Lacustrine Records of Holocene Climate History and Human-Driven Landscape Evolution in the Lofoten Islands, Norway

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Lacustrine Records of Holocene Climate History and Human-Driven Landscape Evolution in the Lofoten Islands, Norway

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science in Environmental Geology from The College of William and Mary

by

Genevieve Pugsley

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# Table of Contents

List of Figures .................................................................................................................. 3  
List of Tables ................................................................................................................... 3  
Abstract .............................................................................................................................. 4  
Introduction ....................................................................................................................... 6  
  Holocene Climate in the North Atlantic ............................................................................. 6  
  Regional Background ....................................................................................................... 9  
  This Study ....................................................................................................................... 11  
  Study Sites ..................................................................................................................... 13  
Methods ............................................................................................................................. 15  
  Sediment Core Collection .............................................................................................. 15  
  Chronology ...................................................................................................................... 15  
  Physical Sedimentology and Organic-Matter Properties ............................................. 16  
  X-Ray Fluorescence and X-Radiography ...................................................................... 17  
Results .................................................................................................................................. 20  
  Lauvdalsvatnet ................................................................................................................ 20  
    Lithostratigraphy .......................................................................................................... 20  
    Physical Sedimentology .............................................................................................. 24  
    Organic-Matter Properties ........................................................................................... 26  
    X-Ray Fluorescence and Principal Component Analysis ........................................... 28  
  Ostadvatnet .................................................................................................................... 31  
    Lithostratigraphy .......................................................................................................... 31  
    Physical Sedimentology and Organic-Matter Properties ........................................... 33  
Discussion .......................................................................................................................... 35  
  Interpreting Lake Sediment Records ............................................................................. 35  
    Clastic Sedimentation Indicators .................................................................................. 35  
    Effects of Weathering on Sediment Properties ......................................................... 36  
    Interpreting Organic-Matter Properties ....................................................................... 39  
    Seasonal Influences on Paleoclimate Records ............................................................. 40  
  Holocene Climate History in the Lofoten Islands ............................................................. 41  
  Anthropogenic Environmental Change on Vestvågøy .................................................... 48  
  Future Directions .............................................................................................................. 49  
Conclusions ....................................................................................................................... 52  
Acknowledgements ............................................................................................................ 54  
References .......................................................................................................................... 55
List of Figures

Figure 1. Holocene insolation forcing and climatic response ........................................... 8
Figure 2. North Atlantic region and Lofoten Islands map ................................................. 12
Figure 3. Vestvågøy location figure .................................................................................. 14
Figure 4. X-ray to dry bulk density calibration .................................................................... 18
Figure 5. X-ray derived and laboratory-measured dry bulk density comparison .......... 19
Figure 6. X-ray derived dry bulk density record ................................................................. 19
Figure 7. Correlating depth in cores LVP-01-17 and LVD-01-17 .................................. 21
Figure 8. Lauvdalsvatnet lithostratigraphy ....................................................................... 22
Figure 9. Lauvdalsvatnet physical sedimentology ............................................................... 25
Figure 10. Lauvdalsvatnet organic-matter properties ......................................................... 27
Figure 11. Lauvdalsvatnet Principal Component and XRF Data ....................................... 30
Figure 12. Ostadvatnet lithostratigraphy ........................................................................... 32
Figure 13. Ostadvatnet physical sedimentology and organic-matter properties .......... 34
Figure 14. Summarized Lauvdalsvatnet data and interpretations ..................................... 42
Figure 15. Enhanced runoff in both lake catchments c. 3.8-2.8 ka ................................ 46
Figure 16. Yttrium abundance, climate and primary production ..................................... 51

List of Tables

Table 1. Radiocarbon Dating Information for the Lauvdalsvatnet Record .................... 23
Table 2. Correlations and PC1 Factor Loadings for Common Detrital Elements .......... 29
Table 3. Radiocarbon Dating Information for Core OSD-02-17 ................................. 32
Abstract

Lake sediments are useful paleoenvironmental archives; however their sensitivity to change depends on lake and catchment-specific characteristics. Here I present analyses of lacustrine records from two contrasting lakes on Vestvågøy in the Lofoten Islands, Norway to investigate regional responses to Holocene climate changes and human-driven landscape evolution. Sediment cores spanning the last c. 7 kyr were collected from Lauvdalsvatnet, a small lake (~0.17 km²) with a steep-sided catchment and large catchment-to-lake-area ratio (~18.8), and Ostadvatnet, a larger lake (~1.2 km²) with a smaller catchment-to-lake-area ratio (~5.2) and lower slope catchment. Sediment analyses included magnetic susceptibility, organic-matter content, bulk density, biogenic silica, CNS elemental analysis, x-radiography and scanning X-ray fluorescence. Chronologies are based on radiocarbon dating of terrestrial macrofossils. In the Lauvdalsvatnet record, which is finely laminated and displays high-frequency variability in all sediment properties throughout, clastic sedimentation indicators increase c. 5.5 ka, and decline c. 2.8 ka. Biogenic silica values abruptly decline c. 3.8 ka. During the late Holocene, a large peak then abrupt, lasting decline in organic-matter content occurs c. 1.9 ka, followed by fluctuations in magnetic susceptibility and increased sedimentation rates starting c. 0.5 ka. In the Ostadvatnet record, C/N values are heightened from c. 3.8-2.8 ka, synchronous with peaks in detrital sedimentation indicators in Lauvdalsvatnet. In the late Holocene portion of the Ostadvatnet record, high-amplitude fluctuations in organic-matter concentration begin c. 2.5 ka, followed by decreasing C/N values and increasing magnetic susceptibility since c. 1.9 ka.

I attribute changes in Lauvdalsvatnet sediment characteristics during the mid to late Holocene to changes in precipitation and weathering patterns c. 5.5 and 2.8 ka, and decreasing temperatures beginning c. 3.7 ka associated with regional termination of the Holocene Thermal Maximum. Ostadvatnet was less sensitive to mid-Holocene climate
changes, likely due its lower catchment-to-lake-area ratio and the lower slope of its catchment. Both lakes record changes in sediment properties after c. 2.5 ka, which are likely related to the onset of local agriculture and early human population expansion. These results have implications for understanding when and how climate in the Lofoten region responded to past global changes, including during the Holocene thermal maximum and neoglacial transition. They also suggest that onset of agriculture in the central corridor of Vestvågøy c. 2.5 ka preceded settlement in at least one peripheral valley, improving understanding of early human-landscape interactions.
Introduction

Holocene Climate in the North Atlantic Region

Paleoclimate studies aim to quantify how climate systems responded to external forcings in the past and to identify drivers of climate variability. Over multi-millennial timescales, insolation fluctuations due to changes in Earth’s orbit around the sun are the primary driver of shifting climate patterns. Since c. 700 ka, global climate has fluctuated between cold glacial and warm interglacial climate states with 100,000 year periodicity, likely due to interactions between the Earth’s eccentricity cycle and global ice sheet mass balance (Abe-Ouchi et al., 2013). During the Holocene, from c. 12 ka to the Industrial Revolution, global climate changes were driven primarily by precessional changes, with the period of greatest warmth, termed the Holocene Thermal Maximum, corresponding to, or lagging close behind, the period of greatest Northern Hemisphere summer insolation (Bradley, 2003; Marcott et al., 2013; Fig. 1). North Atlantic sea surface temperatures reconstructed using alkenone- and diatom-based proxies positively correlate with Northern Hemisphere summer insolation over the last 10,000 years (Fig. 1; Calvo et al., 2002; Anderson et al., 2004; Marcott et al., 2013), demonstrating that higher temperatures in high northern latitudes generally correspond with greater insolation forcing.

Although multi-millennial-scale climate trends correspond with insolation, shorter periods of warming and cooling, abrupt changes over decadal to centennial scales, and regional variations are influenced by internal feedbacks and other external forcing mechanisms. Temperatures globally and in the North Atlantic region generally correlate with summer insolation through time; however, sea surface and site-specific temperatures display considerably more variability than insolation trends (Fig. 1; Calvo et al., 2002; Marcott et al., 2013), and may be influenced by other forcing mechanisms such as variable solar strength and volcanic activity. A mid-late Holocene transition from warmer
to cooler conditions is recorded in paleoclimate records worldwide, and also demonstrates considerable spatiotemporal variability. In the high latitudes of the North Atlantic region, this transition generally corresponds to a shift from warm, dry conditions to cool, moist conditions. Termination of the Holocene Thermal Maximum and onset of mid to late Holocene cooling occurred asynchronously in different regions of the high northern latitudes over a period spanning c. 5 kyr (Kaufman et al., 2004). Understanding factors that influenced regional variability during past climate changes is vital for predicting how Earth’s climate systems may respond to anthropogenic forcings in the future.

Numerous paleoclimate studies have focused on the North Atlantic region, due to connections between climate systems in the high northern latitudes and diverse global climate phenomena. North Atlantic Ocean thermohaline circulation is a crucial element of the Atlantic Meridional Overturning Circulation (AMOC), which is in turn a major driver of global climate variability. Ocean circulation is responsible for global-scale heat transfer from the equator to the poles; thus changes to deep water formation in the AMOC have far-reaching impacts on global climate patterns. Paleoclimate studies have tied variability in diverse climate phenomena to changes in AMOC strength, including African and Asian monsoon precipitation (Chang et al., 2008; Sun et al., 2012), El Niño Southern Oscillation (ENSO) variability (Timmerman et al., 2007), and Pacific Ocean upwelling and productivity (Delworth et al., 2008). Some abrupt global climate changes, such as rapid cooling at the beginning of the Younger Dryas event approximately 12.9 ka, were linked to slowdowns of North Atlantic deep water formation and global ocean circulation (Goslar, 1995). Therefore, detailed studies of temporal and spatial patterns in North Atlantic climate help explain variability in Northern Hemisphere and global climate through time.
Figure 1. (A) Holocene Insolation at 60° N latitude (Berger & Loutre, 1991). (B) Global Holocene temperature anomaly relative to AD 1961-1990 mean based on analyses of 73 compiled records (Marcott et al., 2013). (C) Alkenone proxy record of North Atlantic sea surface temperatures at coring site MD95-2011, 67°N, 7.6°E, (Calvo et al., 2002; Marcott et al., 2013).
Regional Background

The Lofoten Islands in northern Norway are an optimal site for paleoenvironmental investigations due to their connectivity to North Atlantic climate systems. The archipelago is located at 68°N latitude in northwestern Norway, separated from the mainland by Vestfjorden (Fig. 2). Despite their high latitude location, the Lofoten Islands experience a mild maritime climate, due to northward heat transfer by the Norwegian Atlantic Current. Proximity to the Norwegian Current, a component of the larger North Atlantic Current ocean circulation system, increases the sensitivity of climate archives from the Lofoten region to North Atlantic and global climate perturbations (Fig. 2). Previous studies have identified associations between climate changes inferred from variability in Lofoten lacustrine sediment characteristics and nearby marine sediment records (Balascio & Bradley, 2012), indicating regional sensitivity to ocean circulation and temperatures. Lofoten’s climate is also sensitive to changes in North Atlantic atmospheric circulation, since the North Atlantic Oscillation (NAO) influences annual winter precipitation and temperature conditions over northern Europe. The NAO is defined by the strength of the sea level atmospheric pressure gradient between the Icelandic low pressure zone and Azores high pressure zone. A positive NAO state (indicating a strong pressure gradient) enhances the strength of westerlies, which deliver moisture and precipitation to northern Europe, including the Lofoten Islands. Additionally, low-lying lakes and bogs in Lofoten contain records of regional sea level fluctuations during the Holocene (Balascio, 2011), and some lakes are sensitive to changes in glacial extent (Nielson et al., 2016). These characteristics make the Lofoten Islands an ideal site for studies of paleoclimate and paleoenvironmental conditions.

Previous investigations of Holocene climate variability in Lofoten identified a
period of relative climate stability, with warmer summer temperatures than today and relatively dry conditions from approximately 8-4 ka. The period from approximately 4 ka to the present was characterized by a general cooling trend and wetter conditions (Nichols et al., 2009; Balascio & Bradley, 2011). Constraining the timing and nature of these environmental changes could improve understanding of how the regional climate and landscape of northern Norway responded to North Atlantic climate variability in the past.

In addition to natural climate variability, human activities have impacted landscapes in the Lofoten Islands over at least the past several thousand years (Balascio & Wickler, 2018). Humans have occupied northern Norway since at least 11.5 ka, and Lofoten since at least the late Stone Age c. 5.5 ka. The first attempts at agriculture in Lofoten occurred as early as the late Stone Age, and there is evidence for definitive establishment of agricultural practices by c. 2.25-2.5 ka (Johansen & Vorren, 1986; D’Anjou et al., 2012). During the Viking Age from 0.9-1.15 ka, the Lofoten region and particularly the island Vestvågøya, was a center of power and trade controlled by Viking chieftains. Abundant cod fisheries west of Lofoten provided a major resource for the Vikings, and cod stock has been continually utilized as a commercialized commodity since that time (Balascio & Wickler, 2018). This long, rich history of human-environment interaction has influenced landscape evolution in the Lofoten Islands. For example, early agricultural activity likely involved slash and burn land clearance and cultivation practices (Sjögren & Arntzen, 2013), and affected changes in denudation rates and ecological regimes. These landscape transformations leave a signature on the sediment records of adjacent lakes. Human- and livestock- specific molecular biomarkers preserved in lake sediments can also provide indications about presence and size of local human populations within lake catchments (D’Anjou et al., 2012). Examination of these records can inform estimates of when people settled at different
sites in Lofoten, and improve understanding of human impacts on the landscape and lake sedimentation, chemistry and ecology. Integrations of paleoenvironmental reconstructions and archaeological or historic data contribute to knowledge of not only past anthropogenic environmental change, but also the influence of past climate variability on the course of human histories.

This Study

The aim of this project is to examine how the regional climate of the Lofoten Islands has responded to geographically large-scale North Atlantic climate fluctuations through the mid to late Holocene. Lake sediment cores can provide high resolution records of physical sedimentology, geochemical cycling and ecological change that reflect changing environmental conditions. This study presents magnetic susceptibility (MS), bulk density, bulk percent organic matter (OM), bulk percent organic carbon (OC) and nitrogen (N), biogenic silica (BiS), mass accumulation rate (MAR), organic-matter flux (OM flux), x-radiograph greyscale data, and XRF-derived elemental abundances and ratios from three lake sediment cores. These data provide high-resolution records of changing detrital inputs, geochemical processes within the lake catchment and lake productivity through time. My findings contribute to understanding of spatio-temporal variability in North Atlantic climate during the Holocene and reveal possible human impacts on landscape evolution in the Lofoten Islands since the pre-Viking Age.
Figure 2. (Bottom Panel) the location of the Lofoten Islands in the context of broader North Atlantic geography. The arrow depicts the approximate course of the Norwegian Atlantic Current (Jessen et al., 2008). (A) a close up of the Lofoten Islands. (B) Lakes Ostadvatnet and Lauvdalsvatnet on Vestvågøy. Map imagery from GeoMapApp, Norgeskart and Google Earth.
**Study Sites**

For this study, I compare sediment records from two nearby but contrasting lake systems on the island Vestvågøy in the Lofoten Islands (Fig. 2b, Fig. 3). Lauvdalsvatnet (Fig. 2b, Fig. 3) is located in a glacially carved cirque at an elevation of approximately 55 meters above sea level, and has a relatively small, steep-sided catchment, with a mean catchment slope of ~16°. The catchment area is 3.2 km², and the lake surface area is 0.17 km², meaning the ratio of catchment to lake area is 18.8. The Lauvdalsvatnet catchment straddles the contact between mangerite and amphibolite bedrock units (Geologic Survey of Norway, 2018), which are likely the primary source of allochthonous clastic sediment for the lake. Lauvdalsvatnet is fed by streams with headwaters on the steep hillslopes of the catchment and from smaller ponds upslope to the south. Landslides in the catchment may also deliver material to the lake and influence sediment availability. The lake drains to the north, and ultimately to Indrepollen, a sheltered estuarine embayment connected distally to the North Atlantic. I expect lake sedimentation at this site to be sensitive to changes in temperature and precipitation that might impact weathering and erosion rates, due to the steepness of the catchment and high catchment-to-lake-area ratio. Today, humans occupy and farm on the Lauvdalsvatnet catchment; however, the history of human usage and occupation in the valley is unknown.

Ostadvatnet (Fig. 2c, Fig. 3) is located in Vestvågøy’s broad central valley, which has been impacted by human settlement and agricultural activity since at least the beginning of the Viking Age c. 1.15 ka. Its catchment area is 6.2 km², with a mean catchment slope of 8°. The lake area is 1.2 km², meaning its ratio of catchment-to-lake-area is 5.2. Ostadvatnet is fed by a stream that flows from another, smaller lake to the north and drains southeast into another lake, Farstadvatnet, via streams. The Ostadvatnet outlet sits at an elevation of approximately 20 meters above sea level. Land clearance and agriculture activities have probably altered lake sedimentation in Ostadvatnet, and
comparison with the Lauvdalsvatnet record may provide indications about spatial extent of human occupancy and agriculture practices during the Viking Age.

Figure 3. (Top panel) The island Vestvågøy, with the catchments Ostadvatnet and Lauvdalsvatnet outlined; (Bottom left) The Lauvdalsvatnet catchment; (Bottom right) The Ostadvatnet catchment. Coring sites are denoted with red dots. Data from Terrengdata and GoogleEarthPro; Coordinate System: ETRS 1989 UTM Zone 33N; Projection: Transverse Mercator. Catchments were delineated using the ArcMap Spatial Analyst and Hydrology toolboxes.
Methods

Sediment Core Collection

Sediment cores were recovered in May 2017 from Lauvdalsvatnet and Ostadvatnet. We used a Garmin Fish Finder with Integrated GPS to determine the location of the deepest basin in each lake and record coring site locations. The surface of Lauvdalsvatnet was partially ice-covered at the time of core collection, and as a result we were only able to access approximately half the lake for bathymetric profiling and coring. A 2.21 m piston core (LVP-01-17) was collected from the deepest accessible point, with a water depth of 13 m, and split into two shorter sections of 1.185 m and 1.025 cm. In addition, a 40 cm gravity core was collected using a percussion coring device (LVD-01-17). A 1.328 m core with was collected from Ostadvatnet using a percussion corer (OSD-02-17). Following core collection, both cores were stored in a refrigerator at a temperature of 5 °C and analyzed at the College of William & Mary and the Lamont Doherty Earth Observatory.

Chronology

Plant macrofossils were picked from the Lauvdalsvatnet and Ostadvatnet cores and analyzed for radiocarbon content at the UC Irvine Keck Carbon Cycle Mass Spectrometer (UCIAMS) and the National Ocean Sciences Accelerator Mass Spectrometer (NOSAMS). Radiocarbon ages were converted to calendar ages on the Calib 7.1 online software using the IntCal 13 radiocarbon calibration (Stuiver et al., 2017). I constructed age-depth models in Microsoft Excel, using a fourth order polynomial for Lauvdalsvatnet and third order polynomial for Ostadvatnet. From this point forward, all reported ages will be in thousands of calendar years before present (i.e. ka), with “present” corresponding to the year 1950 AD.
Physical Sedimentology and Organic-Matter Properties

Magnetic susceptibility, bulk density and loss-on-ignition analyses were performed on both the Lauvdalsvatnet and Ostadvatnet cores. Magnetic susceptibility (MS) was measured at 0.5-cm resolution using a Bartington MS2E sensor, which measures the degree of magnetization a substance undergoes when exposed to an external magnetic field. Volumetric sampling of 1 cm$^3$ of sediment was performed at 1 cm resolution down the length of the cores. Samples were dried in an oven at 55 °C for approximately 48 hours. Bulk density was measured as the dry mass of the sediment samples. Samples were incinerated at 550 °C for 4 hours for the Ostadvatnet samples and 6 hours for the Lauvdalsvatnet samples. Bulk percent organic matter was calculated as loss-on-ignition (LOI) divided by initial dry mass of sediment. Sedimentation rate was calculated by the inverse of the derivative of the age-depth model. Mass accumulation rate (MAR; in g/yr cm$^2$) was calculated as dry bulk density multiplied by sedimentation rate. Organic-matter flux (OM flux; in g$^2$/yr cm$^2$) was calculated as MAR multiplied by LOI.

Percent organic carbon (OC) and nitrogen (N) across 1 cm intervals were analyzed at 5 cm resolution in OSD-02-17 using a vario MICRO cube CNS elemental analyzer. This instrument combusts sediment samples at high temperatures, and gases produced from the combustion adsorb to a temperature-programmed desorption column. During incremental heating steps, the gases are released from the column, and the instrument measures resulting concentrations of released sulfur, carbon and nitrogen gases based on conductance. All samples were freeze dried and homogenized prior to elemental analysis. Sulfanilamide standards of known composition were used to calibrate the instrument and conduct quality assurance checks during data collection.

LVP-01-17 was analyzed for bulk percentage of biogenic silica (BiS) across 1 cm intervals, sampled at 4 cm resolution. Following similar methodology to Mortloch &
Froelich (1989), 50-80 mg of bulk sample were digested in 5 ml of 30% hydrogen peroxide overnight to remove organic matter. No acid digestion of inorganic carbonates was conducted, because inorganic carbon content was expected to be negligible. Samples then sat in 40 mL of 10 % sodium carbonate for 5 hours in an oven at 80 °C, to extract biogenic silica. The supernatant solution was decanted, and later reacted with molybdate and metol solutions to dye the aqueous silica. After reacting for 12 hours, the solutions were analyzed for absorbance at 812 nm on an AquaMate Plus UV-VIS spectrophotometer (Mortlock & Froelich, 1989), along with several standards containing known concentrations of silica. Based on absorbance values for the standards, I calibrated absorbance to concentration of supernatant silica in ppm. Silica concentration was converted to bulk percentage of biogenic silica, based on the mass of the initial sediment samples and volume of sodium carbonate reacted with the samples.

X-Ray Fluorescence and X-Radiography

The Lauvdalsvatnet and Ostadvatnet cores were scanned using an ITRAX core scanner, which collects core photographs, x-radiographs and x-ray fluorescence (XRF) data, at the Lamont Doherty Earth Observatory. They were scanned at 0.2 cm resolution with a 12 second exposure time, 55 kV voltage and 50 mA current using a molybdenum tube. Grayscale values were extracted from the Lauvdalsvatnet x-radiograph imagery using Image J at approximately 0.02 cm resolution. I used SPSS statistics to perform Principle Component Analysis (PCA) on select XRF elemental data (Al, Si, Ca, K, Ti & Fe). Elements that are common constituents of abundant minerals were selected for PCA. PCA permits identification of variance common between multiple variables, and allows us to visualize trends across the density and XRF data. SPSS syntax used for PCA is provided in the electronic appendix.

I converted greyscale values from x-radiograph imagery of the Lauvdalsvatnet core to high resolution measurements of dry bulk density based on a calibration between
dry bulk density measured at 1 cm resolution and a 50-period (i.e. 1 cm) moving average of grayscale values centered at the same position as the dry bulk density measurements. Several outliers were removed to improve this calibration (Fig. 4). Accuracy of the grayscale to dry bulk density conversion may be tenuous, since the x-radiograph measured wet bulk density. Variability in sediment water content could cause variability in the strength of the relationship between grayscale values and dry bulk density. Mean error between laboratory-measured and 1-cm averaged greyscale-derived dry bulk density values was ~0.043 g/cm³. Visual inspection of the two data sets suggests that the calibration may obscure variability in low density intervals (Fig. 5).

Figure 4. Relationship between greyscale values and dry bulk density. Points illustrated in red were excluded from the calibration.
Figure 5. Dry bulk density measured by drying samples in the lab (shown in red), and values calculated from the greyscale to dry bulk density calibration equations (shown in black; using greyscale values averaged across 1-cm intervals). Density values are plotted on depth below the top of piston core LVP-01-17.

Figure 6. High resolution density data derived from x-radiograph scans of LVP-01-17 and the greyscale to dry bulk density calibration. Denser sediment appears darker on the X-ray imagery, and thus has lower greyscale values, as previously illustrated in Figure 4.
Results

Lauvdalsvatnet

Lithostratigraphy

Due to the nature of the piston core collection technique, the upper stratigraphy of the Lauvdalsvatnet record is missing from core LVP-01-17, necessitating correlation between the piston and a surface core to provide a complete record. Via visual inspection of magnetic susceptibility and XRF-derived elemental data, I infer that the top of piston core LVP-01-17 overlaps with gravity core LVD-01-17 at a depth of 20.4 cm on the gravity core (Fig. 7), although the piston core is somewhat compressed relative to the gravity core. Compression of the piston core may result in underestimated sedimentation rates for the upper intervals of LVP-01-17. Despite uncertainties introduced by utilizing two overlapping cores, impacts on long-term trends observed in the data should be negligible. Herein data reported on the composite depth scale from 0-20.4 cm is from the upper portion of LVD-01-17, and the portion from 20.4-240 cm is from LVP-01-17.

I have divided the Lauvdalsvatnet record into two units on the basis of visual inspection and sediment characteristics (Fig. 8). The bottom 20 cm (Unit A) consists of a sequence of light brown silt with macrofossil layers from 225-220 cm, followed by a fining upwards sequence of poorly sorted clay, sand and gravel from 238-225 cm, and finally a layer of light brown silt from 240-238 cm. The top 220 cm of Lauvdalsvatnet (Unit A), measured from the top of the gravity core, is composed of fine-grained muddy gyttja, with frequent light-colored clastic and black macrofossil-rich laminations. Unit B darkens upwards from 220-60 cm, and is slightly lighter in color from 0-60 cm. From this point forward, only data from Unit B will be reported, because Unit A is interpreted as an instantaneous or non-lacustrine deposit.
Figure 7. Illustration of the method used to determine the depth where gravity core LVD-01-17 overlaps with piston core LVP-01-17. Black dotted lines connect “events” in the titanium abundance data from each core I interpret to correspond to the same sedimentation event.
Figure 8. Core imagery for piston core LVP-01-17, as well as a simplified stratigraphic section. Mass accumulation rate, sedimentation rate and age model are also plotted as a function of depth below the modern lake floor (i.e. the top of gravity core LVD-01-17).
The chronology for the Lauvdalsvatnet record is based on four radiocarbon dates, with $2\sigma$ calendar age ranges of 90 to 250 years (Table 1; Fig. 8). The oldest dated macrofossil horizon places the upper section of Unit A at approximately 7.2 ka. An age-depth model was developed using a 4th-order polynomial, with a composite depth of 0 cm assumed to correspond to present day, i.e. –67 years BP (Fig. 8). Sedimentation rates derived from the age model suggest deposition rates increased from 0.15 mm/yr c. 7.2 ka to 0.4 mm/yr c. 3.5 ka, then decreased to 0.32 mm/yr c. 0.7 ka, and have since increased slightly into the modern. Mean sedimentation rate in Unit B is 0.32 mm/yr. The oldest dated macrofossil horizon places the upper section of Unit A at approximately 7.2 ka (Table 1, Fig. 8).

<table>
<thead>
<tr>
<th>Laboratory ID</th>
<th>Core ID</th>
<th>Composite depth (cm)</th>
<th>Radiocarbon Age (BP)</th>
<th>Std.</th>
<th>2σ calendar age range (BP)</th>
<th>Median calendar age (BP)</th>
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<td>41.9</td>
<td>1330</td>
<td>15</td>
<td>1190-1296</td>
<td>1281</td>
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<td>NOSAMS #147125 LVP-01-17</td>
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<td>3110</td>
<td>20</td>
<td>3252-3381</td>
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<td>4530</td>
<td>25</td>
<td>5054-5309</td>
<td>5154</td>
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<tr>
<td>NOSAMS #147127 LVP-01-17</td>
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<td>6280</td>
<td>25</td>
<td>7168-7259</td>
<td>7216</td>
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</table>
Magnetic susceptibility (MS) and dry bulk density are relatively high in Unit B, averaging $\sim 25 \times 10^{-5}$ SI units and $\sim 0.18$ g/cm$^3$, respectively. High frequency variability in MS and bulk density occur throughout the Lauvdalsvatnet record (Fig. 9), with MS varying between 0.6-53 SI units $\times 10^{-5}$, and bulk density varying between 0.13 and 0.53 g/cm$^3$ in Unit B. Mean-state MS and bulk density are relatively stable c. 7-5.4 ka, and both display high-frequency variability. After c. 5.4 ka, MS undergoes a stepped increase, and bulk density remains relatively similar to the previous time period. After 3.8 ka, there are a series of peaks in both MS and bulk density, followed by a decline in both at c. 2.9 ka. Large magnitude fluctuations in both occur from c. 1.8 ka to 0.5 ka. Since 0.5 ka, dry bulk density and MS have increased. MAR, a product of both sedimentation rates and dry bulk density, behaved similarly to sedimentation rates (Fig. 8), starting out low in the early mid-Holocene, plateauing between 5.4 and 2.8 ka, then declining until a slight increase in the last several hundred years. In this case, interpretations of MAR should only be made cautiously, due to low specificity of the presently available radiocarbon chronology.
Figure 9. Sedimentological characteristics, including magnetic susceptibility (MS) and dry bulk density of Lauvdalsvatnet sediments plotted on age. The bottom panel shows both high-resolution (.02 cm resolution) density data derived from grayscale values in light purple and laboratory measured values (1 cm resolution) in dark purple.
**Organic Matter Properties**

Throughout the Lauvdalsvatnet record, OM varied between roughly 20% and 35%, fluctuating frequently (Fig. 10). Mean OM values remained relatively constant from c. 7.2-4 ka, then increased steadily from c. 4-2 ka. An anomalous peak occurs c. 1.9 ka, with OM reaching 50%. Immediately following this peak, OM abruptly declines and shifts to a lower baseline for the remaining c. 1.9 ka of the record.

OM flux, a function of both MAR and OM, generally increases steadily from c. 7.2-4 ka, plateaus between 3-4 ka then declines until c. 0.5 BP, when it abruptly increases. It remains elevated from c. 0.5 ka to recently. Variability in OM flux is greatest between c. 5-2 ka, with slower sedimentation before and after corresponding with more gradual fluctuations.

Biogenic silica content fluctuated widely between ~4-8% throughout the Lauvdalsvatnet record (Fig. 10). There is a general increasing trend from c. 7.2-4.2 ka, followed by an abrupt decline and minimums between c. 3.8-3 ka, then a slight increase and relatively stable BSi from c. 3 ka to 0.6 ka. A period of low BiS values from 3-3.8 ka corresponds with previously noted heightened MS, bulk density and OM flux values.
Figure 10. Organic-matter characteristics for the composite Lauvdalsvatnet record, including BiS (top panel), OM flux (middle panel) and percent OM (bottom panel) plotted on age.
X-Ray Fluorescence data and Principal Component Analysis

Factor analysis, as well as examination of select elemental ratios and comparison with other sediment characteristics helped elucidate trends present in the XRF data. Principal component analysis (PCA) of select Lauvdalsvatnet Unit B elemental data (Al, Si, Ca, K, Ti, Fe) helped identify variance common to abundant constituents of clastic sediment derived from granitic bedrock. PCA was performed on both raw and counts-per-second (cps) normalized XRF elemental abundance datasets. A priori Kaiser-Meyer-Olkin tests of sampling adequacy (KMO =0.797 and KMO=0.805, respectively) and Bartlett’s Test for Sphericity (p<0.001) indicated the XRF dataset was well-suited for factor analysis. All variables were significantly correlated, with most correlation coefficients >0.5 between all variables except Al (Table 2), which may have been poorly detected during µXRF core scanning, based on the noisiness of the data. PCA identified first principal components (PC1) with eigenvalue=3.702 in the non-normalized analysis, and eigenvalue=3.741 in the cps-normalized analysis. The first principal components correlated closely (r=0.97) and explained approximately 62% of the total variance in each dataset. Factor loadings of each variable on PC1 (i.e. correlation coefficients between the factor and each variable) are shown in Table 2. All additional factors had eigenvalues below 1, and accounted for relatively small proportions of the remaining variance (<15%). PC1 and raw elemental data for Ti, K and Ca show particularly strong correspondence (Table 2; Fig. 11). Henceforth, only data from the CPS-normalized PC1 will be reported to avoid redundancy.

PC1 and Ti elemental abundance data both displayed high-frequency variability throughout the record (Fig. 11). There is a long-term decreasing trend in PC1 from c. 7.2-2 ka, including two abrupt steps down c. 5.5 and 3 ka, synchronous with changes in MS and Ti/MS. A slight increase and several large-magnitude fluctuations occurred from c. 1.8-0.5 ka. A One-Way Analysis of Variance (ANOVA) indicated a significant difference
between Unit B PC1 values from c. 7-5.5 ka, c. 5.5-3 ka, c. 3-1.8 ka and c. 1.8-0.5 ka (F=117.5, p<0.001), and a post hoc Tukey test indicated significant differences between values from all four time intervals. Fe/Ti is negatively correlated with cps-normalized PC1 values (r= -0.63) and Ti (r= -0.79). It remained relatively stable from 7.2-3 ka, and shows an overall increasing trend from 3-0.5 ka, with low values at c. 1.3 ka, 1.0 ka and 700 BP. Ti/MS and Fe/MS are relatively high from c. 7-5.5 ka, then abruptly shift to a lower mean state until c. 3 ka, when they increase to a new, slightly higher mean state. One-Way ANOVA indicates statistically significant differences in Ti/MS values between these three intervals (F=27.2, p<0.0001), with the period from 3-5.5 ka having significantly lower values than the rest of the time series. After 1.8 ka, Ti/MS displays abrupt and large magnitude fluctuations.

**Table 2. Correlations and PC1 Factor Loadings for Common Detrital Elements**

<table>
<thead>
<tr>
<th>Non-normalized</th>
<th>Al</th>
<th>Si</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Al</td>
<td>1.000</td>
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<tr>
<td>Si</td>
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<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>0.181</td>
<td>0.571</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>0.302</td>
<td>0.660</td>
<td>0.778</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>0.222</td>
<td>0.557</td>
<td>0.868</td>
<td>0.851</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>0.198</td>
<td>0.443</td>
<td>0.606</td>
<td>0.464</td>
<td>0.620</td>
<td>1.000</td>
</tr>
<tr>
<td>PC1 Factor Loadings</td>
<td>0.367</td>
<td>0.756</td>
<td>0.902</td>
<td>0.900</td>
<td>0.924</td>
<td>0.720</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CPS-normalized</th>
<th>Al</th>
<th>Si</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
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<tr>
<td>Si</td>
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<td>1.000</td>
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</tr>
<tr>
<td>K</td>
<td>0.192</td>
<td>0.566</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>0.303</td>
<td>0.655</td>
<td>0.790</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>0.223</td>
<td>0.548</td>
<td>0.872</td>
<td>0.859</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>0.184</td>
<td>0.425</td>
<td>0.648</td>
<td>0.502</td>
<td>0.655</td>
<td>1.000</td>
</tr>
<tr>
<td>PC1 Factor Loadings</td>
<td>0.361</td>
<td>0.740</td>
<td>0.910</td>
<td>0.906</td>
<td>0.928</td>
<td>0.742</td>
</tr>
</tbody>
</table>
Figure 11. (Top panel) Principal Component 1 (PC1), Titanium abundance (Ti) plotted on age. (Lower Panel) Iron to Titanium abundance ratio (Fe/Ti) and Ti/MS plotted on age. Ti/MS and Ti reported from 0.5 ka-Present is derived from z-scored LVD-01-17 data, and should be interpreted with caution.
Ostadvatnet

Lithostratigraphy

The entire 131 cm length of OSD-02-17 consists of a single homogenous lithostratigraphic unit of fine-grained muddy gyttja, and contains occasional lighter colored and dark brown to black macrofossil-rich layers. The Ostadvatnet chronology (Table 4; Fig. 12) is based on 3 radiocarbon dates, with $2\sigma$ calendar age range widths between 90 to 340 years, and greater uncertainties deeper in the core. I constructed an age-depth model using a 4th-order polynomial, assuming 0 cm depth corresponds to present day, i.e. ~67 years BP (Table 3, Fig. 12). Age estimates for depths in the core greater than 112 cm are extrapolated from the age model polynomial, and have a high degree of uncertainty. Extrapolation places the basal age of the Ostadvatnet record at c. 7 ka, but it is possible (and perhaps likely) that the basal age is younger than estimated.

Sedimentation rates derived from the Ostadvatnet age model suggest increasing accumulation rates and MAR from 130 to 62 cm (c. 7-3.5 ka; Fig. 12), and declining sedimentation rates and MAR from 62 to 0 cm (c. 3.5 ka to present). Accumulation rates vary from 0.07 to 0.056 mm/yr, with a mean of 0.27 mm/yr. MAR is less variable in Ostadvatnet than Lauvdalsvatnet, due to relatively homogenous bulk density throughout OSD-02-17.
### Table 3: Radiocarbon Dating Information for Core OSD-02-17

<table>
<thead>
<tr>
<th>Laboratory ID</th>
<th>Core ID</th>
<th>Mean depth (cm)</th>
<th>Radiocarbon Age (BP)</th>
<th>Std.</th>
<th>2σ calendar age range (BP)</th>
<th>Median calendar age (BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOSAMS #147128</td>
<td>OSD-02-17</td>
<td>23.25</td>
<td>2010</td>
<td>15</td>
<td>1903-1996</td>
<td>1963</td>
</tr>
<tr>
<td>UCIAMS #191994</td>
<td>OSD-02-17</td>
<td>52</td>
<td>2890</td>
<td>15</td>
<td>2962-3067</td>
<td>3018</td>
</tr>
<tr>
<td>UCIAMS #191993</td>
<td>OSD-02-17</td>
<td>111.75</td>
<td>4425</td>
<td>20</td>
<td>4878-5213</td>
<td>5005</td>
</tr>
</tbody>
</table>

Figure 12. Mass accumulation rate, sedimentation rate and calendar age-depth model for OSD-02-17 plotted as a function of depth below the modern lake floor. Error bars on calendar ages show the 95% confidence interval.
Physical Sedimentology and Organic-Matter Properties

Overall, sedimentological and organic-matter properties of sediments from the Ostadvatnet record display lower frequency and magnitude fluctuations than the Lauvdalsvatnet record (Fig. 13). Magnetic susceptibility and dry bulk density are significantly lower than values for Lauvdalsvatnet, and vary little, with only small fluctuations from c. 7-1.7 ka. Higher frequency variability occurs synchronously with higher sedimentation rates c. 4-2.7 ka, along with increases in sedimentation and mass accumulation rates. Starting c. 1.7 ka, there is an increasing trend in magnetic susceptibility and dry bulk density that continues into the modern.

Organic-matter content is relatively stable from c. 6.5-3 ka. OM and OC decline from 3-2.5 ka, then abruptly increase and experience large magnitude fluctuations from 2.5 ka to present. C/N ratios display a gradual declining trend from c. 7 to 1 ka. From c. 2.7-3.7 ka, there was a period of slightly elevated values and higher frequency variability. C/N declined dramatically from 1 ka to 250 BP, followed by one recent peak in the last several hundred years BP.
Figure 13. Sedimentological and organic-matter properties of the Ostadvatnet record, including OM, OC, MS, C/N, MAR and OM flux, plotted on time. OC and OM are plotted together on the bottom panel and MAR & OM flux are plotted together on the top panel.
**Discussion**

*Interpreting Lacustrine Sediment Records*

Interpreting lacustrine records can be challenging, as lake sediment characteristics depend on interactions among a diverse suite of processes operating on molecular up to landscape scales. Conditions created by interactions between bedrock geology, climate, weather, terrestrial and aquatic geochemistry and ecology, and both natural and human-driven geomorphic processes determine the physical and chemical characteristics of lake sediment. Here I will discuss proxies utilized in this study, and some uncertainties and assumptions associated with my interpretations of their significance.

**Clastic Sedimentation Indicators**

For this study, I measured a variety of sediment properties associated with clastic sedimentation, including titanium abundance (Ti), magnetic susceptibility (MS), mass accumulation rate (MAR), the first principal component extracted from XRF data (PC1), and dry bulk density. XRF data provide high-resolution non-quantitative information about changes in relative abundance of different elements with depth. Ti can serve as a useful proxy for catchment derived minerogenic input into a lake, since titanium is a biologically conserved element within the water column and chemically inert (Croudace & Rothwell, 2015). Magnetic susceptibility (MS) in lake sediments is also traditionally interpreted to reflect influx of allochthonous clastic sediment to a lake basin (Thompson et al., 1975). Ferrimagnetic minerals (i.e. magnetite, maghemite, titanomagnetite) have high positive values, paramagnetic minerals (i.e. ilmenite, biotite, pyrite, siderite) have weakly positive values and diamagnetic materials (i.e. quartz, calcite, water) have weakly negative MS values (Hatfield & Stoner, 2013). MS is probably predominantly controlled by allochthonous sediment influx in these records, evident in the positive relationship between MS values and dry bulk density in Lauvdalsvatnet Unit B (Fig. 9; r =0.67). MS and OM are generally inversely related due to dilution of ferrimagnetic minerals by
organic matter, while MS, bulk density and Ti are typically positively correlated. There are however, several instances in the Lauvdalsvatnet and Ostadvatnet datasets when these expected relationships are absent, and even instances when trends in MS, PC1, Ti and bulk density diverge. There are several reasons why MS and OM values may not always covary in expected ways. Precipitation or runoff events that wash clastic material into a lake may also deliver terrestrial organic matter, resulting in a positive or variable relationship. Simultaneous influx of terrestrial vegetation may also cause a dilution effect, dampening the MS signal. For these reasons, it is important to consider concurrent trends and changes in other variables like OM when making interpretations about detrital input to lakes.

Effects of Weathering on Sediment Properties

Several instances of incoherence between detrital indicators Ti, MS, PC1 and dry bulk density in the Lauvdalsvatnet record are likely attributable to weathering and diagenetic effects. Despite typical application of MS as a straightforward indicator of terrigenous sediment input, weathering intensity and redox conditions within both a lake and its catchment can influence MS of sediments and soils (Feng & Johnson, 1995; Hilton & Lishman, 1985; Vigliotti et al., 2010; Hatfield & Stoner, 2013). The influence of biogeochemical processes may make MS a less reliable indicator of clastic sedimentation than bulk density, for example, which is not as heavily influenced by chemical alteration (Croudace & Rothwell, 2015). Ti and PC1 may also be vulnerable to diagenetic effects, due to the influence of weathering and soil development processes on elemental abundances. By comparing MS and select elemental abundances, I hope to elucidate what processes control variability in sediment properties in the Lauvdalsvatnet record.

Examining ratios between select XRF elemental abundance data is useful for understanding the influence of geochemical alteration on sediment from Lauvdalsvatnet.
The Fe/Ti elemental abundance ratio reflects geochemical alteration of sediments due to iron reducing processes. Both iron and titanium are relatively insoluble components of rock forming minerals; in the absence of alteration and assuming no change in sediment provenance, I expect them to display strong covariance. Since titanium is insensitive to changing redox conditions, it is minimally vulnerable to chemical dissolution processes. In contrast, iron and some other elements such as manganese are redox sensitive and biologically important (Croudace & Rothwell, 2015). Dividing Fe by Ti enables isolation of variability in sediment composition due to biologically-mediated reduction and dissolution processes. It is important to note that in-situ weathering processes that do not result in mobilization and transport of ions in aqueous solution will not alter Fe content; other proxies such as Fe/MS and Ti/MS may be useful for understanding in-situ geochemical alteration and will be discussed later.

The Fe/Ti ratio is typically applied to interpret changing redox conditions within lakes, because Fe is commonly reduced to its soluble form under low-oxygen conditions. Redox-sensitive elemental ratios such as Fe/Ti may be climate sensitive if changing temperature or precipitation conditions result in changes to lake stratification, productivity, frequency of lake turnover, or other processes that influence oxygenation (Aufgebauer et al., 2012; Meyers & Ishiwatari, 1995). If interpreted as a lake redox state indicator, higher Fe/Ti should indicate more oxygenated conditions, due to greater favorability of oxidized and insoluble ferric iron (III). When these ratios are low, meaning a relative depletion in Fe, we can infer that reducing conditions in the lake favor reduction to ferrous iron (II) and mobilization. Alternately, variability in redox-sensitive ratios could reflect sediment alteration prior to deposition related to human or climate-driven landscape changes. For example, mobilized ferrous iron from anoxic groundwater or peat bogs might be transported into the relatively oxygenated lake and precipitate as iron oxides (Ng and King, 2004). I favor the latter interpretation for the majority of the
Lauvdalsvatnet record, because Fe/Ti is lower in Unit A and high density clastic layers in
Unit B (which presumably have undergone less alteration prior to deposition; \( r = -0.63 \)
between dry bulk density and Fe/Ti in Unit B), compared with more organic-rich layers,
suggesting a diagenetic enrichment effect. If processes internal to Lauvdalsvatnet were
altering Fe/Ti ratios, I would expect depletion rather than enrichment of Fe/Ti relative to
source material. Fe/Ti enrichment in Lauvdalsvatnet sediments may be due to reducing
processes in the catchment mobilizing redox-sensitive elements into ground and surface
waters.

Comparison of MS values and select XRF data is useful for understanding the
influence of in-situ geochemical alteration on sediment from Lauvdalsvatnet. Throughout
the Lauvdalsvatnet record, MS and Fe/Ti are inversely correlated (\( r = -0.601 \)). One possible
explanation for the relationship between MS and Fe/Ti variability could be the influence
of weathering processes that result in dissolution or conversion of ferrimagnetic minerals
to antiferromagnetic iron compounds. Magnetite, \( \text{Fe}_3\text{O}_4 \), necessarily contains both ferrous
iron (II) and ferric iron (III) to achieve a neutral charge balance. Under anaerobic
conditions, some bacteria utilize Fe (III) from magnetite as an electron acceptor in
cellular respiration processes, converting magnetite into antiferromagnetic minerals
(Kostka, 1995; Hatfield & Stoner, 2013), and converting ferric iron (III) to the more
soluble ferrous (II) form. Oxidative weathering processes during soil formation can also
result in alteration of ferrimagnetic minerals to antiferromagnetic oxides such as hematite
and goethite, resulting in reduced magnetism relative to source material (Maher, 1998;
Hatfield & Stoner, 2013). This relationship only holds true in certain settings like the
Lauvdalsvatnet catchment, with ready supplies of fresh bedrock-derived detrital material;
later stages of development tend to enhance rather than deplete soil magnetism (Kostka,
1995). Chemical alteration of magnetite or titanomagnetite to non-magnetic minerals
during weathering or soil formation processes results in reduced magnetic susceptibility
without necessarily changing Fe and Ti content, increasing Fe/MS and Ti/MS. Fe/MS has previously been utilized as a proxy for reductive diagenetic alteration of iron minerals in marine settings (Hepp et al., 2009). I propose that Ti/MS may also be a useful indicator for in-situ diagenetic alteration and weathering processes, since Ti is both a common impurity in magnetite and insensitive to Fe dissolution or precipitation effects. In most of the Lauvdalsvatnet record, Ti/MS and Fe/MS covary closely. When Fe/Ti begins increasing c. 3 ka, normalized Fe/MS becomes slightly elevated relative to normalized Ti/MS, likely due to iron enrichment (Fig. 14), indicating the usefulness of comparing MS to an inert element such as Ti.

Anaerobic conditions in the lake catchment could promote both magnetite reduction and iron reductive dissolution, resulting in enhanced Fe/MS and Fe/Ti in lake sediment relative to the original source rock; therefore positive correlations between Fe/MS, Ti/MS and Fe/Ti throughout most of the Lauvdalsvatnet record are unsurprising (see electronic appendix). At c. 1.8 ka, the relationship of Ti/MS and Fe/MS to Fe/Ti becomes inverse. This instance is incongruent with the assumption that Fe/Ti reflects input of aqueous redox-sensitive elements from the catchment and Ti/MS reflects chemical weathering of magnetite-containing clastic material prior to deposition. Instead, this inverse relationship suggests a eutrophication signature, with anaerobic conditions in the lake causing reductive dissolution of magnetite, elevating Fe/MS and Ti/MS while simultaneously leaching iron from the sediment and lowering Fe/Ti.

**Interpreting Environmental Change from Organic-Matter Properties**

The ratio of C/N is a useful proxy for identifying changes in organic matter source material. Cellulose-containing terrestrial vegetation is enriched in carbon relative to aquatic vegetation, so an increase in C/N indicates a relative increase in influx of terrestrial vegetation compared to aquatic vegetation (Kasper et al., 2013). Alternately, in some cases C/N can reflect changes in lake redox state. Anoxic conditions can result in
changing rates of organic-matter decomposition, lowering C/N ratios (Meyers & Ishiwatari, 1995; Aufgebauer et al., 2012). When interpreting the Ostadvatnet record, I am assuming variability in C/N primarily reflects changes in terrestrial sediment influx relative to aquatic vegetation.

Biogenic silica is a proxy for lake productivity over time, and may be influenced by changes in water temperature, light availability and nutrient availability (McKay et al., 2008). BiS is also vulnerable to dilution effects. For the purposes of this investigation, I assume changes in lake productivity drive BiS concentration trends. This assumption is probably relatively sound, because although in the short term, peaks in clastic sedimentation indicators like MS and PC1 correspond with minimums in BiS, sustained reduced BiS in the late Holocene is accompanied by reduced values in clastic sedimentation indicators and slowing mass accumulation rates. This indicates that dilution effects might be problematic in the short term, but long-term BiS trends reflect productivity changes rather than dilution by clastic sediment.

**Seasonal Influences on Paleoclimate Records**

Recent developments in the Holocene paleoclimate literature highlight the importance of considering proxy biases when interpreting paleoclimate data. Marcott et al.’s (2013) widely accepted Holocene global and regional temperature reconstruction, which is based on a compilation of over 70 ice core, sea surface temperature and lake proxy records, clearly indicates global cooling in the late Holocene, consistent with reduced summer insolation in the Northern Hemisphere (Fig. 1). However, some recent evidence from climate model simulations and speleothem records suggest global and Northern Hemisphere warming in the late Holocene, forced by slightly increasing winter insolation and increasing atmospheric greenhouse gas concentrations through the late Holocene (Liu et al., 2014; Baker et al., 2017). Although climate model error and biases are possible, seasonal biases in climate proxies are also one possible cause of the
discrepancy. Common proxies dependent on biogeochemical characteristics of sediments (such as GDGT and alkenone-based paleotemperature proxies) and fossil organisms (such as Mg/Ca ratios in foraminiferal calcite and chironomid transfer functions) are more sensitive to changes during the growing season of their source organism. The Lauvdalsvatnet BiS record is likely vulnerable to the same biases, primarily reflecting productivity and lake temperatures during the ice-free summer season. Geochemical proxies in my records may similarly record conditions during the warm season, when groundwater and pore water in the catchment soil is liquid. Finally, the clastic sedimentation data likely primarily reflect magnitude of the spring runoff (and therefore the amount of winter snowpack), rather than year-round precipitation and sedimentation.

Holocene Climate and Environmental Change in the Lofoten Islands

In general, North Atlantic climate was characterized by a warm and dry middle Holocene, which transitioned into a cooler and wetter state sometime c. 7-3 ka (Kaufman et al., 2004). Cooling trends observed in paleoclimate records during the mid to late Holocene are attributable to decreasing summer insolation across this interval (Berger & Loutre, 1991). Here, I will interpret and compare data from the Ostadvatnet and Lauvdalsvatnet records to other regional paleoclimate reconstructions, to identify signals associated with broader North Atlantic climate changes.

Sediment Deposited Prior to 7 ka

Although an approximately 20 cm section of sediment exists below Lauvdalsvatnet Unit B, Unit A is unlikely to contain records of early Holocene climate and environmental change. I interpret Unit A as either basal Younger Dryas glacial till from beneath the margins of Lauvdalsvatnet’s sedimentary basin, or the result of near-instantaneous deposition during a landslide event. The presence of an uneven surface beneath the grey fining upwards sequence suggests possible basal scouring during rapid sediment transport and deposition, supporting the latter explanation. Following
Figure 14. Important indicators and summarized interpretations about climate and environmental change in the Lauvdalsvatnet catchment. Data shown are 5-cm running averages of normalized values, except BiS, which was sampled at 4-cm resolution.
degloaciation, northern Norway experienced a period of increased seismic activity due to isostatic adjustment and release of stresses previously contained under the Fennoscandian ice sheet. An earthquake during the latter part of that period could have triggered landslides in the Lofoten region during the early to mid Holocene (Bungum, Lindholm & Faleide, 2005). It is worth noting that the upper age of Unit B at c. 7.2 ka corresponds with the end of a period of low North Atlantic sea surface temperatures (Fig. 1; Calvo et al., 2002), temperatures in northern Sweden (Grudd et al., 2002) and a wet shift noted in peat bogs from Vestvågøy (Vorren, Jensen, & Nilssen, 2012). Despite these associations, reconstructions of equilibrium line altitudes in nearby Troms indicate that from c. 8.8-3.8 ka, glaciers didn’t exist below 1200 meters elevation (Bakke et al., 2005), making a glacial advance c. 7.2 ka in the Lauvdalsvatnet catchment unlikely.

**Mid Holocene: c. 7-3.8 ka**

On the basis of the Ostadvatnet and Lauvdalsvatnet records, I can make several inferences about Holocene climate in Vestvågøy over the past c. 7 kyr. Maximum values and an overall increasing trend in BiS values from the Lauvdalsvatnet record suggest a period of enhanced primary productivity during the mid-Holocene from c. 7.0-3.8 ka (Fig. 14). I expect summer temperatures to be the primary driver of millennial-scale BiS trends, with dilution by clastic sediments influencing shorter-term variability. These results are consistent with previous paleoclimate reconstructions that identified an early to mid Holocene thermal maximum (Calvo et al., 2002; Marcott et al., 2013), resulting from heightened Northern Hemisphere summer insolation.

Changes in Ti/MS, a proxy for weathering intensity and diagenetic alteration, and MS, which is partially sensitive to diagenetic alteration, support separation of the mid-Holocene into two weathering/diagenetic regimes. Heightened Fe/MS, Ti/MS and low MS (Fig. 14), which I interpret to indicate a greater degree of alteration prior to
deposition, occur in sediments from c. 5.5-7 ka. Interestingly, Fe/Ti remains low at this time, indicating that Fe reduction and dissolution processes may not be the primary processes controlling the diagenetic signal. Low Fe/Ti along with heightened Ti/MS may suggest a greater role for oxidative weathering and soil development processes. Geochemical enrichment of immobile elements in soil or mobilization of soluble elements into Lauvdalsvatnet during soil development may explain heightened PC1 values during this time as well (Fig. 11). At c. 5.5 ka, there is an abrupt and lasting transition to a new mean state, with higher MS values and lower Ti/MS after the transition. Here, I define weathering intensity as the degree of geochemical alteration detrital material undergoes prior to deposition. Greater weathering intensity during the early mid-Holocene could account for the observed change. Alternately, greater rates of biogenic magnetite production in the later mid-Holocene could have amplified the MS signal. I favor the former explanation, in the context of increasing sedimentation and mass accumulation rates across this interval (Fig. 8), particularly since imprecision in the Lauvdalsvatnet age-depth model may not permit detection of abrupt changes in sedimentation rates and MAR. Reductions in catchment stability and increasing erosion signal that the Lauvdalsvatnet catchment likely experienced higher frequency and magnitude runoff events starting c. 5.5 ka.

Evidence from Lauvdalsvatnet for a climatic shift c. 5.5 ka is consistent with previous work indicating an abrupt shift in North Atlantic temperature and precipitation regimes. Calvo et al. (2002) reported a stepped sea surface temperature cooling in the North Atlantic Ocean, and cooling recorded in chironomid and pollen records from Lake Tsuolbmajavri, Finland (Korhola et al., 2002) c. 5.5-6 ka. Lacustrine sediment records from Iceland also suggest a shift to cooler temperatures, onset of neoglacialation and reduced catchment stability c. 5.5 ka (Geirsdóttir et al., 2013). Interestingly, although the
Lauvdalsvatnet record contains evidence for increased runoff and decreasing catchment stability in the Lofoten region beginning c. 5.5 ka, there is no evidence for a cooling event in the BiS data until c. 3.8 ka. Timing of the shift in weathering intensity and sedimentation rates from this record is inconsistent with other climate reconstructions from the Lofoten Islands, which identified either a later shift to wet conditions c. 4.3 ka (Balascio & Bradley, 2011) or an earlier shift c. 6 ka (Nichols et al., 2008).

**Middle Holocene Transition: c. 3.8-2.8 ka**

In the Lauvdalsvatnet record, the transition from a warmer Mid Holocene to cooler Late Holocene occurs c. 3.8 ka. An abrupt shift to lower BiS values (Fig. 14) indicates a sudden decline in lake productivity due to a stepped cooling. The magnitude of BiS minimum froms c. 3.8-2.8 ka may be attributable to dilution by detrital input; however, the maxima are also lower than prior values, and low BiS persists even after later decreases in clastic sedimentation indicators.

Maximum sedimentation rates and MAR, as well as peaks in clastic sedimentation indicators PC1, Ti, MS and dry bulk density indicate that this period was characterized by continued or intensifying high frequency and intensity runoff events in the Lauvdalsvatnet catchment. Low Fe/Ti and Ti/MS values also support this conclusion, suggesting dominance of runoff over soil development and chemical weathering signals. Peaks in C/N, sedimentation rate, MAR and OM also occur synchronously in the Ostadvatnet record (Fig. 15). Simultaneous C/N maxima in the Ostadvatnet record and MS maxima in the Lauvdalsvatnet record indicate that inwash of terrestrial vegetation rather than ferrimagnetic minerals may be the dominant runoff signal in Ostadvatnet sediments. These simultaneous changes in both records suggest that enhanced runoff was not confined to the Lauvdalsvatnet catchment, indicating a regional climatic shift.

Several previous studies have identified climatic shifts in the Fennoscandian and North Atlantic regions c. 3.7 ka, and have referred to the period as a climatic
Figure 15. Data from both the Ostadvatnet (top panel) and Lauvdalsvatnet (bottom panel) records indicate a period of enhanced runoff c. 2.8-3.8 ka.
rearrangement. Bakke et al. (2005) report onset of neoglacialation in northern Norway c. 3.8 ka, and paleoclimatic records from geographically distal areas of northern Europe contain evidence for cooling between 3.7 and 4 ka (Badino et al., 2018). In contrast, paleoceanographic records suggest this period was marked by reduced ice-rafted debris, warming mean annual but cooling summer North Atlantic SSTs, and reduced seasonality (Moros et al., 2004). The cooling evident in the Lauvdalsvatnet BiS record probably reflects reduced summer temperatures, whereas enhanced runoff is likely due to increased winter precipitation related to milder winters. The results presented here suggest that neoglacialation in northern Norway c. 3.8 ka was due to the synergistic effects of cooling summer temperatures and enhanced winter precipitation.

Late Holocene: c. 3-1.9 ka

Evidence from the Lauvdalsvatnet record suggests relatively cool temperatures, reduced frequency of intense runoff events, and greater chemical weathering intensity from c. 3-1.9 ka. BiS values remain low relative to the Mid Holocene, but increase slightly after 3 ka. This effect is likely due to decreased dilution by clastic sediments, as indicated by reductions in sedimentation rates, MAR, MS, dry bulk density, PC1 and Ti. Reductions in detrital components of the sediment are concurrent with increasing OM concentrations. Gradual increases in LOI, Ti/MS and Fe/Ti starting c. 3 ka indicate increased weathering intensity and the influence of iron reductive dissolution in the Lauvdalsvatnet catchment. Ti/MS is not as high as in the earliest part of the record; however it does increase relative to the period from 5.5-2.8 ka.

One possible explanation for increasing Fe/Ti in the Lauvdalsvatnet record is peatland or bog expansion in the lake catchment, which could lead to increased reductive dissolution of redox-sensitive elements (Damman, 1978). Several paleoclimatic reconstructions from northern Norway, including one from Vestvågøy, have reported increasing Fe/Ti concentrations in lake sediments during the late Holocene beginning c. 5
ka (Balascio, 2011; Nielson et al., 2016). Korhola et al. (2010) proposed widespread lateral peatland expansion due to increased moisture availability in the late Holocene as a driver of increasing atmospheric methane concentrations observed in Greenland ice core records. *Sphagnum* peat moss abundance increased on Vestvågøy between 3 and 4 ka based on pollen records (Vorren, Jensen and Nilssen, 2012), and synchronous late Holocene increases in Fe/Ti and *Sphagnum* have been reported elsewhere (Camill et al., 2012).

**Anthropogenic Environmental Change on Vestvågøy**

Differentiating climate and anthropogenic signals in paleoenvironmental records is not straightforward, as both natural and human-driven processes can cause similar environmental changes and influence sediment properties. On Vestvågøy, onset of agriculture and neoglacia- tion co-occurred over the past 2 ka. Without more specific indicators of human-driven environmental change than those utilized in this investigation, it is not possible to draw definitive conclusions about the role of humans in driving inferred environmental changes. However, by comparing late Holocene changes that may be associated with human activities to several thousand years of environmental changes in the mid-Holocene record, I can make inferences about what events or signals may fall outside the range of natural variability.

The first changes in sediment properties I attribute to anthropogenic influences occurred between c. 2.7-2.5 ka in the Ostadvatnet record, when OM values, which are relatively constant throughout the rest of the record, begin a series of large magnitude fluctuations that continue into the present (Fig. 13). A subsequent increasing trend in OM and decline in C/N signal increases in aquatic productivity, possibly due to changes in nutrient cycling and onset of agriculture in the lake catchment. Based on these changes in sediment characteristics, I infer that agricultural practices began c. 2.5 ka in the Ostadvatnet catchment.
In Lauvdalsvatnet, the onset of human-driven landscape disturbances appears c. 1.9 ka, as a dramatic peak in OM content close to 50% (Fig. 10). I attribute this short-lived peak to deforestation or destructive slash and burn land clearing practices. After 1.9 ka, enhanced bulk density and Ti along with low OM values suggest increased input of soil and sediment to Lauvdalsvatnet, perhaps because devegetation destabilized the catchment. C. 1.8-1.9 ka, a dramatic increase in Ti/MS and a simultaneous decrease in Fe/Ti are indicative of iron reduction processes in an anoxic or stratified lake environment. Based on these observations, I infer that initial agricultural development in the Lauvdalsvatnet catchment occurred during a second wave of human population expansion c. 1.9 ka (D’Anjou et al., 2012).

Future Directions

Yttrium abundance as a possible paleoproductivity indicator

One interesting feature of my dataset is a puzzlingly close relationship between Yttrium abundance (Y) in the Lauvdalsvatnet record, Northern Hemisphere June insolation, some features of reconstructed solar irradiance and North Atlantic sea surface temperatures (Fig. 16; Berger and Loutre, 1991; Calvo et al., 2002; Steinhilber et al., 2012). Together, this evidence suggests that some aspect of Y cycling in the Lauvdalsvatnet catchment may be climate-sensitive. Y abundance is typically well-detected in µXRF core scanning and in one previous study displayed close correspondence with abundance data obtained using traditional methods such as ICP-MS (r=0.94; Rodríguez-Germade et al., 2015). Emission spectra for Y do closely resemble Sr due to similar electron configurations; however, the moderate correlation between Y and Sr in Lauvdalsvatnet Unit B (r=0.27) is no greater than expected from two elements with clastic sources, suggesting low levels of interference. Yttrium enrichment in Unit B compared to the relatively unaltered Unit A suggests a geochemical or biogenic effect, rather than a primarily clastic signal. One possible explanation for these relationships is Y
uptake by aquatic primary producers, as has been noted in several studies of modern marine algae and diatoms (Spooner, 1949; Horovitz, 2000). Concentrations of Y are between 100-40,000 times greater in aquatic producers relative to the ambient environment (Horovitz, 2000). In Lauvdalsvatnet, when normalized to Ca or Ti to control for potential elatic influx of Y, Y and BiS display a moderate positive correlation (r=0.582 when normalized to Ca, r=0.52 when normalized to Ti; Fig. 16). The relationship between Y and OM is negative (r= -.19 in Unit B), perhaps due to dilution of aquatic vegetation and phytoplankton by terrestrial vegetation. I suggest that Y abundance might be useful as an aquatic primary productivity indicator, and exploring this possible link could be an interesting direction for future inquiry.
Figure 16. Relationships between Yttrium abundance in the Lauvdalsvatnet record, solar forcing and regional climate. (Top Panel) June insolation and total solar irradiance (Berger and Loutre, 1991; Steinhilber et al., 2012); (Middle Panel) Yttrium abundance superimposed on North Atlantic sea surface temperatures at site MD95-2011 (Calvo et al., 2002); (Bottom Panel) BiS concentrations and Y/Ti in the Lauvdalsvatnet record.
Conclusions

For this project, I produced high-resolution records of environmental change in the Lofoten Islands of northern Norway. I analyzed sediment cores from two contrasting lake systems in an effort to examine both natural patterns of climate variability and anthropogenic environmental perturbations. Changes in local temperature, runoff intensity and geochemical cycling in the catchments of the lakes were inferred based on sedimentation rates, dry bulk density, MS, Ti abundance, Fe/Ti, Ti/MS, C/N and BiS. Sediment characteristics in cores from the two lakes displayed different responses to the same regional variability, due to differences in catchment sensitivities. These differences as well as complexity observed in relationships among variables analyzed for this investigation highlight the necessity of a site-specific approach to interpreting lacustrine sediment records.

Comparison with previous local and regional paleoclimate reconstructions indicates that abrupt environmental changes in the Lauvdalsvatnet and Ostadvatnet catchments were regionally extensive and correspond with broader shifts in North Atlantic climate systems. Inferred changes in runoff and weathering intensity in the Lauvdalsvatnet catchment c. 5.5 and 3 ka were synchronous with North Atlantic sea surface temperature cooling events, and a step-wise cooling event in the Lauvdalsvatnet BiS data c. 3.7 ka is consistent with other reconstructions of temperature change in Fennoscandia and northern Europe. The data presented here concur with a robust body of paleoclimate literature reporting non-linear responses to gradual insolation forcing through the Holocene, modulated by the influence of other external forcings and internal feedbacks. Further refinement of the Lauvdalsvatnet chronology could permit assessment of temporal relationships between climate changes in Lofoten and elsewhere and identification of potential forcing mechanisms.

In addition to contributing to the body of work on climate variability in the
Lofoten Islands during the mid to late Holocene, changes in sediment characteristics from the Ostadvatnet and Lauvdalsvatnet catchments provide clues to the spatial extent of human settlement and agricultural practices on Vestvågøy through time. Organic-matter content fluctuations beginning c. 2.5 ka in the Ostadvatnet catchment correspond to previous estimates for onset of agriculture in Vestvågøy’s primary agricultural corridor between 2-2.5 ka (Johansen & Vorren, 1986; D’Anjou et al., 2012). Changes in organic-matter content, detrital inputs and lake redox state starting c. 1.9 ka indicate that human settlement and agricultural practices commenced in the Lauvdalsvatnet catchment during a secondary wave of human population expansion. Future investigations utilizing more diagnostic indicators, such as fecal sterols or polycyclic aromatic hydrocarbons, could focus their efforts on these intervals to examine to what extent late-Holocene environmental changes in the Lauvdalsvatnet and Ostadvatnet catchments were indeed driven by human impacts.
Acknowledgements

This project has been a collaborative effort, and I want to thank everybody who helped bring it to fruition over the past year. Funding for this project was provided by National Science Foundation Grant PLR-1504270 and a generous scholarship donated by William and Mary alumnus Dr. Ellen Stofan. I’d like to thank my advisor Nick Balascio, who has provided patient guidance throughout every stage of this process, opened doors to a number of opportunities over the past two years and trusted me to take this thesis in a direction I thought was exciting and interesting. I also want to thank all the other wonderful people who contributed to field work in Norway, including Scott Anderson, Lorelei Curtin, Stephen Wickler and Kevin Krajick. An especially big shout out goes to Moussa Dia, for his contributions and companionship while traveling and in the lab, and to Billy D’Andrea, for enabling both of us to participate in fieldwork under extenuating circumstances. Jim Kaste kindly provided useful insight when I was struggling to understand geochemical data. I also want to thank my committee members, Billy D’Andrea, Chris Hein and Rowan Lockwood, for the time and energy they put into considering and providing thorough feedback on this document, and for asking lots of thought-provoking and challenging questions during my defense. Next, I have to thank my peers and the faculty of the William & Mary Geology Department, for pushing me intellectually and welcoming me personally; it’s been a delight to learn about the inner workings of the Earth as a part of this community. Finally, an emphatic thank you to my family, friends and my boyfriend Jared, who provide love, encouragement and laughter throughout every endeavor.
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