. Bachelor's theses studying the sedimentation in Linnévatnet have been produced annually. The following theses are of particular relevance to this study. Perrault (2006) used X-Ray Diffraction (XRD) and grain size analysis to identify provenance of lacustrine sediments. Walther (2015) used XRD to investigate the effects of major late season precipitation events on the sedimentary record of Linnévatnet. McCabe (2016) employed ITRAX scanning X-Ray Fluorescence (XRF) analysis to identify geochemical markers of late season precipitation events, as it relates to provenance and transport of sediment. Potter (2017) used XRF and grain size analysis to examine how large late season precipitation events are recorded in the sedimentary record. This study continues previous work, employing XRF and grain size analyses to identify the annual sedimentation signature, as well as identify provenance and transport of sediment. Understanding the pattern and timing of sedimentation in this past year will extend the valuable hydroclimatic record that has demonstrated the connection between a warming arctic and the shift in hydrological regime.

Chapter 2 Methods

Field Methods

Linnévatnet is situated 3 km inland from Kapp Linné, where both an ecotourism hotel center and a weather station with a longstanding record are located. Field work at Kapp Linné occurred from July 18-28th, 2017.

Moorings

Since 2004, 7 moorings have been deployed and recovered annually, with locations seen in Figure 2.1. The moorings are located strategically to best analyze sedimentation patterns, creating a north-south proximal to distal transect (G, H, D, C) and an east-west transect (D, E, F). Moorings C and D are located in the east sub-basin, proximal and distal to the Linnéelva inlet, with the intervalometer mooring deployed adjacent to C. Mooring E, at only 5 m depth, is located on the bathymetric ridge separating the east and west sub-basins. Mooring F is located in the west sub-basin, receiving inflow from the LIA cirque. Mooring H is located at the south end of the deep north basin, proximal to an alluvial fan, which extends in Linnévatnet. Mooring G is located in the deep main basin, recording the sedimentation signature of the Linnévatnet as a whole and is not directly influenced by a single sediment source.

Sediment Traps

Each of the 6 moorings contains between 1 and 6 sediment traps, arranged on the mooring line as seen in Figure 2.2. Attached to a rock on the bottom, the mooring sits approximately 1m below water level so that the moving lake ice does not displace the mooring. Each trap is affixed using brackets and zip ties, spaced 3 m apart (C and D) and 6 m apart (H,G,F), with the basal trap 1 m above the rock. A 12.1 cm-diameter funnel delivers sediment to the receiving tube, and the 1 cm² baffle atop prevents laminar flow from upsetting sediment still in suspension in the funnel as well as sediment already deposited in the receiving tube. The use of the funnel amplifies the sedimentary signature (Asper, 1987)

Mooring Collection

All of the sediment traps were gathered in July 2017. After the traps were taken carefully out of the water upright to preserve the annual sediment signature, they were taken ashore and propped upright overnight to finalize sediment settlement. After settling, Zorbitrol Plus was added atop each receiving tube before being capped to preserve the water sediment interface. The tubes were then taped closed and carried out of the field. Ten of the twenty-four traps recovered in July 2017 had sediment overflow the receiving tube into the funnel.

Intervalometer

The intervalometer sediment trap system is moored adjacent to C at 1m above the lake floor and is retrieved annually. The system is similar to a sediment trap, as it is affixed to a line, sits vertically in the water column, and has a funnel, baffle, and receiving tube (Figure 2.3). On either side of the receiving tube there are series of LED lights and corresponding photo diodes, activated every 30 minutes. As the sediment accumulates, the light is obstructed and this is

recorded as a change in voltage by a HOBO logger, measured voltage is proportional to the amount of sedimentation in the receiving tube.

Time Lapse Photography

There are 3 remote time lapse cameras in Linnédalen. A pair of cameras are situated on a ridge atop the south-eastern shore of Linnévatnet, a “plume camera” facing southwest towards the inflow and one facing northerly looking down-lake. An additional camera overlooks Linnébreven from the Little Ice Age maximum moraine. Each camera is programmed to take 2 images a day. The plume and down-lake cameras provide a record of the hydrogeological and lacustrine processes such as snow and ice formation and melting, Linnéelva flow, and plumes of sediment delivered into the lake.

Meteorological Data

Svalbard has one of the longest meteorological records in the arctic (Førland et al., 1997), making it an ideal location to study the changing arctic climate. The Longyearbyen Airport, located 50 km up Isfjord from Linnévatnet, has been recording temperature and precipitation for over a century. The weather station at Kapp Linné has been recording temperature and precipitation since the 1930's. These meteorological data are available from the Norwegian Meteorological Institute (eklima.met.no).

The meteorological conditions in Linnédalen were recorded by an ONSET HOBO U30 weather station, located near the southern shore of Linnévatnet. This station has been in place since 2003 and records air and ground temperature, wind speed and direction, relative humidity, precipitation, and solar insolation, each at a 30-minute sampling interval.

Figure 2.1: Bathymetric map of Linnévatnet, mooring sites marked C-H (Nelson, 2010)

Figure 2.2: Diagram illustrating the mooring setup, including an image of the C3 receiving tube from 2017.

Figure 2.3: Håvard Larsen holding the intervalometer after July 2017 retrieval.

Figure 2.4: The drill press with a circular blade and the accompanying jig used for scoring the receiving tubes in the machine shop at Bates College.

Lab Methods

Receiving Tube Preparation

The receiving tubes were transported from Svalbard to Bates College, refrigerated when possible. All of the basal receiving tubes were analyzed. In addition, traps C3 and D4 were analyzed due to proximity to inflow source. The receiving tubes were split in two, facilitated by Carnegie Science Center technician Peter Beach using a circular blade on a drill press and an accompanying jig designed specifically for splitting receiving tubes (Figure 2.4). The tubes were scored on either side, only scored to prevent contamination from the saw blade or shards of plastic. A flathead screwdriver was then implemented to split open the core. A sheet of metal was then inserted between the split core, creating two receiving tube halves. The two halves were then photographed. The more complete half was archived for non-destructive analyses, XRD and XRF, and the working half was subsampled for grain size analysis.

Grain Size Analysis

Grain size analysis took place at Bates College and was performed using the protocol described in Arnold (2009). The working half was subsampled at continuous 0.25 cm increments, with each sample being transferred to a 47 mL Oak Ridge centrifuge tube. Enough 30% hydrogen peroxide was added to cover the sediment and the tubes were allowed to sit overnight partially capped in order to remove any organic matter as well as resulting gasses. After sitting overnight, 20 mL deionized water and 17 mL dispersant (0.7 g/L sodium metaphosphate) were added to each sample. Each sample was shaken with a Vortex Genie 2 for 1 minute and then sonicated with a Fischer Science Sonic Dismembrator for 1 minute. The samples were run in the Beckman-Coulter Laser Particle Size Analyzer, which uses the diffraction of light incident to grains in suspension to determine particle size. Each sample ran 3 times, and the result of the 3rd run was selected to characterize the sediment due to increased deflocculation with each run. Data reported for each sample is the mean, median, 10th, and 90th percentile grain size.

Geochemical Analysis

The geochemical analysis was done using a Cox ITRAX XRF Core Scanner located at the Ronald B. Gilmore XRF Laboratory, University of Massachusetts Amherst. This instrument is ideal for geochemical analysis of sediment downcore due to its ability to yield non-destructive sub-millimeter elemental analysis of cores on a track. Each core was scanned twice, initially to obtain an RGB image (50 kV, 40 mA, 975 ms exposure time) and a laser triangulated topographic profile of the core's surface. For the second, slower scan, a thin plastic film is placed atop the core to prevent drying. The intervals of XRF analysis are programmed into the ITRAX atop the RGB image. The XRF measurements were done at 10 second exposures at 500 micron steps, using a molybdenum (Mo) X-ray tube at 30 kV and 55 mA. During analysis the XRF detector moves according to the topographic profile to maintain a consistent height (Figure 2.5) (Croudace et al., 2006).

Figure 2.5: Diagram of the ITRAX XRF Core Scanner (Croudace et al., 2006)

Chapter 3 Results

Meteorological Results

The main weather station, located at the southwest shore of the lake, recorded meteorological data at 30 minute intervals from 7/22/2016-7/27/2017. The daily rainfall and temperature data for the 2016-2017 hydrological year are presented in Figure 3.1. While rain fell in every month of the year, the majority of liquid precipitation fell during the fall months: September, October, and November. The temperature decreases through the fall and becomes more variable during the winter. Above freezing temperatures occurred during early February with corresponding rainfall. Variation in temperature decreases with an increase in temperature throughout the spring and into the summer.

Figure 3.1: Precipitation and air temperature data for Linnévatnet for the 2016-2017 hydrological year.

Intervalometer Results

Pairing the intervalometer results and the meteorological data allows for the temporal calibration of sedimentary events. The intervalometer recorded sedimentation at mooring C in 30 minute intervals, deployed on 7/25/2016 and recovered on 7/26/2017. As seen in the intervalometer data, a continuous voltage recording at 2.45V indicate that the intervalometer was overfilled on 10/15/2016 (Figure 3.2). Jumps in voltage in the intervalometer correspond to depth of sedimentation, and using this proportionality allows for the dating of sedimentary events in the intervalometer receiving tube.

Figure 3.2: Daily rainfall (black) and intervalometer data (red) for the fall of 2016. Intervals 1, 2, and 3 are sedimentary events.

Identification of Sedimentary Events

Correlations are made with the general understanding that changes in factors such as precipitation and temperature can cause increased terrestrial sediment transport, leading to increases in lacustrine sedimentation in this glacial-fluvial-lacustrine setting. For the purpose of identifying sedimentary events and their timing from the intervalometer record that will be identifiable in the receiving tube logs, the 2016-2017 sedimentation signature of Linnévatnet has been divided into 3 intervals. The transition between intervals 1 and 2 is known due to it occurring before the intervalometer overfilled, and the transition between intervals 2 and 3 is estimated as the intervalometer was overfilled. Interval 1 is all sedimentation from deployment on 7/25/2016 until 10/14/2016 and is identified as the basal 64mm of sediment in the intervalometer receiving tube. Interval 2 is a massive 81+ mm single-day sedimentary event that overfilled the intervalometer on 10/15/2016, corresponding to at least 56% of sediment received in the intervalometer. Interval 3 is all sedimentation from 10/16/2016 through recovery. Due to the precision of the intervalometer, additional subintervals within interval 1 have been identified: Subintervals 1.1, 1.2, and 1.3.

Subinterval 1.1 represents the sedimentation from mooring deployment on 7/25/2016 through 8/18/2016, and the jump in the intervalometer voltage follows a number of mid-August light rainfalls, notably 10.6 mm precipitation on the previous day (8/17/2016). Figure 3.3 shows a composite remote image taken on 8/18/2016 in the AM, with an extensive plume of suspended sediment visible. The plume is confined to the eastern sub-basin by the island and the bathymetric ridge along strike and to the left (south) of the island.

Subinterval 1.2 represents the sedimentation from 8/19/2016 through 9/20/2016, and the jump in the intervalometer represents the sedimentation which followed 33.6 mm of rain on 9/14/2016 and continued precipitation through 9/20/2016, as seen in Figure 3.1. Figure 3.4 shows a composite remote image taken on 9/15/2016 in the P.M., following 33.6 mm of precipitation the

previous day. The well-defined suspended sediment plume is the result of Linnéelva delivering sediment into Linnévatnet.

Subinterval 1.3 represents the sedimentation from 9/21/2016 through 10/13/2016, and the gradual increase in the intervalometer voltage represents the gradual sedimentation rate associated with over 100mm of rain during that period.

Interval 2 represents the day 10/15/2016 in which at least 81mm of sediment were deposited in the intervalometer receiving tube, overfilling it. On the day prior, 10/14/2016, 58.4 mm of rain fell (Figure 3.5). Figure 3.6 is a down-lake remote image taken on 10/15/2016, on which an additional 24.2 mm of rain fell. Activated flow in the alluvial fans, as well as wave washing of soliflucted sediment along the shoreline, provide abundant suspended sediment into the lake.

Interval 3, not recorded on the intervalometer, represents all sedimentation from 10/16/2016 until recovery on 7/25/2017. As seen on Figure 3.1, 162.6 mm of rain fell on 11/7/2016, within interval 3. Figures 3.7 and 3.8 show remotes image taken on 11/6/2016 and 11/7/2016, respectively. Note the snowpack on the terrain in the former image. This image, supported by the subzero temperature record for the week prior, indicates that this major fall rain storm fell on a frozen active layer. With no mobile sediment available, this event was not prominently recorded in the sedimentary record.

Figure 3.3: Composite image taken on 8/18/16 AM. Note the sedimentary plume, confined by the bathymetric ridge running along strike with the island.

Figure 3.4: Composite image taken on 9/15/16 PM. Note the sedimentary plume along the eastern shore due to Coriolis deflection.

Figure 3.5: Down-lake image taken on 10/14/16 PM, 58.4 mm of rain fell on this day.

Figure 3.6: Down-lake image taken on 10/15/16 AM, note activated flow in the alluvial fans.

Figure 3.7: Down-lake image taken on 11/6/16 AM.

Figure 3.8: Down-lake image taken on 11/7/16 AM, 162.6 mm of precipitation fell on this day.

Sediment Receiving Tube Stratigraphy

Figures 3.9-17 are composite logs of geochemical profiles for Ca, K, Zr, and Ti plotted alongside median grain size. These elements were chosen as they are indicators of distinct geological provenance, which can indicate the sedimentary process responsible for deposition. In each log the intervals were identified, preliminarily done comparing the plot to the calibrated intervalometer log, and then altered with respect to trends seen in the plots from other moorings. Certain receiving tubes are missing sections of geochemical data due to negative interactions between the ITRAX scanner and sections of cores with irregularities, cracks, or compaction. Geochemical and grain size trends vary spatially throughout the lake as a function of proximity to sedimentary sources and as well as bathymetric restrictions.

Figure 3.9 shows the composite log for the overfilled intervalometer, with the depth of transition from interval 1 to interval 2 known precisely. Interval 1 is composed of consistently sized sediment with an increase of Ca from 115-130 mm depth which varies inversely with a simultaneous drop in K, Zr, and Ti. Interval 2 contains sediment with a peak in grain size at 55 microns centered at 30mm depth, as well a peak in calcium, centered at 2mm depth. Corresponding spikes in K and Zr indicate some level of covariance, and there is an increase in Ti from 20-40 mm depth.

Figure 3.10 shows the composite log for the C3 receiving tube, which is one of the receiving tubes not overfilled in the fall storm. Interval 1 is composed of consistently sized sediment with an increase in Ca from 170-180 mm depth. Counts in calcium steadily increased upward, and trends in Zr and Ti are indistinguishable. Interval 2 contains sediment with a peak in grain size at 130 mm depth, with a maximum grain size of 88 microns. In addition, 2 bladed clasts of phyllite were found between 130-140 mm depth during subsampling, long axes measuring 5 and 7 mm. There are two smaller peaks in calcium on either side of the grain size peak, centered at 120 and 155 mm depth, as well as a larger peak in calcium at 50 mm depth. Counts in K steadily increase upward, there is a peak in Zr at 95 microns, and no trends are visible for Ti. Interval 3 consists of sediment containing peaks in Ca and K, which co-vary, at 20 mm depth. Counts in Zr increase upward, and no trends are visible for Ti.

Figure 3.9: Composite log for the intervalometer, which was overfilled on October 15, 2016. The intervalometer is located adjacent to mooring C. Intervals 1 and 2 are annotated.

Figure 3.10: Composite log for the C3 receiving tube, which was not overfilled. Two fragments of phyllite were recovered from the receiving tube between 130 and 140 mm in depth. Intervals 1-3 are annotated.

Figure 3.11 shows the composite log for the overfilled basal receiving tube C4. Interval 1 is composed of consistently sized sediment with a peak in Ca centered at 270 mm depth. While highly variable, counts in K and Ti appear to co-vary and roughly vary inversely with Zr. Interval 2 consists of sediment containing a peak in grain size of 84 microns centered at 85 mm depth. Calcium presents a peak centered at 5 mm depth and varies inversely with grain size. There is a peak in Zr centered at 75 mm depth, and highly variable counts in K and Ti appear to roughly co-vary.

Figure 3.11: Composite log for receiving tube C4, which was overfilled. Intervals 1 and 2 are annotated.

Figure 3.12 shows the composite log of the overfilled D4 receiving tube. Interval 1 is composed of sediment containing a slight increase in calcium upward, and K, Zr, and Ti roughly co-vary, presenting a peak at 100 mm depth. Interval 2 is composed of sediment containing a peak in grain size of 33 microns at 30 mm depth. There is a peak in Ca at 65 mm depth, and a larger peak at 5 mm depth. Again, K, Zr, and Ti roughly co-vary with peaks at 40 and 200 mm depth.

Figure 3.12: Composite log of receiving tube D4, which was overfilled. Intervals 1 and 2 are annotated.

Figure 3.13 shows the composite log of the overfilled basal D5 receiving tube. Interval 1 is composed of sediment in which there is a covariance in grain size and calcium, with a small peak at 290 mm depth. Highly variable counts in K, Zr, and Ti present no identifiable trends. Interval 2 contains a peak in grain size of 32 microns at 170 mm depth. Counts in K and Ti co-vary and are roughly inversely variant to counts in Zr.

Figure 3.13: Composite log of receiving tube D5, which was overfilled. Intervals 1 and 2 are annotated.

Figure 3.14 shows the composite log of the not overfilled basal G5 receiving tube. Interval 1 contains sediment with small peaks in grain size at 90 and 120 mm depth. There is an increase in calcium at 100 mm depth, and no trends are distinguishable for K, Zr, and Ti. Interval 2 contains a large covariant peak in Ca and grain size, centered at 50 mm depth, with a maximum grain size of 12.8 microns. Counts in K and Ti are lowest at 50 mm depth and appear to vary with Ca and grain size. No distinguishable trends in Zr are present. Interval 3 contains sediment with an additional smaller peak in grain size at 10 mm depth. Calcium decreases upward, K and Ti co-vary, and no distinguishable trends in Zr are present.

Figure 3.14: Composite receiving tube log for G5, which was not overfilled. Intervals 1-3 are annotated.

Figure 3.15 shows the composite log of the overfilled basal H5 receiving tube. Interval 1 contains sediment with a covariance between grain size and Ca counts. Counts in K and Ti roughly co-vary, and no distinguishable trends in Zr are present. Interval 2 contains sediment with a peak in grain size of 15.8 microns at 18 mm depth, and a sharp increase in calcium between 2-22 mm depth. Counts in K and Ti seem to co-vary, with counts lowest between 15-20 mm depth. No distinguishable trends in Zr are present.

Figure 3.15: Composite log for receiving tube H5, which was overfilled. Intervals 1 and 2 are annotated.

Figure 3.16 shows the composite log for the not overfilled single receiving tube E. Interval 1 contains sediment with an upward trend decreasing grain size and increasing counts in Ca. Trends in K, Zr, and Ti are indistinguishable. Interval 2 contains sediment with co-varying peaks in grain size (11 microns) and Ca at 35 mm depth. Again, trends in K, Zr, and Ti are indistinguishable. Within interval 3, there is a sharp drop in Ca, K, and Ti at 8mm depth. Grain size decreases upwards until 12 mm depth and then increases upcore for the remainder of the core. No distinguishable trends in Zr are present.

Figure 3.16: Composite log for receiving tube E, which was not overfilled. Intervals 1-3 are annotated.

Figure 3.17 shows the composite log for the not overfilled basal F3 receiving tube. Interval 1 contains sediment with a peak in grain size microns at 50 mm depth. A portion of the geochemical data for this interval was invalid, the remaining data does not present any trends other than decreased values on either side of the invalid section. Interval 2 contains sediment with a slightly larger peak in grain size of 10.5 microns at 35 m depth. Counts in Ca, K, Zr, and Ti all show a major trough at 25 m depth. Calcium presents a peak at 24 mm depth. Interval 3 contains sediment with a smaller peak in grain size at 3 mm depth. Counts in Ca decrease upward, K and Ti co-vary, and no distinguishable trends in Zr are present.

Figure 3.17: Composite log for receiving tube F3, which was not overfilled. Intervals 1-3 are annotated.

Grain Size Analysis

Error! Reference source not found. shows a composition of down core median grain size plots, plotted proximal to distal of the Linnéelva source, along a transect. Receiving tubes with an asterisk next to the name indicate an overfilled trap, with their plots moved relatively down core to account for the approximate amount of overfilled sediment, improving visualization of correlations. Each of the receiving tube grain size plots demonstrate a unimodal trend, with a prominent peak. The peak has the largest grain size for receiving tubes C3 and C4, and continues to decrease along the transect, distal to the Linnéelva source. The onset of the 10/15/16 event can be accurately plotted on the intervalometer grain size plot, as seen in **Error! Reference source not found.** as a solid blue line, which indicates the separation between intervals 1 and 2. This solid line was then extrapolated as a dotted line across each grain size plot for each receiving tube. The border between intervals 2 and 3 was extrapolated to be after the peak in grain size.

Figure 3.18: Grain size plot of down-lake receiving tubes, with intervals 1-3 annotated. Overfilled receiving tubes are annotated with an asterisk, and additional depth has been added.

Chapter 4 Discussion

Differentiation of Sedimentary Layers

The intervalometer results coupled with the meteorological and time-lapse imagery records indicate 3 distinct sedimentary intervals, which can be identified in the grain size and geochemical results of the receiving tubes throughout Linnévatnet. Although the records are incomplete due to the overfilling of the majority of the receiving tubes from unprecedented quantities of sedimentation, the idealized stratigraphic column can still be reconstructed and correlated from mooring to mooring. The intervals consist of one or more sedimentary events, with interval divisions based on sudden changes in sediment properties reflected in the grain size and geochemistry.

Interval 1, Subintervals 1-3

Interval 1 consists of sedimentation from deployment on 7/25/16 until 10/13/16. Within interval 1, additional sedimentary subintervals were identified from the intervalometer (Figure 3.2). Subinterval 1 consists of post deployment late-summer sedimentation with minor nival contributions, followed by a rainstorm on 8/17/16 which induced a sedimentation event (8/18/16) which represents the end of the subinterval. Subinterval 2 includes the period from 8/19/16 until 9/15/16 in which less than 2mm of sediment accumulated in the intervalometer receiving tube. The sedimentation in this subinterval came primarily from the rainfall-induced sedimentation event (9/20/16) which represents the end of this subinterval. Subinterval 3 consists of the sediment delivered gradually from 9/21/16 through 10/13/16; during this period 161.4 mm of rain fell.

The sedimentation signature of interval 1 varies spatially throughout the lake as a function of proximity to sediment sources. The receiving tubes along the proximal to distal transect of Linnévatnet (Intervalometer, C, D, H, G) all presented geochemical and grain size plots with trends reflective of location and mode of sediment delivery (Figures 3.9-17). Specifically, sediment quantity decreases distally from the Linnéelva delta, and all receiving tubes logs show a sharp increase in grain size in interval 2. Consistent Zr and Ti counts reflect sediment sourced from the valley floor quartzite, as these elements are found in typical detrital minerals within quartzite. Counts of K are consistently higher in interval 1 than in the rest of the core, indicative of phyllite sediment from the west valley wall being delivered by Linnéelva. There are inconsistent variations in calcium for these receiving tubes in interval 1. Consistently present in interval 2 is an increase in Ca, occurring in line or up-core of the peak in grain size. The increase is most likely due to contributions from the eastern carbonate valley wall and the variations are due to the spatial location of moorings relative to the contributing sources.

The receiving tubes in the western sub-basin (E, F) present different sedimentation signatures due to the lack of Linnéelva derived sediment being transported across the bathometric ridge that defines the sub-basin. It has been assumed that the predominant source for the western sub-basin sediment is meltwater stream inflow from the LIA cirque (Snyder et al., 2000). However, no meaningful interpretations of the geochemistry of interval 1 in these receiving tubes can be made as trends are indistinguishable in E aside from a gradual increase in Ca, and a portion of the

geochemical results in F3 were invalid (Figures 3.16-17). The grain size plots present peaks in grain size, among the largest grains throughout their respective receiving tubes, indicating a high energy of the meltwater stream during interval 1.

Interval 2

Interval 2 consists of all sedimentation occurring during to the 10/15/16 “shoulder season” storm. The boundary between interval 1 and 2 is precisely defined using the intervalometer. In the 22 days prior to 10/14/16, meteorological records indicate 161.4 mm of rain fell. On 10/14/16 58.4 mm of rain fell and an additional 24.2 mm fell the following day, 10/15/16. The intervalometer results indicate overfilling on 10/15/16, with this sedimentary event delivering at least 81 of the 144 mm of sediment in the receiving tube (Figure 3.9).

The sedimentary signature of interval 2 is more distinct than interval 1, as it is defined by a sharp peak in grain size, seen throughout all of the receiving tubes (Figure 3.18). Geochemical trends vary based on location. The sedimentary signature of the receiving tubes of the intervalometer and moorings C and D show trends of a large peak in grain size occurring below a sharp increase in calcium (Figures 3.10-13). In all but the C3 receiving tube there are consistently less counts of K throughout Interval 2 as compared to interval 1. No meaningful trends of Zr and Ti exist in this set of receiving tubes. Figure 4.1 shows location and field images of a debris flow channel and deposits along the east valley wall, taken during the July 2017 Linnédalen field work. Observations made on the annual field excursion indicate that the debris flow occurred within the past hydrological year of 2016-2017 (Retelle, personal communication). The intervalometer and meteorological data indicate that the majority of sediment transportation occurred on October 15th. A number of mass movement events were recorded on 10/15/16 across the Nordenskiöld peninsula and near the town of Longyearbyen, approximately 50km up-fjord from Linnédalen. The most notable was the massive debris flow (5000 m³) that occurred in Longyeardalen (Figure 4.2) (Christiansen et al., 2017).

In Longyearbyen, Christiansen et al. (2017) attributed the slope instability event to be caused by high intensity precipitation atop an active layer at its annual thickest, abnormally deep due to a recent increase in air temperatures. Similar factors, exacerbated by the additional precipitation Linnédalen receives in comparison to Longyeardalen (Figure 1.5), supports and explains the occurrence of the Linnédalen debris flow. This debris flow, high in energy and with a source along the eastern carbonate wall, would be represented in Linnévatnet by an idealized sedimentary signature consisting of corresponding significant peaks in grain size and calcium, values higher for the most proximal receiving tube D. This is not the case for the receiving tubes at mooring C and D where, the peaks in grain size and calcium are offset throughout. As seen in Figure 3.18, receiving tubes C3, C4, and the intervalometer had peaks in median grain size at 56.8, 85.3, and 82.5 microns, respectively. Also note that in the C3 receiving tube two phyllite clasts were found at the peak grain size depth (Figure 3.10). Receiving tubes D4 and D5 had peaks in medium grain size at 33.4 microns and 32.0 microns, respectively. Comparing the grain size results for the intervalometer and C receiving tubes to the D receiving tubes indicates significantly coarser grain sizes proximal to the Linnéelva source, indicating that the pulse of coarse sediment was most likely delivered from the main river delta. The decrease in energy from Linnéelva entering Linnévatnet causes the rapid settling of suspended sediment proximal to inflow, in this case amplified by the abnormally coarse sediment (Ashley et al., 1985). The

debris flow from the southeast valley wall occurred following the delivery of coarse grained sediment by Linnéelva, creating the gap in peaks between grain size and Ca. The peaks in Ca corresponds with a small grain size, indicating that the debris flow likely did not make it all the way to the lake. Rather, the Ca peak resulted from fine-grained Ca-rich sediment that was mobilized into Linnévatnet by continued rainfall atop the debris flow deposits. An additional source of fine-grained Ca-rich sediment is the entire eastern lake shore, where soliflucted sediment, enhanced by the deepened active layer, is reworked into Linnévatnet by wave-washing along the shoreline. (Figure 3.6). Soil saturation due to rainfall combined with warm temperatures creates an active layer susceptible to sourcing mass sedimentation events, explaining both the coarse sediment in Linnéelva and the debris flow (Favro and Lamoreaux, 2014). The antecedent catchment condition explain the presence and chronology of these major shoulder season sedimentation events.

The geochemical and grain size trends in receiving tubes H5 and G5 reflect the 10/15/16 event, recorded by the sediment differently due to spatiality from sediment sources. The sedimentary signature of interval 2 is defined by high values of grain size and Ca throughout with defined, corresponding peaks. Counts of K and Ti are distinctly lower throughout interval 2 and significant and trends in Zr are indistinguishable. The covariation and increase in grain size and Ca are explained by contributions made by the alluvial fan that extends into Linnévatnet from the east shore. The decrease in K and Ti suggest the lack of Linnéelva derived sediment, indicating sedimentation in these receiving tubes in interval 2 was dominated by sediment contributions from the alluvial fan.

The west sub-basins receiving tubes display different trends due to location and bathymetric restriction. The sedimentary signature of Interval 2 is roughly defined, with corresponding peaks in grain size and Ca in E, and lagged peaks in F3. No distinguishable trends are seen in K, Zr, or Ti. It is likely that the Linnéelva plume, plus contributions from the debris flow, entered the western sub-basin by wrapping around the north shore of the island.

Interval 3

Interval 3 consists of all sedimentation in the 2016-2017 hydrological year that occurred following, or was in the water column after 10/15/2016. The contact between intervals 2 and 3 is estimated; the intervalometer overfilled before sedimentation associated with this event had ceased. It is likely that the settling of sediment related to this event continued for many days after. The contact was taken to be shortly after the peak in Ca, constrained by the overfilling of the intervalometer correlating to this event, which provides a conservative estimate of interval 2.

Major shoulder season events in the 2016-2017 hydrological year caused unprecedented sedimentation in Linnévatnet, overfilling the majority of the receiving tubes prior to interval 3. Only the C3, G5, E, and F3 traps record the signal of interval 3. Additional fall sedimentation is minor due to the decrease in temperature shortly after interval 2, which immobilizes sediment. Interval 3 consists of minor fall sedimentation and continuing settling through the winter, in addition to nival contributions atop the receiving tube in the spring. Due to the lack of receiving tubes recording interval 3 and the varied special distribution of the ones that did, no conclusive geochemical and grain size signature can be associated with this interval.

Figure 4.1: Image of the southeast corner of Linnévatnet showing the location of the debris flow, moorings C and D, and images taken in the field in July 2017 (Photos: Mike Retelle)

Figure 4.2: Image of the October 15th debris flow in Longyeardalen. (Christiansen et al., 2017)

Comparison of Annual Sediment Yield

Sedimentation in Linnévatnet in the 2016-2017 year was anomalously heavy, overfilling the majority of the receiving tubes, with a number overfilled well into the funnel. The majority of sedimentation occurred in the fall, continuing the recent trend of high-Arctic catchment sedimentation being dominated by “shoulder season” rain events (Nowak and Hodson, 2013). This year’s results follows the work of Retelle and others in Linnévatnet since 2004, which has indicated that sedimentation in 6 out of the 7 past hydrological years have been dominated by shoulder season storms. Figure 4.3 shows a stack of mean grain size plots for the basal trap in mooring C from 2005-2017, with the dominant mode of sediment delivery for each year annotated. Note that sedimentation from 2005-2010 and 2012 was dominated by the nival pulse, while in 2011 and 2013-2017 the majority of sedimentation was the result of shoulder season storms. In those years dominated by late season events, as much as 70% of the annual sedimentation occurred in the shoulder season. Percentage of shoulder season contribution for the 2016-2017 hydrological year is estimated due to the intervalometer being overfilled. The grain size of sediment associated with the October 15th storm was abnormally coarse, with a maximum of 130 microns, compared to 38 microns, the largest previously documented grain size in the basal C trap. The phyllite fragments found in the subsampling of C3, long axes 5 and 7 mm, are more than an order of magnitude larger than any particle size plotted in Figure 4.3. This highlights the abnormality of the catchment conditions during that time. The upward trend in Figure 4.3 shows the transitioning of the dominant sedimentary process from nival pulse to shoulder season dominated.

The recent work of Nowak and Hodson (2013) and Schiefer et al., (2017) support the occurrence of a changing hydrological regime in high-Arctic proglacial lakes, reflected by a change in sedimentation as a result of anomalous meteorological conditions. Nowak and Hodson considered climate change’s influence on the hydrology of high-Arctic catchments, and found changes most notable in the last 10 years, with warmer and wetter winters, effects most prominent in the fall shoulder season. Scheifler et al. (2017) examined sediment yield in Linnévatnet on numerous temporal scales using varve and receiving tube records, as well as recent monitoring of catchment conditions. Changes in sedimentation rates were not seen through the Medieval Warm Period and the Little Ice age, and dropped by three times into the mid-Holocene, change associated with smaller glaciers. Sedimentation rates were higher in the 20th century, increasing steeply in mean yield from 240 to 425 Mg km⁻² yr⁻¹. Annual sediment yields for 2004-2010 were variable from 294-1330 Mg km⁻² yr⁻¹. Schiefer et al. (2017) attributed increases in sedimentation occurring since the mid-21st century to be positively related to temperate and precipitation, with high seasonal, daily and hour variability in 2010-2016. The 2016-2017 sediment yield data was not available for Schiefer et al. (2017), however the additional data in Figure 4.3 firmly continues a trend of an increase in sediment yield over the past 7 years. Continuing the study of sedimentation and catchment conditions in Linnédalen will allow for the identification of the annual dominant sedimentary process, highlighting changes in the high-arctic hydrological regime.

Figure 4.3: Grain size stack for basal mooring C4 for '05-'17 sedimentation. Depth is annotated by calendar year, and dominant mode of sediment transport is annotated by hydrological year. Additional depth has been added in '16-'17 due to overfilling of the sediment trap.

Chapter 5 Conclusions

The annual sediment yield in Linnévatnet for the 2016-2017 hydrological year was dominated by sedimentation associated with a shoulder season storm occurring on October 14-15, 2016.

During this 2 day period 82.6 mm of rain fell, causing a flood of Linnéelva, which delivered sediment an order of magnitude coarser than recorded in the past 13 years. This storm overfilled the intervalometer sediment trap unit, delivering at least 81 mm of sediment which correlates to 56% of the sediment in the intervalometer receiving tube.

A major debris flow during the storm originated on the southeast valley wall and nearly reached the lake shore. Fine grained Ca-rich sediment was reworked into the lake by stream and wave action.

Sediment quantity delivered from fall 2016 to summer 2017 was significantly greater than recorded in the past 13 years, with the majority of the sediment traps overfilled into the funnel. Late season rain storms have been the dominant mode of sediment transport and deposition in 6 of the 7 past years.

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