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A Geomorphic and Sedimentological Study of the Periglacial Processes and Environments, Vardeborgsletta, Western Spitsbergen Svalbard

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by

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Lewiston, Maine
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Note to Reader

Many geographic features mentioned in this study are referred to by their Norwegian names. Thus, Cape Linné is Kapp Linné, the Linné valley is Linnédalen, the Linné glacier is Linnébreen, the Linné River is Linnéelva and Lake Linné is Linnévatnet.

Acknowledgments

The creation of this thesis has been an incredible opportunity and my advisor Michael Retelle is responsible for making it such a wonderful experience. Between the adventures at Kapp Linné during the field season and the constant support during the laboratory analyses and the writing process, I've realized that this project would not have been possible without all your help. Thanks so much Mike. A big thank you goes to Hanne Christiansen and Sara Cohen from the University Centre in Svalbard. You both have taught me so much and working with you has been very rewarding. Tusen takk and Tack så mycket to the AG-212 and REU crew for the wonderful field season and helpful teamwork between all our different projects. Also thanks to the solid crew in LYR and at Isfjorden Radio for a wonderful summer. Thanks to all from the Quaternary Geology Department at UMASS Amherst for the help and guidance and many thanks to the Bates Student Research Fund for financially supporting this project. To the Bates Geology Department, your consistent support has made this process so enjoyable. I couldn't have asked for a better community to be a part of at Bates College; GCAs for everyone! A Shout to my friends for always being able to make me laugh when I need it and lastly, I would like to thank my family for being so incredible, inspirational, and unconditionally supportive throughout the years.

Abstract

Periglacial environments in today's polar regions are highly susceptible to current and future climate change. In arctic regions, climate has warmed significantly as compared to mid-latitude regions. This study investigates geomorphological and sedimentological evidence of late Holocene changes in Vardeborgsletta, a unique high arctic periglacial landscape situated in karst terrain in western Spitsbergen, Svalbard. Fieldwork was conducted in the summer of 2012 and included geomorphological mapping and investigations of the current status of the active layer of the permafrost and karst hydrologic processes. In addition, two pilot surface sediment cores were recovered from two lakes, informally named Lake 4 and Lake 7, within this periglacial terrain. Laboratory analyses of the cores shed light on recent changes in climate and in the karst hydrologic system. In Lake 4, field season measurements and geomorphic evidence (raised shorelines, outlet channels and exposed lake floor interbedded with fan-delta deposits) illustrate the dynamic nature of karst and periglacial processes. In Lake 7, the lack of similar geomorphic evidence indicates that lake level has remained stable in recent times. Laboratory analysis conducted on two surface cores (up to 35 cm) from Lake 4 and 7 include loss-on-ignition, bulk density, grain size analysis, color photospectroscopy, magnetic susceptibility, percent organic carbon, carbon and nitrogen ratio and isotopes, and plutonium ($^{239+240}Pu$) and radiocarbon age determination. Both cores contained complex lithostratigraphic sedimentation patterns likely reflecting distinct changes in hydrological and limnological regimes and changing lake level. In one lake, called Lake 7, the basal 15 cm of the core is massive organic-rich silt, containing finely disseminated organic matter. This unit is most likely deposited in stable quiet water with autochthonous biogenic sedimentation. The upper 20 cm contains alternating terrigenous sediment from reworking fine-grained Holocene-age marine sediments in the watershed and biogenic sediment similar to the basal unit. Another lake, called Lake 4 is dominated by terrigenous sediments, similar in composition to the upper sediment in Lake 7, with alternating coarse fine layers of inorganic fine sandy silt and clayey silt. This unit reflects a series of lake level fluctuations. A 2 meter-deep soil pit excavated at the margin of the delta fan on a section of former lake floor exposes alternating clay-rich and silty sand layers, similar to the core stratigraphy. The sediment core and pit stratigraphy likely reflect periodic (seasonal) input from snow melt and slope processes as well as episodic fluctuations in lake level. The development of a clear understanding of the modern and recent processes shaping the periglacial landscape in the Vardeborgsletta terrain will provide insight to the response of the high arctic periglacial environments to future climate change.

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Introduction

1.1 Purpose

Periglacial environments in today's polar regions are highly susceptible to current and future climate change. In arctic regions climate has warmed significantly as compared to other mid-latitude regions (Åckerman, 2005; Serreze, 2009). This study investigates geomorphologic and sedimentological evidence of changes during the late Holocene in Vardeborgsletta, a unique periglacial landscape situated in karst terrain on the western coast of central Spitsbergen, in the Svalbard archipelago, Norwegian high arctic (Figure 1.1). Fieldwork was conducted in the summer of 2012 and included geomorphological mapping and investigations of the current status of the active layer of the permafrost and karst hydrologic processes. In addition, two sediment cores were recovered from two lakes (informally named Lake 4 and Lake 7) within this periglacial terrain. These cores preserve a detailed record of environmental changes and their laboratory analyses shed light on recent climatic changes in Svalbard's periglacial landscape.

The purpose of this research is to develop a better understanding of the periglacial landscape, with a focus on how lake systems interact with the permafrost in a karst bedrock terrain. Lakes can be used to interpret current shifts in the climate as well as act as an archive of long-term changes (Svendsen, Mangerud, 1997). The development of a clear understanding of the modern and recent processes shaping the periglacial landscape in the Vardeborgsletta terrain will provide insight to the response of the high arctic periglacial environments to future climate change.

Figure 1.1: Svalbard is an archiapelago in the Norwegian high arctic (Image: Norsk PolarInstittut).

1.2 Justification

Today's periglacial environments are experiencing general warming of ground temperatures and high arctic environments and regions underlain by permafrost are being affected (Solomon et al., 2007). Over the last several decades the mean annual air and ground temperatures recorded have increased in these high arctic environments at a pace significantly greater than mid-latitudes. Christiansen et al., (2010) explained that in the last decade, there has been an overall increase in the ground temperatures recorded on Svalbard and that the permafrost has warmed by 1.58˚C in the last six to eight decades. As air temperatures rise, active layer depths increase and the thermal state of permafrost start to warm (Christiansen, 2010; Smith & Risenborough, 2002).

1.3 Site Description

Svalbard is an archipelago with an area of 62, 160 km^2 situated between 71˚N and 82˚N and is located at the northernmost branches of the North Atlantic Current and the southern limit of the polar pack ice (Humlum et al., 2003). Svalbard's local climate, glaciers, periglacial landscape and permafrost are directly influenced by the interaction of these two systems (Humlum et al., 2003).

The investigated area of Vardeborgsletta lies between the northern end of the Linnédalen valley, south of Isfjorden, and several kilometers to the east of Kapp Linné on the west coast of Spitsbergen. Vardeborgsletta is a part of the Nordenkiöldkysten strand flat that extends from Isfjorden south to Bellsund (Landvik et al., 1987). Running parallel to the mountains east of Vardeborgsletta is a 2 km wide trough-like channel, cutting into the Quaternary sediments (Salvigsen & Elgersma, 1985). Within this long channel several relatively small lakes are found. These lakes have been informally named Lake 2, Lake 3, Lake 4, and Lake 5 and extend from Isfjorden south down Linnédalen, respectively (Figure 1.2).

The Vardeborgsletta area is a periglacial landscape that has developed on a carbonate bedrock terrain (Figure 1.3). Long-term weathering of the carbonate has formed a karst hydrologic system. In karst systems subsurface drainage follows fractures and pathways dissolved in carbonate rock, can occur all around the globe. However, it is rare to find this type of integrated subsurface drainage in regions with continuous permafrost (Salvigsen, 1985).

This region of western Spitsbergen exhibits large variations in the local climate due to its location bordering a landscape of maritime arctic and more continental arctic conditions (Humlum, 2003; Åckerman, 2005).

1.4 Periglacial Environments

'Periglacial' is a term that was first used to describe the climatic and geomorphic conditions of areas, such as the polar regions, peripheral to today's ice sheets and glaciers (French, 2007). The periglacial domain is part of the cryosphere which has both terrestrial and maritime components. The terrestrial components are snow cover, mountain glaciers, ice sheets, perennially-frozen ground (permafrost), and seasonally-frozen ground (active layer), while the marine component includes the arctic sea ice (French, 2007). Air temperatures and

Figure 1.2: Aerial photograph of the Vardeborgsletta region (Norsk PolarInstitutt) including Lake 4 to the north, and Lake 7 closest to Linnéelva

meteorology are defining characteristics of periglacial and ground climates (French, 2007).

1.5 Bedrock Geology

The strata of the bedrock of outer Isfjorden are steeply dipping due to the formation of the NNW-SSE trending Tertiary fold and thrust belt of Spitsbergen. The fold and thrust belt reveal an almost continuous record of Paleozoic to Tertiary sedimentary rocks (Braathen et al., 1995). The rocks become younger in age and steeper in dip moving from Kapp Linné, east towards Grønfjorden, where the sandstones of the early Cretaceous Helvetiafjellet Formation dip vertically. Linnévatnet is situated on top of slightly metamorphosed sandstone (quartzite) of the Orustdalen Formation, which was deposited during the late Devonian to the early Carboniferous (Dallman et al, 1992). To the northeast of Linnévatnet is the Gipshuken Formation (Figure 1.3). These carbonate and gypsum/anhydrite rocks that lie below Vardeborgsletta represent a shallow marine and sabkha deposits during the mid-Carboniferous to lower Permian (Worsley, 2008). These highly soluble rocks lying beneath the unconsolidated sediments of the quaternary marine terraces allow for subsurface karstification.

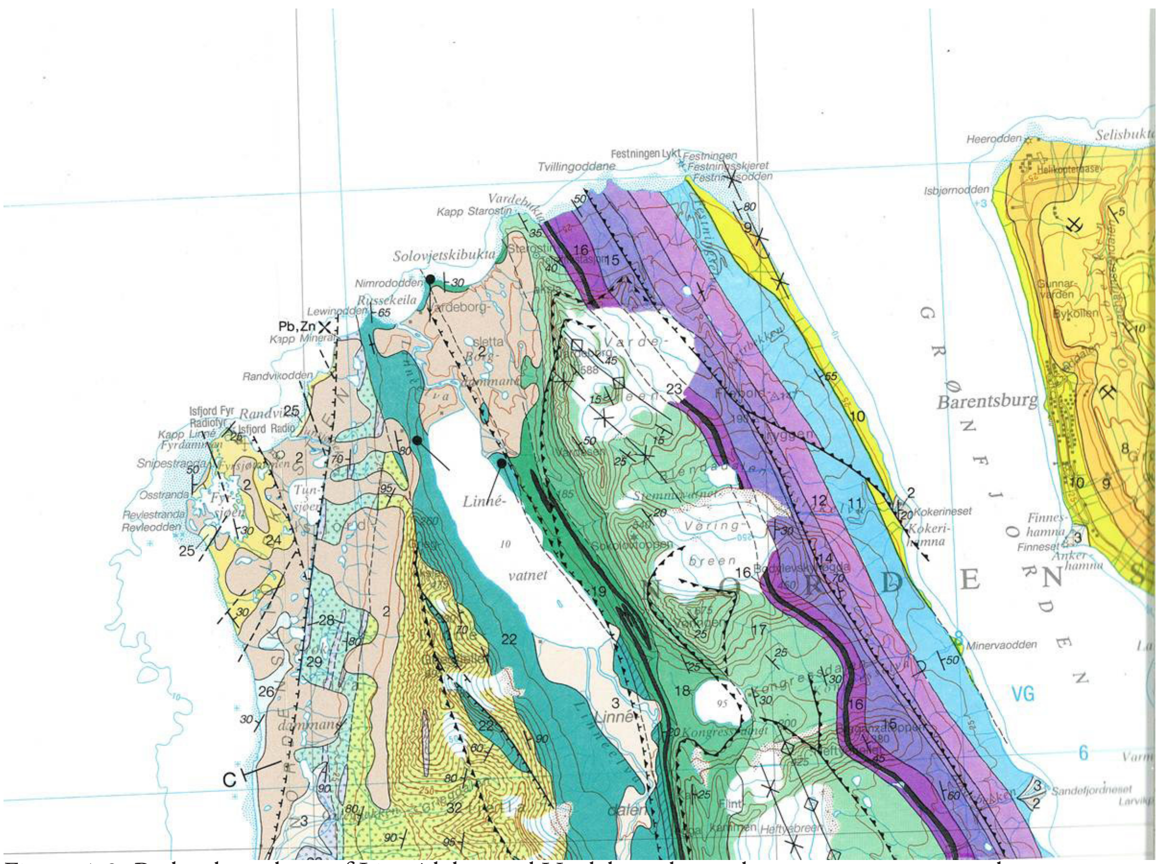


Figure 1.3: Bedrock geology of Linnédalen and Vardeborgsletta; the green represents carbonate bedrock, gypsum, and anhydrite of the Gipshuken Formation and the tan is the overlying unconsolidated marine sediments (Dallmann et al., 1992).

1.6 Glacial Geology

Today, glaciers cover roughly 60% of Svalbard. These ice caps and glaciers cover a total of 32,600 km^2 of the islands of Svalbard (Ingólfsson, 2011). Glaciation is most extensive in areas on the western and eastern coasts of Spitsbergen, with large valley glaciers and cirque glaciers, whereas central Spitsbergen has smaller glaciers due to its dry climate and lower precipitation records than those from the coasts (Ingólfsson, 2011; Humlum, 2003). Most of the glaciers in the dry interior of Spitsbergen are cold-based glaciers and only move 1-2 m per year, unlike the glaciers found in the humid coastal regions that have glacial velocities of 10-30 m per year (Ingólfsson, 2011). Today especially, the highly erosive polythermal valley glaciers are some of the most important in the geomorphic process and present climate. The net mass balance of glaciers has been negative most years for the past 100 years (Ingólfsson, 2011).

Svalbard's glacial history and glacial sediment records can be divided into full-glacial mode (Figure 1.4), when Svalbard and the Barents Sea were covered by a large-marine based ice-sheet, and into interglacial mode. Interglacial mode is what is seen today where the glacial system is dominated by highland ice fields, ice caps and numerous valley and cirque glaciers (Ingólfsson, 2011). Full glacial mode has clearly shaped the continental shelves and slopes, depositing sediments and landforms especially as a result of deglaciation. The interglacial mode is characterized by landform-sediment assemblages especially seen in fjord and valley sedimentation below and in front of polythermal and surging glaciers (Ingólfsson, 2011). Most of the glacial imprints seen on Svalbard are in response to the transition from full-glacial mode to interglacial mode.

Linnédalen is a glacially over-deepened basin that was carved out when Svalbard and the Barents Sea were glaciated with the expansive Svalbard-Barents Sea Ice Sheet (Snyder

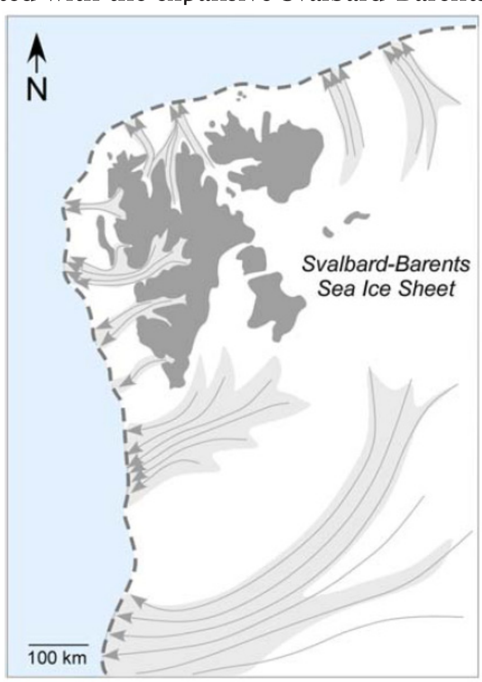


Figure 1.4: The Svalbard-Barents Sea Ice Sheet during the Last Glacial Maximum (Ingólfsson, 2011).

et al, 1999). This ice sheet started to form during the late Pliocene-early Pleistocene and culminated with the extent of the Last Glacial Maximum (LGM) ice sheet 18,000 years B.P. (Ingólfsson, 2011). At this time, it is suspected that Linnébreen may have been a tributary glacier to a larger glacier situated in Isfjorden (Lønne & Mangerund, 1991).

During the Weichselian glacial maximum (22,000 yr B.P) it is believed that glaciers on Svalbard were at their full extent; ice streams flowing into larger ice rivers, coherent with the large Barents Ice Sheet (Humlum, O. pers comm.). It is debated whether large mountains, especially in western Spitsbergen, may have protruded the ice cover as nunataks (Humlum, O. pers comm.). The landscape of Svalbard is shaped by the extensive glacial activity and it has been concluded by Svendsen et al. (1989) that the high alpine landscape of Svalbard has not been shaped by the large sheets, but more by the cirque and valley glaciers.

Mangerud and Svendsen (1990) describe acoustic basement data for Linnévatnet has showing basal till as a thin veneer lying directly on the bedrock surface, this shows that any pre-existing marine or lacustrine sediments in the closed basins of Linnévatnet would have been removed by glacial advances prior to 12, 500 BP, marking this onset of marine sedimentation.

There is surficial evidence of glacial advance and retreat throughout Linnédalen and western Spitsbergen. On the north side of Isfjorden, the extent of glaciers during the Younger Dryas is seen as end moraines in front of moraines formed during the Little Ice Age (Mangerud & Svendsen (1990). During the Holocene, Linnébreen formed moraines 300-400 m in front of the [1988] terminus; the ice-cored moraines mark the furthest extent of the glacier as occuring during the last century (Werner, 1988).

Sediment records in Linnédalen suggest that Linnébreen melted away after 10,000 years B.P. when the was sea level 70 meters higher then present sea level, making Linnédalen an open fjord at that time (Svendsen & Mangerud, 1997). Due to the glacio-isostatic rebound, Linnédalen became isolated by long shore drift of sediments, which is seen today in Vardeborgsletta with the thick and extensive accumulation of unconsolidated marine sediments. In the sediment records from Linnévatnet, Mangerund and Svendsen (1997) observed a well-preserved transition between bioturbated marine sediments and lacustrine silts and clays and dated it to 9,600 years before present. This transition from marine to lacustrine sediments supports the isolation of Linnévatnet from Isfjorden. Subsequently low sedimentation rates during the early and mid-Holocene suggest that there were no glaciers in Linnédalen until 4,400 years B.P., when Linnébreen started to redevelop (Svendsen & Mangerud, 1997). The Holocene marine limit is at 55 meters above sea level, which is well above most large-scale karst features (Salvigsen & Elgersma, 1985). These coastal areas are characterized by strand flat topography, which consists of low-lying bedrock plains that are often covered by raised beaches of varying sizes of marine sediments (Ingólfsson, 2011).

1.7 Permafrost

Permafrost occurs in periglacial environments due to the long period of winter cold and the shorter periods of thaw during the summer; because of these seasonal climatic trends, ground temperatures remain frozen for at least two consecutive years. Permafrost normally occurs when the MAAT is around -2°C (Humlum et al., 2003). The term permafrost was first used to describe permanently frozen ground by S. W. Muller in 1943, but has since been corrected to describe perennially frozen ground (French, 2007).

Permafrost is defined as ground material that remains at or below 0˚C for more than two years. Overlying the permafrost is the active layer, which is the surface material that exhibits seasonal freeze and thaw (Christiansen et al., 2010). Both the active layer and the permafrost are affected by the local climate and air temperatures and exhibit responses to major climatic warming episodes which make both likely permanently affected by recent large scale warming (Smith & Risenborough, 2002).

Over 20% of the world's land area is underlain by permafrost. The occurrence of permafrost is relevant to high latitudes and high altitude, meaning permafrost can occur in both polar regions or in high altitude, mountainous regions (French, 2007). Permafrost is classified by its extent, occuring as continuous (90-100%), discontinuous (50-90%), sporadic (10-50%), or isolated (0-10%).

Due to the widespread occurrence of permafrost in the periglacial landscape of Svalbard, the area is considered to be well within the region of continuous permafrost (Salvigsen & Elgersma, 1985). The permafrost, however, occurs outside the 60% glacier-covered areas of Svalbard because beneath glaciers, permafrost is usually shallow or even absent (Humlum et al., 2003). The geothermal gradient on Svalbard is between -2 and -2.5°C/100m (Humlum, 2003).

Permafrost is typically 100m thick in the valleys and can be 400-500m thick in the mountains (Christiansen et al., 2003). Generally the permafrost in the mountains is of Weichselian age while the permafrost from the valley and coastal landscapes date from the late Holocene (Christiansen et al., 2003). Humlum (2003) concluded from the dating of organic material in ice wedges found near sea level and adjacent pingos, that the permafrost did not occur near sea level in central and western Spitsbergen until the late Holocene.

In areas of continuous permafrost, permafrost is present with the exception of some unfrozen ground typically adjacent to lakes or other water bodies; discontinuous permafrost consists of areas of frozen ground separated by areas of unfrozen ground. Sporadic and isolated permafrost is used to describe restricted areas or 'islands' of frozen ground within unfrozen ground (French, 2007).

Within the high-latitudes and polar regions, climate acts as one of the most important influences on the large-scale distribution of permafrost. Topography (relief and aspect) physical properties of soil, rocks, and lithologies, vegetation, snow cover, wind, geothermal heat flow, and distance from the ocean are some of the local controls and factors that also influence the distribution and thickness of permafrost on islands such as the Svalbard archipelago (Humlum, 2003; French, 2007). Many of these factors can be described as "topoclimate" which refers more specifically to the ground surface climate. This applies to elevation, aspect, slope angle, vegetation cover, and material of the near surface layer, which are influenced by seasonal snow cover, affecting both ground temperatures and moisture regimes (Humlum et al., 2003).

Relief and slope orientation influence both the accumulation of snow and the amount of solar radiation received by the ground surface. Though in some cases local weather conditions have more of a direct impact on this ground surface, but most circumstances, the orientation of the slope can dictate the state of permafrost. This is due to its exposure or lack of exposure to prevailing winds which in turn influences the potential evaporation and potential heat loss from the exposed slopes, especially during summer months (French, 2007).

Topography is especially important as it is related to both altitude and aspect in the Svalbard context of permafrost. The permafrost is typically thicker at high altitudes than in the valleys, this is partially due to enhanced cooling on the exposed on the topographic highs. Lithology is a main control on geothermal heat flow, therefore having a huge influence on this permafrost thickness (Humlum, 2003).

Thermal conductivity and albedo values are influenced mainly by rock and soil type especially in areas of continuous permafrost where the climate is considered to be sufficiently cool to produce permafrost despite the type of terrain (French, 2007). The permafrost thermal regime and active layer thickness will vary with rock and soil type. Frozen soils have higher thermal conductivity than unfrozen soils whereas loose fresh snow and unconsolidated dry organic peaty soil have low conductivity values and therefore act as good insulators of the ground (French, 2007).

Most of Spitsbergen is considered to be an arctic desert with exception of the western region of Kapp Linné, which receives roughly 400-600 mm w.e. of precipitation annually (Ingólfsson, 2011). Thermal offset of solar heat reaching the permafrost is a function of the percentage of vegetation in the surface cover (French, 2007). Vegetation and peaty surface material can act as a buffer and therefore affect the thickness of the active layer above the permafrost. This influence is commonly seen in areas of continuous permafrost, (French, 2007).

Snow cover also has an impact on permafrost conditions and active layer depth because, like vegetation, it also functions as a good insulator (French, 2007). Snowfall regime, snow type, and the length of time that snow is on the ground are a few critical factors that determine how much of an effect the snow cover will have on the underlying permafrost. Snow cover can inhibited frost penetration if is it during the fall months, but if the snow cover persists into the spring time, the thawing of the ground is delayed (French, 2007). On a more local scale, snow cover variation is controlled by micro-relief, vegetation, and the direction of dominant snow-bearing winds. Wind determines where snow will accumulate during the winter and where the ground surface will be kept free of snow (Humlum, 2003). On Spitsbergen, the central more arid parts receive a thin annual layer of snow and the ground cools efficiently; in contrast, in the western and eastern coastal regions of Spitsbergen have thicker snow cover, therefore reducing heat loss from the ground surface during the winter (Humlum, 2003).

The characteristics of the wind and snow cover appear to have a noticeable impact on the Vardeborgsletta region due to the substantial depressions in the landscape and constant inflow into the lake of melt water and sediment. Snow cover and accumulation on the shallow and steep slopes of the depressions surround the lakes has a large impact on slope hydrology, mass wasting, active layer failures, and sedimentation processes into water bodies.

The distribution of permafrost is influenced most by climate, given that permafrost is a thermal ground condition and considered to be a climatic phenomenon (Smith and Risenborough, 2002) Permafrost closely reflects and responds to large-scale changes in climatic trends and polar ground and air temperature, therefore a slight changes in mean annual air temperature, wind speed, and precipitation have the potential to change the state of large regions of currently frozen ground (Humlum, 2003). Long-term investigation is done comparing the temperatures at the top of the permafrost with the atmospheric climate to determine how climate, especially changes, inhibits the widespread permafrost distribution (Smith and Risenborough, 2002). The permafrost and active-layer monitoring at Kapp Linné is the longest record in the world and a valuable resource for permafrost-karst studies (Christiansen, 2003; Humlum, 2003).

The location of permafrost in relation to the ocean and other major water bodies can affect its overall depth. Water bodies such as rivers and lakes act as a major source of heat and their thermal effects tend to reduce the permafrost below or near such water bodies (Humlum, 2003). These areas of unfrozen ground are known as taliks (French, 2007; Muller, 1943). It is generally assumed that in regions of continuous permafrost, the perennially frozen ground inhibits any groundwater movement. Taliks, however, are important conduits of groundwater flow through permafrost and they allow the recharge and discharge of subpermafrost water. Isolated and closed taliks provide reservoirs for unfrozen groundwater (Michel & Everdingen, 1994). Permafrost hydrology is restricted to different types of taliks because the permafrost acts as an impermeable layer (French, 2007). Supra-permafrost taliks exist immediately above the permafrost table but below the depth of the seasonal frost; intra-permafrost taliks are unfrozen zones confined within the permafrost, and sub-permafrost taliks refer to the unfrozen zones beneath the permafrost (French, 2007). Taliks form based on a number of different environmental characteristics, some being the proximity to water bodies, underlying bedrock type and susceptibility to chemical weathering.

1.8 Karst and Permafrost

Karst systems are subsurface drainages that often follow fractures and pathways in carbonate bedrock. These systems can form globally, however it is rare to find this type of integrated subsurface drainage in regions classified as continuous permafrost (Salvigsen & Elgermsa, 1985). Traces of karstification have been identified in polar regions, including the Canadian high arctic (Ford, 1987), Siberia, and Svalbard (Salvigsen & Elgermsa, 1985). These studies all emphasis the infrequency and lack of knowledge regarding this phenomenon. Salvigsen and Elgersma (1985) have recognized large-scale karst features and well-developed karst morphology in the Vardeborgsletta region, located on outer Isfjorden in Svalbard.

The periglacial landscape of Vardeborgsletta area has developed on a carbonate bedrock terrain. Åckerman and the Norsk Polarinistitutt, in 1980 and years subsequent, studied and mapped the rare occurrence of basins forming in large depressions with subsurface drainages found in this region (Salvigsen & Elgersma, 1985) . It was first hypothesized by Åckerman that these features are a result of thermokarst processes and intra-permafrost taliks drainages (Salvigsen & Elgersma, 1985). Unconsolidated sediments that are found in Svalbard usually are not as thick and as expansive as those of Vardeborgsletta, making it difficult to believe that these depressions and basins formed solely due to the melting of ice in the unconsolidated sediments. It is more probable that the lakes in the depressions are a result of differential weathering of the underlying calcareous bedrock, developing a karst hydrologic system (Salvigsen & Elgersma, 1985).

Vardeborgsletta most likely had no permafrost when it first emerged from the sea during the early Holocene, allowing for the subterraneous ground water systems to form in the late Holocene (Salvigsen, 1985). The depressions found on the surface in the unconsolidated sediment formed subsequent to the establishment of the groundwater karst system as a result of the increase in groundwater movement and karst dissolution (Salvigsen et al, 1983).

1.9 Geomorphology and Slope and Surficial Processes

There is variation in geomorphology and slope processes because of the differences in topography in the Vardeborgsletta region, especially in the trough-like feature running parallel to the eastern mountains. These depressions vary in pitch therefore demonstrate differing levels of slope stability. When the slopes are steeper they are less stable and pebbles and cobbles slide down into the accumulated snowdrifts; the slopes on the other sides of the trough-like depression are less steep and consequently more stable (Salvigsen & Elgersma, 1985).

Surficial processes and features relating to permafrost mapped and monitored around the study landscape including: solifluction and active-layer detachments and polygons, patterned ground, and frost hummocks. The surficial processes are considered to be forms of mass-wasting, which is defined as the downslope movement of debris under the influence of gravity (French, 2007). Solifluction is a slow mass-wasting process and active-layer detachment is considered to be a rapid mass-wasting process. Both of these processes are especially common in periglacial regions for a number of reasons. French (2007) explains that frost action promotes rock disintegration therefore providing loose material ready for transport, diurnal and short-term freezing of the ground surface accelerates near-surface sediment movement, high moisture content characteristic of the thawed active layer assists downslope movement and finally the permafrost both restricts the downward infiltration of water from the active layer and acts as a slip plane for the unconsolidated material lying above it. Solifluction is the long-term, slow movement of freeze heaving and thaw settlement of particles downslope (French, 2007). Active-layer detachments are confined to the active layer and commonly found in ice-rich unconsolidated sediments on the upper and middle sections of the slopes. The failure refers to the thawing of the ice rich active layer and vegetation cover detaching from the underlying material (French, 2007).

The surface features that were observed in the study region are polygons (potentially ice-wedge) and frost hummocks which are typical of periglacial regions. Ice-wedge polygons form when foliated or vertically banded ice develops in thermal contraction cracks (French, 2007). Though ice-wedge polygons can occur in bedrock and on slopes, their favored environments of formation are in unconsolidated sediments found in poorly-drained tundra lowlands underlain by continuous permafrost (French, 2007). Frost hummocks or non-sorted circles are a type of patterned ground that typically forms in frost susceptible soil and have a dominantly circular shape yet lack a defined border of well sorted stones (Washburn, 1956).

1.10 Climatology, meteorology

Svalbard's winter weather is highly influenced by the Siberian high pressure cell, an intense, cold, anticyclone that forms over Siberia and it is associated with frequent cold air outbursts and regional cooling during the winter but warm moist air in the spring and summer (Humlum et al., 2003). The North Atlantic Drift from the North Atlantic Ocean also transports warm water up the coast of Svalbard, relatively heating the land (Christiansen et al., 2010). At the beginning of the 21st century, MAAT for central Spistbergen was -5°C (Humlum, 2003). The mean annual air temperature measured at Isfjord Radio at Kapp Linné between 1946 and 1975 was -4.5°C and annual precipitation was around 400mm, (calculated for the period 1934-1975) (Salvigsen & Elgersma, 1985). However in recent years annual precipitation was ranged from 700-900mm (per.comm.with Humlum) while MAAT is at -1.4°C (per.comm.with H. Christiansen). Because Svalbard lies within the border zone of the cold arctic air and the warm maritime air from the oceans to the south occur around Svalbard, meteorologically it is very active with cyclones that generate unstable and often stormy weather (Ingólfsson, 2011). The summer climate is a function of incoming radiation with constant sunlight during the summer months (per.comm.with.O. Humlum).

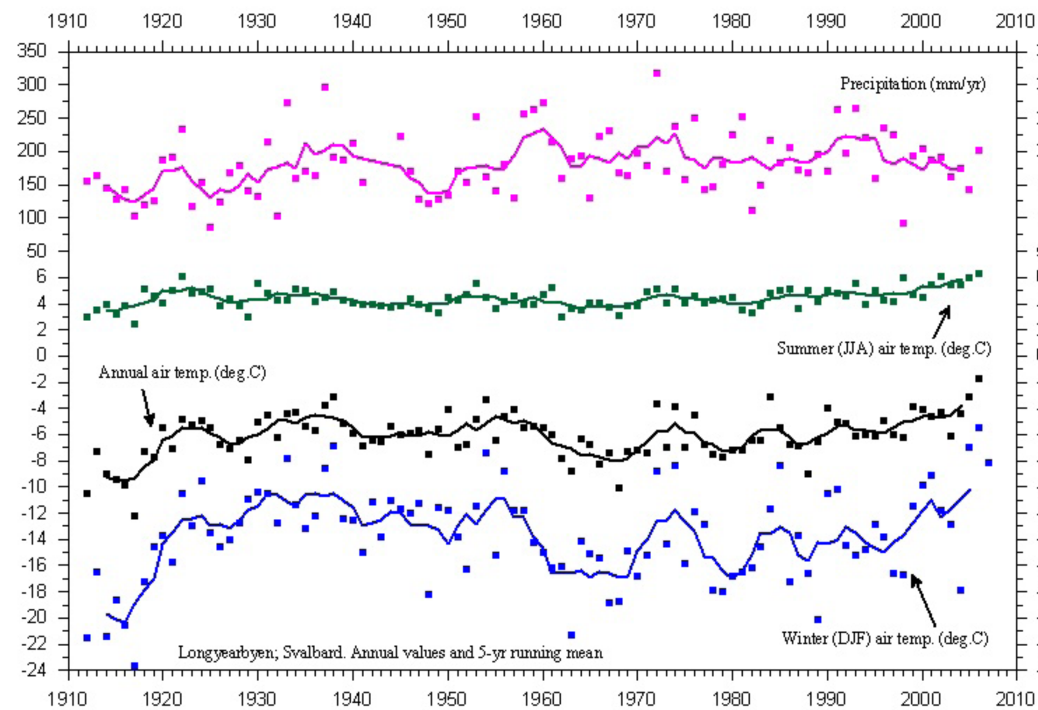


Figure 1.5: The climate for Longyearbyen for the last century (1910-2010) is shown with precipitation, summer and winter air temperatures, and annual air temperatures (Humlum, O.)

METHODS

Field Methods

To better understand the study environment and help reconstruct the processes that shaped it, a geomorphological map was produced during the field 2012 season for Lake 4 and the entire watershed (current and historic) in which it is located. Hydrologic paths, sediment movement and slope processes were monitored and mapped as well as surface material (lithology and grain size), landforms and topography. While mapping special attention was paid to the location of periglacial features relative to lakes to better understand how proximal water bodies affect ground thermal regime (Figure 2.1). Aerial photographs, base maps, and photographic monitoring were used as field references and a handheld Garmin Montana 600 GPS unit was used to log data tracks and waypoints in the field. The data was then imported using DNRGPS Version 6.0.0.11, coordinates were corrected to UTM, and with ESRI ArcGIS Desktop 10, a geomorphological map was created.

Surveying of the watershed from sea level to the southern end of the Vardeborgsletta plateau was undertaken using a TOPCON® GTS-226 Electronic Total Station (Figure 2.2). Former high lake level stands and previous water levels were measured as well as Holocene-age marine terraces. Cross sections were created using ArcGIS for this topographical data.

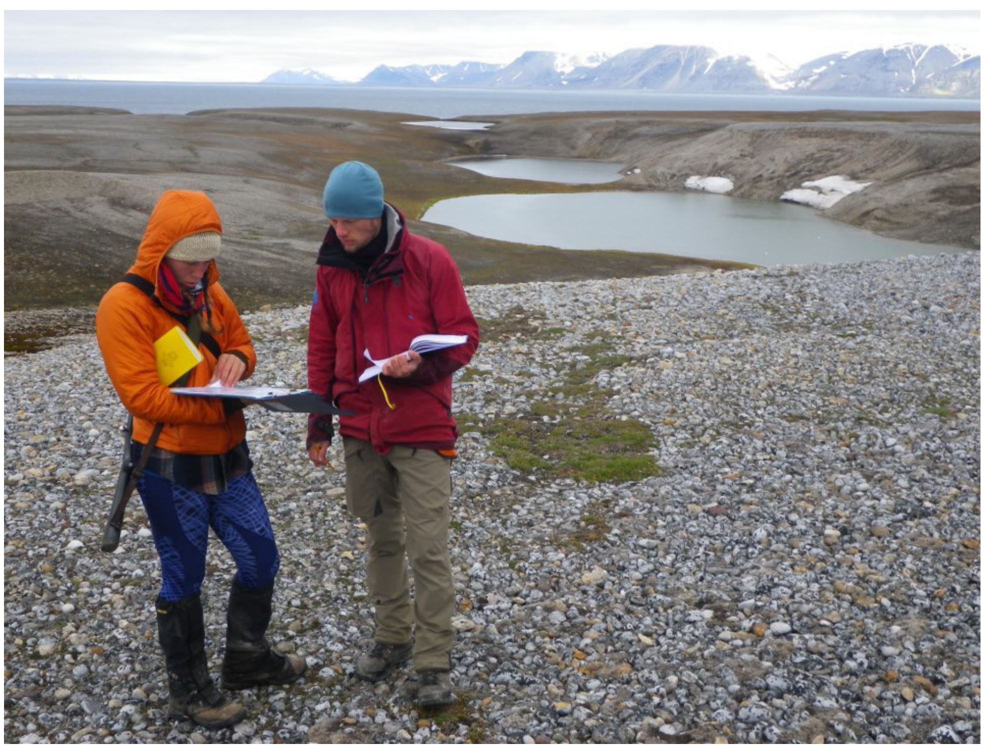


Figure 2.1: Mapping of the Lake 4 watershed required both a large-scale view of the study site as well as a more detailed record of the local geomorphology (Photo: M. Retelle)

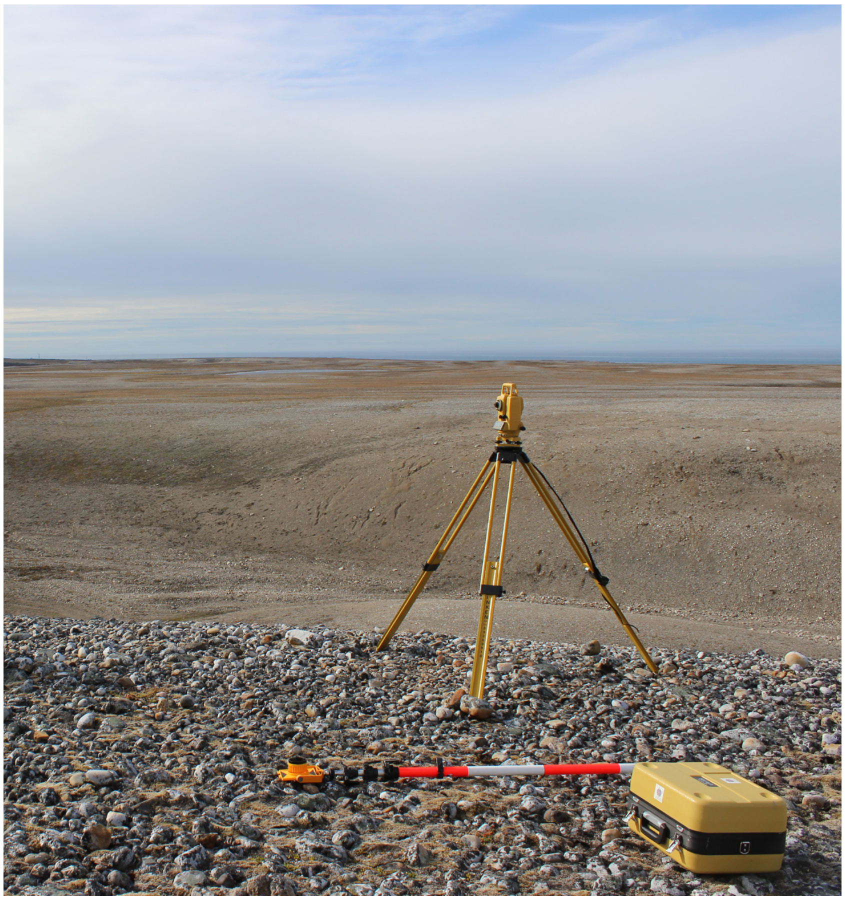


Figure 2.2: A beam from the total station is sent to the reflector prism which calculates the distance between points and changes in elevation.

Active layer probe transects were conducted both distal and proximal to the lakes and in periglacial features to determine the thaw depth of the active layer. This, in turn provides insight to the influence of the lakes on the ground thermal regime in the presence of karst in a continuous permafrost area. Probe transects ran from the lakes edge to 100 meters distance away. The active layer probe is a 146 cm metal shaft with a t-shaped handle. The depth measurements were taken every ten meters by pushing on the t-shaped handle and driving the metal shaft down into the ground, and then the exposed section of the metal shaft was measured and subtracted from the total length to determine the total thaw depth within the active layer. This method, however, was deemed inaccurate for this study area due to the coarse grained, rocky surface cover.

Soil pits were excavated to examine ground temperature trends and how they relate to the different lakes and periglacial features found throughout the continuous permafrost landscape (Figure 2.3). Temperature profiles were measured distal and proximal to Lake 4 in order to detect any lake influence on the ground thermal regime. A shovel was used to excavate the pits and sheets of plastic were laid down to protect the surface cover surrounding the pits. Once water or ground temperatures of 0°C were reached, the pit temperature profile was measured, using a PT1000 thermometer (Ebro TFX 410) taking measurements every ten centimeters from depth to the surface. Notes were taken on the lithology and grain size, and stratigraphic columns were created. Samples were hand-picked from two pits at varying intervals down pit for grain size analysis, organic analysis and ^{14}C age determination. More than 10 pits were excavated around the lakes of Vardeborgsletta including the distal location on the east and west marine terraces of Lake 4, proximal to the lake in both vegetated and clastic surface covers, in different periglacial features such as ice wedges and polygons and at the margin of the delta fan on former lake bottom of Lake 4, and near the karst sink hole.

Figure 2.3: Pits were excavated, temperature profiles were measured and stratigraphy was recorded and photographed (photo: S. Cohen).

Long-term ground temperatures have also been collected from miniature temperature dataloggers installed by Professor H. Christiansen in 2005 which contribute to the International Polar Year (IPY) and Thermal State of Permafrost (TSP) Norway project. These long-term ground temperature profile monitors are located at varies sites surrounding Lake 4 (Figure 3.5). All of these ground temperature loggers were first deployed on July 25th of 2005 and have been logging to the present with the exception of the bi-annual retrieval for maintenance. They have one hour temporal resolution and their logging is continuous, except when logging stops due to battery issues or water damage. This long-term data presents changes observed in ground temperatures based on their distance or proximity to the lake and potentially to surficial karst features (i.e. sinkhole).

Air temperature data for the valley is collected in the "English hut" or Stevenson Screen at Isfjord Radio, Kapp Linné as well as at the REU weather station (as part of the Research Experience for Undergraduates (REU) ten year monitoring program), at the south end of Linnévatnet. The data is compared to and used to explain ground and lake temperatures logged throughout the field season.

Karst Lake Research

Bathymetric data was acquired at the karst lakes using a Lowrance LC-X-17 echosounder with a GPS unit. Both were mounted on the stern of a small inflatable zodiac boat. The echosounder took depth measurements that corresponded to the GPS location values. Transects were then paddled in a grid on the lake. The GPS measurements were converted to UTM-coordinates and then imported into ArcGIS. Using natural neighbor interpolation, a factor of 10 was applied to convert the layer elevation to scene units, and three-dimensional profiles of the lakes' bathymetry were created using ArcScene. The scale for the depth is in 0.5 m contour intervals.

Water column parameter data was measured with a Seabird Electronics Seacat 23 CTD, which measured conductivity, temperature, and depth. In addition to these measurements, the In-Situ Troll 9500 casts recorded dissolved oxygen (DO) and pH. The instruments were calibrated daily for pH and DO before their use in the field. These casts were made in the deepest sections of the lakes. Raw data files were converted to ascii files for spreadsheet manipulation and compiled and plotted using SigmaPlot 12.3.

Sara Cohen deployed a thermistor string in Lake 4 with three HOBO temperature loggers on the 13th of July, 2012. Using a fish finder, the deepest part of Lake 4 was determined to be 3.8 m and this is where the thermistor string was deployed. Temperatures were logged at 10 cm below the water surface, 2 m below the water surface and 3 m below the water surface. The loggers were retrieved on the 4th of August, 2012. Temperature loggers were initially deployed in Lake 7 earlier in the season (May 4th, 2012) by drilling through 1.2 m of ice. (There was an attempt to also deploy temperature loggers but Lake 4 had drained at one point during the winter of 2012, making this impossible (Figure 4.6)). The thermistor was redeployed in Lake 7 on the 17th of July, 2012 to account for the summer lake depth. The temperature logger was deployed at 8 m depth and temperatures were logged at 50 cm, 3.5 m, and 8 m below the water depth. These loggers monitor temperatures at three different levels throughout the water column twice a day.

Conductivity, temperature, and level loggers, (HOBO U20 Water Level Data Logger) were also deployed in Lake 4 on the 21st and 25th of July located 78° 04.827' N and 13° 48.405 E at a depth of 1.3 meters and retrieved on the 7th of September. The level and conductivity loggers monitor the changes in water level and conductivity over the course of the field season.

Sediment Cores

The sediment coring in Lake 4 and 7 was done from an inflatable Zodiac boat, anchored at the bow and stern. Cores were retrieved using a K-B type surface corer from the deepest basin of Lake 4, (at roughly 3 meters depth of water, GPS location: 78° 04.840N, 013° 48.408E). When coring, distance was maintained away from the active sediment input from the northeastern slope of Lake 4. The corer was brought just below the surface of the water and the core was capped. This process was repeated in Lake 7. In the field laboratory water on top of the sediment was decanted using a siphon tube. Muffled sand and green floral foam was added to the top of the tube to prevent disturbance of the sediment during transport of the cores back to Longyearbyen and to Bates College where they were stored in the refrigerator core locker at 4°C (as described by Frost, 2005).

Laboratory Analyses

In the fall of 2012 in the sedimentology laboratory at Bates College the two cores from Lake 4 and 7 were cut, photographed, and logged. The cores were subsampled for bulk density, percent water, loss on ignition (percent organic matter), and grain size analysis. High resolution line-scan imagery, color photospectrometry, and magnetic susceptibility were measured using the Geotek core scanner in the Hartshorn Quaternary Laboratory in the department of Geosciences at the University of Massachusetts, Amherst. Percent organic carbon, percent nitrogen, and isotopic measurements were made in the Environmental Geochemistry Laboratory at Bates College.

The cores were split lengthwise using a table saw and a Dremel tool into working and archive halves. The archive half was photographed and then covered in plastic wrap and stored in the core refrigerator locker. A detailed visual log and stratigraphic column were produced for the working half of the core; logging color (Munsell Soil Color), grain size, sediment type, and sediment structures. The working half of the sediment cores were then subsampled for bulk density, LOI, grain size, and plutonium age determination analyses.

Bulk Density and Loss-on-Ignition were measured to determine the estimated lithology and the amount of total organic matter in the core. First 1 cm^3 sediment samples were taken at 1 cm intervals down the core using a hollow aluminum cube. This sampling was done consistently down the length of the core, retrieving equal amounts of sediment using a clean stainless steel tools. These subsamples were extruded from the 1 cc aluminum cube into previously weighed porcelain crucibles. Using the Mettler Toledo scale, the wet sediment was weighed yielding wet bulk density (g/cc). The wet sediment in their crucibles was then put into a Fisher Isotemp 500 series oven at 100°C to dry for at least 24 hours. When the samples were taken out of the oven, they cooled for one hour and then their weight was measured again to yield dry bulk density (g/cc). The dry samples and crucibles were then roasted in the Thermolyne 6000 muffle furnace for one hour at 550°C, cooled for another hour and weighed again to find the percent loss-on-ignition. Sediment weights were entered into Microsoft Excel to calculate the following equations:

Wet Bulk Density= wet mass/1cc

Percent Water= ((wet mass-dry mass)/(wet mass))*100

Dry Bulk Density= dry mass/1cc

Percent LOI= ((dry mass-roasted mass)/(dry mass))*100

Values were then entered into Sigma Plot 12.3 to plot bulk density and percent loss-on-ignition.

Grain size analysis was done using a Beckman Coulter LS 13 320 Particle Size Analyzer. For Lake 4 the sampling volume was 0.25 cm stratigraphic width by 0.5 cm by 1.0 cm and the sampling frequency was every 0.5 cm down core. For Lake 7 a volume of 0.5 x 0.5 x 0.5 cm was sampled every 0.5 down core. Lake 4 samples were transferred into Oak Ridge centrifuge tubes and covered with 1 mL of hydrogen peroxide in order to disintegrate organic matter. These samples were lightly capped and left over night. Next, a mixture of 20 mL deionized water and 17 mL of dispersant solution (sodium metaphosphate) was added to the sediment sample in each tube.

The organic rich samples from Lake 7 required several more steps to remove all organic material. Samples were transferred to Oak Ridge centrifuge tubes and covered in 5 mL of hydrogen peroxide (H_20_2, 30% volume) and left to sit in a heat bath for ~l hour with temperature setting at 5 (around 50°C). When samples were very reactive they were removed from the bath and left to react overnight under the hood. Oak Ridge centrifuge tubes were then filled with 35 mL of deionized water and samples were centrifuged for one ten-minute cycle. After the first cycle the clear supernatant is carefully decanted using a siphon. Samples are filled to the top again with deionized water and centrifuged for two more times for five minutes each, decanting and diluting the sample between each cycle. Then a mixture of 20 mL of deionized water and 17 mL of dispersant solution was added to the Lake 7 sediment sample in each tube.

Before running these samples, all solutions were shaken using the vortex genie for one minute and then sonified using the Fisher Scientific 60 Sonic Dismembrator for two minutes to break apart any fine grain particle flocs. The solutions were added to the sample chamber in the Coulter LS 13 320 for analysis. The samples were run three times (as described by Arnold, 2009)

The GEOTEK core Scanner (multi-sensor core logger) (Figure 2.4) was used to perform high-resolution line-scan imagery (≥25 um), color spectrophotometry (≥3mm), and magnetic susceptibility (≥2 mm) (UMASS geoscience website) at 0.5 cm intervals. The entire core was photographed at high-resolution.

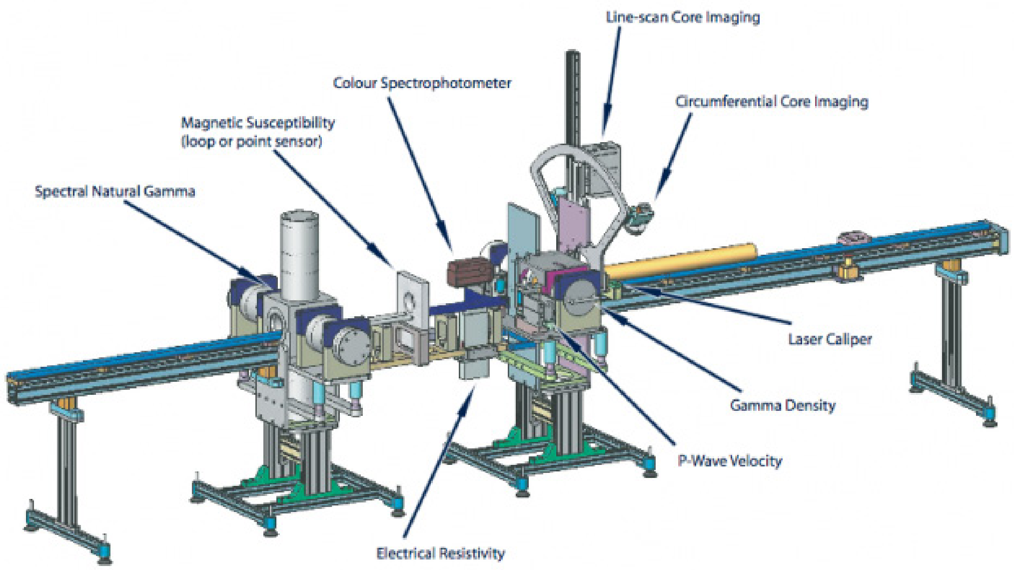


Figure 2.4: The GEOTEK multi-sensor core scanner and logger used for line-scan imaging, color spectrophotometry, and magnetic susceptibility analyses (http://www.geotek.co.uk/node/14).

Wet sieve analysis was performed on the organic rich sediment sample collected from the base of the Lake 4 delta fan soil pit (Pit#7). This separated the terrigenous sediment from the organic material that was imaged for ^{14}C age determination. The organic sample was suspended in deionized water for microscope photography using the SMZ 1500 Stereoscope with a 1.0X magnification. When dateable organic matter was identified it was separated and dried overnight at 65°C. Approximately 17 mg of homogenous, dried plant matter was sent to the Center for Applied Isotope Studies at the University of Georgia where an age was determined for the sample. The sample was treated with 5 % HCL at 80°C for one hour, washed with deionized water in a fiberglass filter, then rinsed with dilute NaOH to remove any contaminating humic acids. The HCl treatment was repeated a second time and the sample was rinsed with deionized water, dried at 60°C and combusted at 900°C in the accelerator mass spectrometry in sealed ampoules in the presence of CuO. Carbon dioxide was converted to a graphite target and the graphite $^{14}C/^{13}C$ ratios were compared with the sample ratios measured separately using a stable isotope ratio mass spectrometer (methods from Cherkinsky, 2013).

Percent organic carbon was measured in the Bates Environmental Geochemistry Laboratory (EGL) using the stable isotope ratio mass spectrometer and elemental analyzer and gas chromatograph with flame interface (EA-GC-C-IRMS). This was only performed on the

Lake 7 sediment core. 2 cc subsamples were taken down core and transferred to plastic bags to be freeze dried. Sediment samples were then weighed and transferred to 55 mL Oak Ridge tubes for demineralization. 85% phosphoric acid was used as the demineralizing reagent. The first demineralization process used 0.33 M solution of H_3PO_4 acid, but due to irregular $d^{13}C$ values this step was repeated with a different concentration. The second demineralization used 45 N (15 M) H_3PO_4 acid that was diluted to make a 3.3 M solution. 40 mL was added to all ten sediment samples and samples were sonicated for 15 minutes in a bath and left overnight. Another 15 mL of H_3PO_4 solution was added to the oak ridge tubes and samples were sonicated for another 15 minutes. Demineralized samples were filtered through pre-weighed 0.4um nuclepore filters. Filters were dried in the oven at 60°C overnight. Sediment and filters were weighed again in the morning yielding total weight of dried demineralized sediment. Using the microbalance, 5 mg of dried and demineralized sediment was weighed into tin cups for percent organic carbon, nitrogen and isotope analysis.

For the plutonium ($^{239+240}Pu$) age determination, Lake 7 was sub-sampled every 0.5 cm down core to 10.0 cm depth. Samples were stored and dried in vials overnight at 70°C and then powdered and sent to Prof. Michael Ketterer at Northern Arizona University for the age determination analysis.

Results

Geomorphological Site Map

The geomorphological map (Figure 3.1) was constructed to provide a visualization of the Lake 4 watershed including the influence of permafrost, hydrology, surface cover, and surface features. The total area of the mapped watershed was calculated to be 178,297 m^2. There is not much variation in surface cover because the entire watershed lies on marine beach terraces. Most of the surface material consists of siliciclastic sediments ranging from clays to rounded cobbles. There are also areas covered with vegetation but these are less extensive.

Water bodies are represented in blue and include from south to north Lake 4, Lake 3, Lake 2, and to the west, Lake 1 (Figure 3.1). Lake 2 and Lake 1 were mapped outside of the Lake 4 watershed. Blue arrows on the map mark the current inflows that are from both surficial and subterraneous sources. Water travels south intermittently down the channel bed connecting Lake 5 and Lake 4. For the most part, this water flow is observed on the surface but drains into a mossy sinkhole in the well-rounded unconsolidated sediments near the southern end of Lake 4. Other inflows are coming mainly from underneath or within snow packs along the southern and eastern slopes of Lake 4. The surface cover is a combination of unconsolidated sediment and vegetation on the surface. The different layers of patterns represent common periglacial features such as frost hummocks and polygons but also include surface features like sinkholes. Other patterns on the map represent surficial properties, which mainly result due to slow and rapid mass wasting processes. This includes solifluction, active layer detachments, and a series of gullies on the surrounding slopes, resulting from headward erosion.

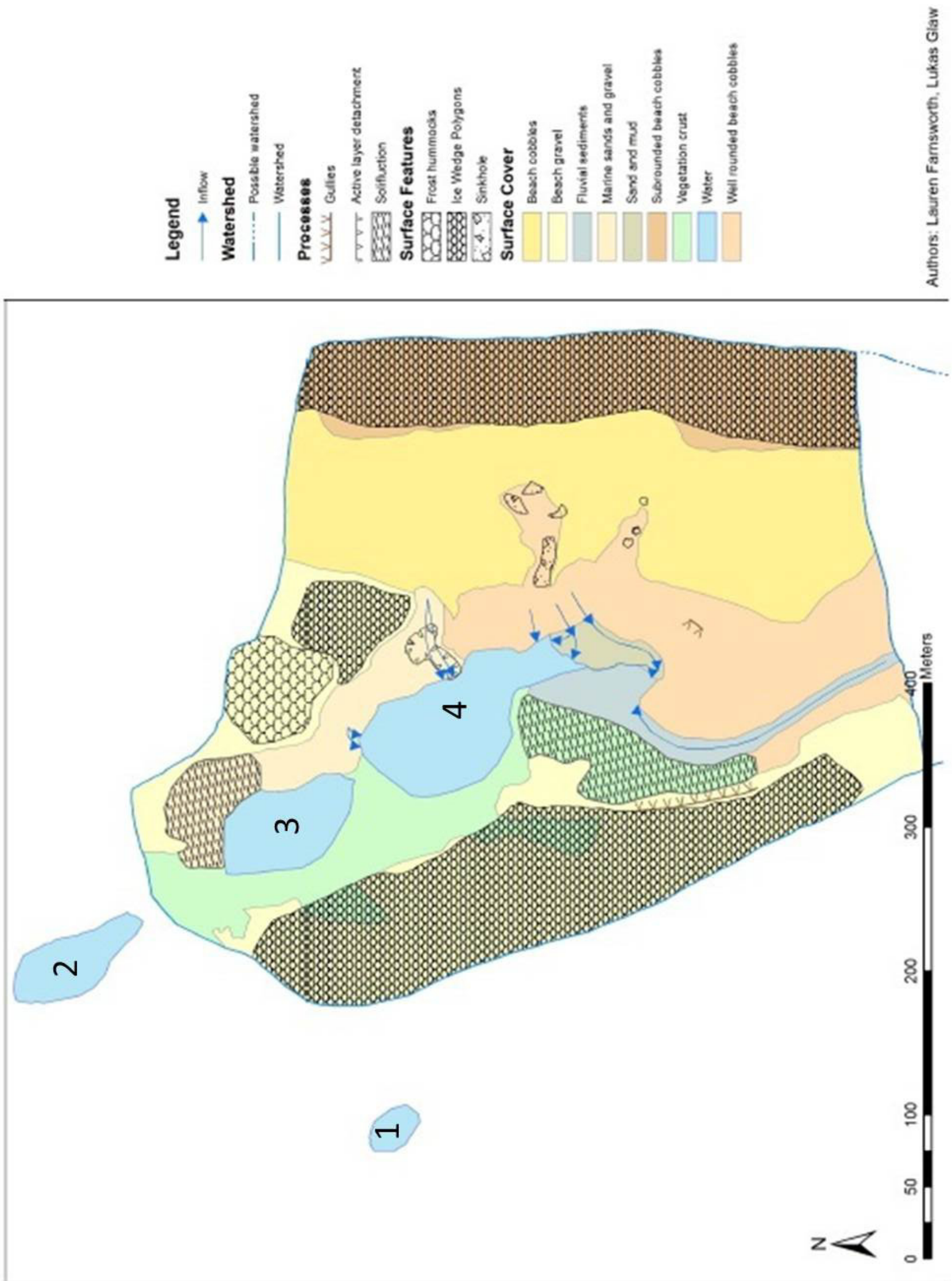


Figure 3.1: The geomorpholgical map includes surface cover, features, and the processes that shape them.

At the southern end of Lake 4, the dark grey color represents fluvial sediments found in the channel running from Lake 5. These sediments vary greatly in grain size ranging from fine grained clays and sands to coarser cobbles and even boulders measuring 50 cm in length. There is abundant vegetation and moss cover in this channel due to the stream flowing into the ground just above Lake 4.

The terrace to the east of Lake 4 consists of dark, well-rounded marine cobbles that are covered in lichens, shown as dark tan on the map (Figure 3.1). This area is relatively flat and also contains polygons (they resemble ice-wedge polygons but there is still a debate as to whether they contain ice wedges). Closer to Lake 4 there are fewer polygons and more evidence of slope processes. Large gullies incise the steep eastern slopes of Lake 4 and the snow packs that accumulate in these gullies and are thought to be perennial (H. Christiansen, personal comm. 2012).

Figure 3.2: The dark cobbles on the terrace surface are covered in lichen and the orange and white cobbles have ben recently exposed due to erosion.

Further north along the eastern terrace, the surface cover changes to a pebbly gravel lag on top of marine mud (light yellow). This surface cover contains patterned ground features frost hummocks as well as polygons. The western part of this terrace has shallow slopes with evidence of soliflucted material as well as steeper sections exhibiting rapid mass-wasting events such as active layer detachments (observed on the 25th of July). This steeper section of the eastern slope contained a small depression filled with moss covered sub-angular carbonate rocks. At times during the field season water was observed flowing through this depression providing moisture to the vegetation. This inflow also may have been a potential source of moisture for the mass-wasting events occurring on this slope (Figure 3.3).

Figure 3.3: Active layer detachment first seen on July 25th on the northeastern slope. This event contributed substancial sediment to Lake 4.

On the western side of Lake 4 there is similar surface cover to the northeastern terrace with some polygons; however this area lacks patterned ground. Along the southern end of Lake 4 a very steep slope consists mainly of large well rounded beach cobbles with pebbles and sand underneath. These cobbles are similar in size to those found on the eastern terrace but showed little to no lichen growth. At the base of the steep south slope sand, silt, and clay are forming a delta fan from the melt out of the snowpack in the eastern gullies. During the field season, there was commonly an outflow from Lake 4, cutting through this delta, flowing to the sinkhole at the southern end of the lake.

Below the western terrace, the slope is shallower and covered by a thin mat of vegetation. There are also minor solifluction lobes on this shallow slope. On the upper section of the slope, dessication cracks can be seen in the vegetation mat. The vegetation is thicker and greener closer to the lake edge due to an increase in moisture content in the sediment. Depending on lake level, the thick vegetation cover can detach from the sediment beneath it and will float in the lake, and at times will detach completely.

Surveying

A cross-section was created for the Lake 4 watershed including Lake 2 and Lake 3 and their elevations relative to sea level. The beach in Isfjorden marked sea level, the bluff to the north of Lake 2 is 27.1 m above, the north shore of Lake 3 is 21 m, and the Lake 4 water's edge is around 20.8 m above sea level.

Lake 7 has a significant inflow and outflow. The inflow is at the northeast corner of the lake

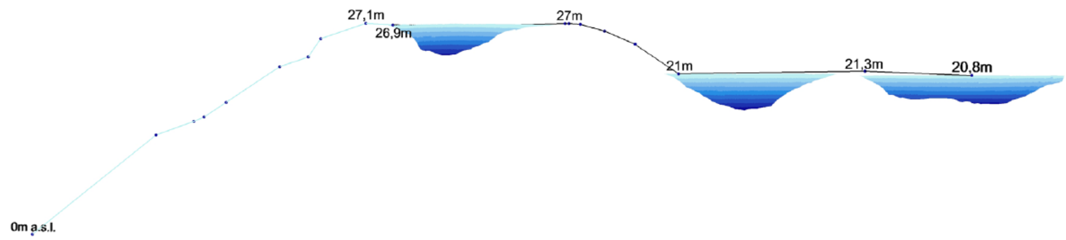


Figure 3.4: Bathymetry data is plotted with the lake elevations measured during the surveying (L. Glaw).

coming from Lake 8 which is slightly higher in elevation. There is a slight movement of water on the surface running over well-rounded clasts ranging from 1 cm to 50 cm in length. The channel, between both lakes, is rich in organics and moss cover and near Lake 7 the inflow drops below the surface just before it enters Lake 7. Gypsum is exposed in channel between Lake 8 and Lake 7 and the outlet at the southwest corner of Lake 7 flows through the fractured carbonate bedrock exposure to Linnéelva. There are signs of solifluction on the eastern slope of Lake 7. This is a potential source of sediment and organics into the lake. On the western and northern side of the lake the ground is entirely covered by sorted and unsorted ground features and these features maintain their shape as they move into Lake 7.

Soil Pit Excavation

Ground temperature monitoring

Long-term ground temperature data has been collected around Lake 4 in the NORPERM temperature loggers and data from the summer field season are both shown on the surface cover and measurements map (Figure 3.5). Soil pits that were excavated proximal and distal to Lake 4 are also shown on the map with the frost table probe transects and the water column data.

Stratigraphic Column

Pit #7 was excavated 22 m from the southeast slope of Lake 4 and the stratigraphy consists of cobbles in a matrix of frozen clay at the base of the pit (140 cm depth). The temperature of this material was measured to be -0.1°C at the time of the pit excavation. A potential source of these cobbles could be from movement and erosion of the steep south slope. On top of these cobbles was a 9 cm thick layer of dark brown, moist organic matter comprised predominately of plant macrofossils that were hand-picked for ^{14}C age determination. The 20 cm on top of the organic layer is a coarsening upwards unit that also graded from clay to fine-grained sand. The upper section consisted of a coarsening upwards from clay to coarse-grained sand. The layers of coarse sand contained both angular and well-rounded gravel. The surface of the pit was a braided silt and clay bed formed by the modern inlet of the delta fan. The alternating layers of clay, silt, and sand and the coarsening of sediment moving up the core can be attributed to the consistent sediment input from the east slope snowpack as well as the reworking of sediment with level changes. The asterisks notes the organic layer (Figure 3.8) that was sampled for ^{14}C age determination.

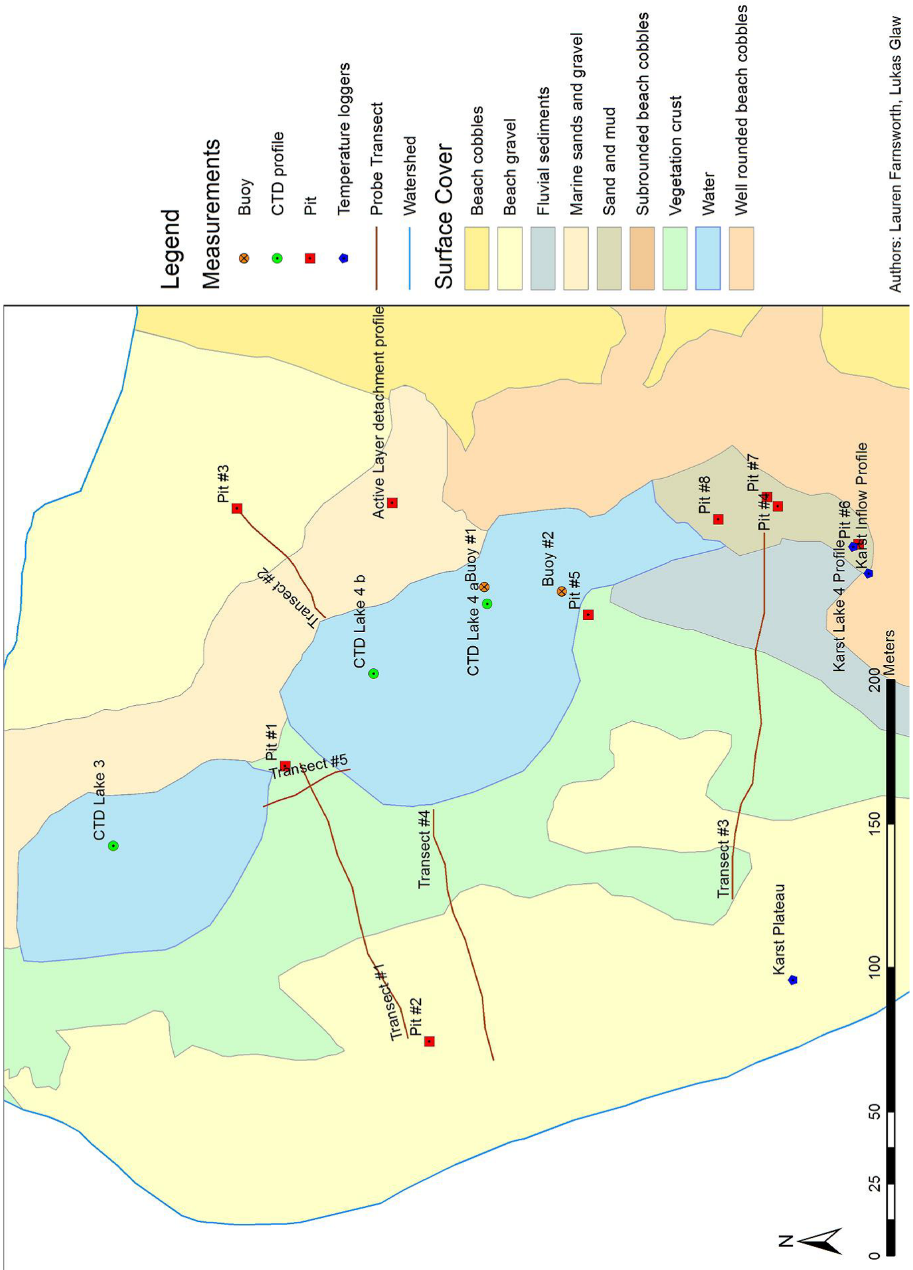


Figure 3.5: Labeled on top of the geomorphological map of the Lake 4 watershed are different water column monitors (green and brown circles) as well as ground temperatures. Ground temperatures were logging (blue) in the southern slope, in the western "karst plateau" terrace as well as measured in excavated soil pits. The majority of the temperature profiles measured close to the lake did not drop below 5°C with the exception of Pit #7 and Pit #4.

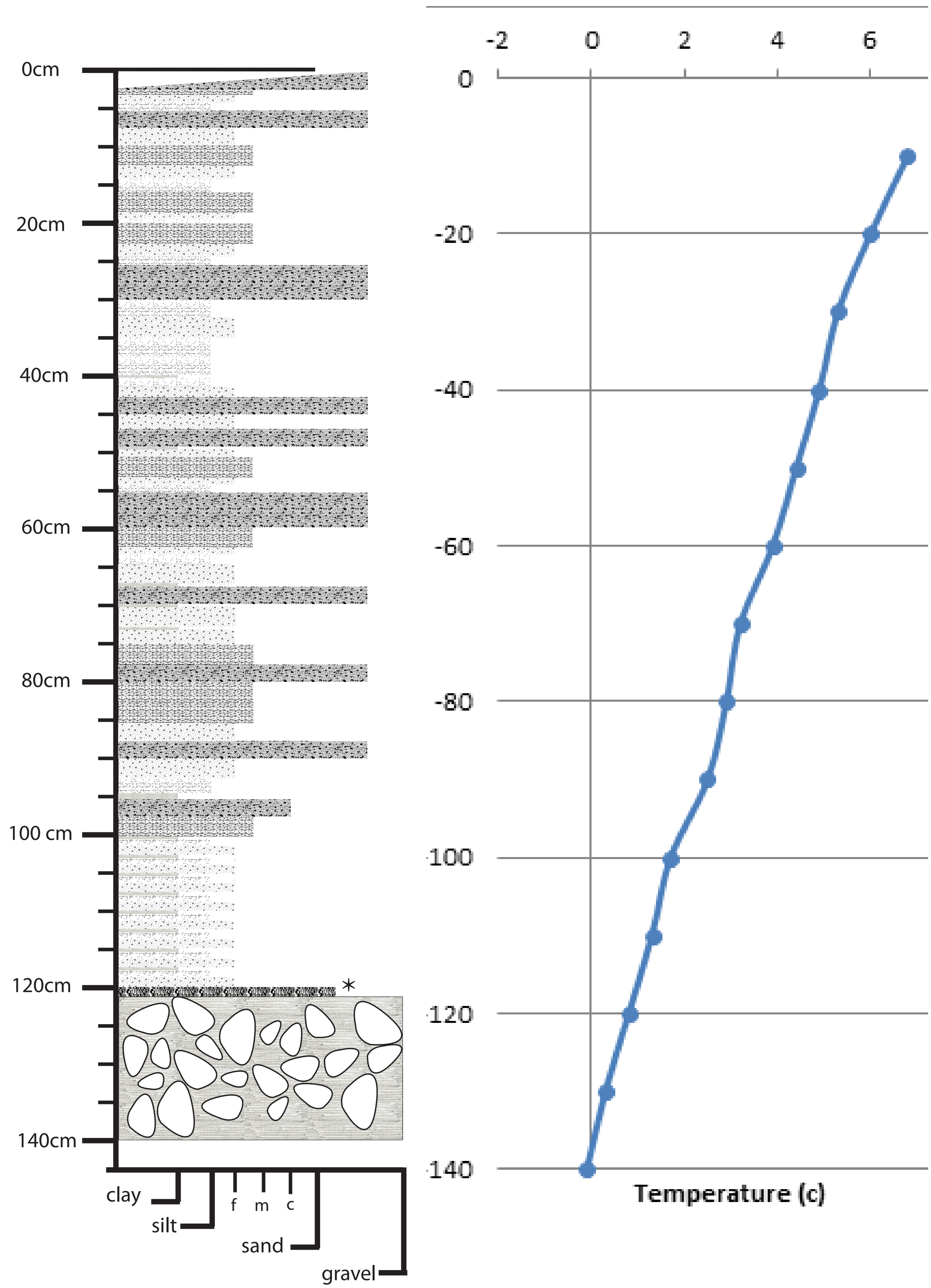


Figure 3.6: The stratigrpahic column for Pit #7 shows the alternating layers of fine to coarse sediment on top of the organic layer (*), handpicked for ^{14}C age determination, and the cobbles in the frozen clay matrix. The temperature profile, shows decreasing temperatures down core and -0.1°C at depth.

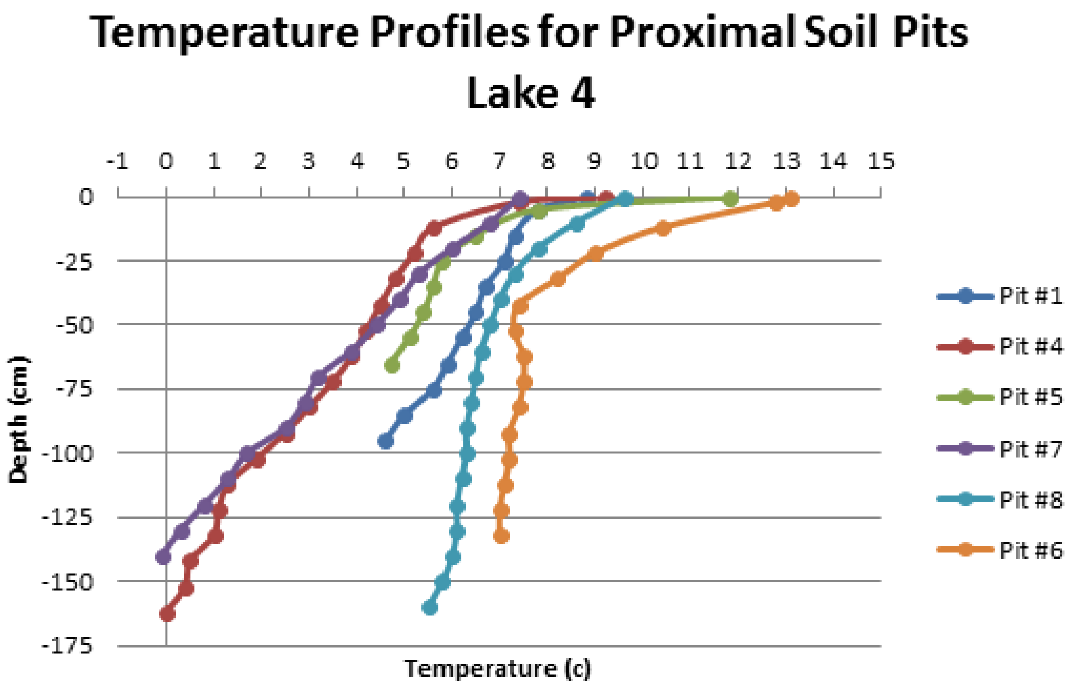


Figure 3.7: Temperature profiles are shown for all pits excavated proximal to Lake 4. Excavation sites are shown in Figure 3.5.

Temperature Profiles

Temperature profiles were measured in a number of different excavated soil pits. Pit #7 was the pit closest to the lake exhibiting temperatures below freezing. The pit was excavated in the delta fan just south of the eastern slope, 22 m from the snowpack gully and inflow (Figure 3.5). Temperatures in the upper 20 cm of sediment ranged between 6°C and 7°C. Between 20 cm and 100 cm depth temperatures steadily decreased to 2°C and within the last 40 cm temperatures hovered just above freezing until reaching the cobbles and frozen clay matrix. Air temperature at the time of the temperature profile was ~6.5°C.

As plotted above, the temperature profiles of soil pits surrounding Lake 4 vary in both depth and base temperatures. Pit #1 is found to the north, halfway between Lake 4 and Lake 3 where surface and ground water is seen flowing south into Lake 4. Temperatures remained relatively warm due to this groundwater flow and water was reached at depth in the pit. Digging to water and temperatures of 5°C is normal given the proximity of the pit to both lakes. The temperature profile for Pit #5 is very similar due to its location next to the western shore of the lake. The pit was excavated in the moss-rich vegetation mat, therefore the high temperatures encountered near the surface. Water was reached around 60 cm depth and the base of the pit was also around 5°C. Pit #8 was much deeper than #1 and #5, and was excavated in the delta fan at the south end of Lake 4. This pit was excavated 8 m from the water edge in the dried outflow channel to the sinkhole. The temperature profile spanned 160 cm and did not reach temperatures below 6°C. This may be evidence of a talik through which lake water could potentially percolate during lake level changing events. The last two temperature profiles are from pits excavated in the same delta fan as Pit #8 but closer to the south slope. Pits reach between 140 cm and 160 cm depth and at the base temperatures measured between 0.0°C and -0.1°C. This may be the only area proximal to Lake 4 where slope processes, talik, and the karst drainage has less of an affect on the ground geothermal regime and the frost table.

Pit # 7 Organic sample

Figure 3.8: Plant macrofossils from the Lake 4 pit #7 photographed at 4000um.

Leafy organic material was found at the base of the soil pit at 140 cm depth where temperatures were measured as -0.1°C. The sample, sent to the University of Georgia AMS Laboratory yielded a “modern” age.

Physical Limnology

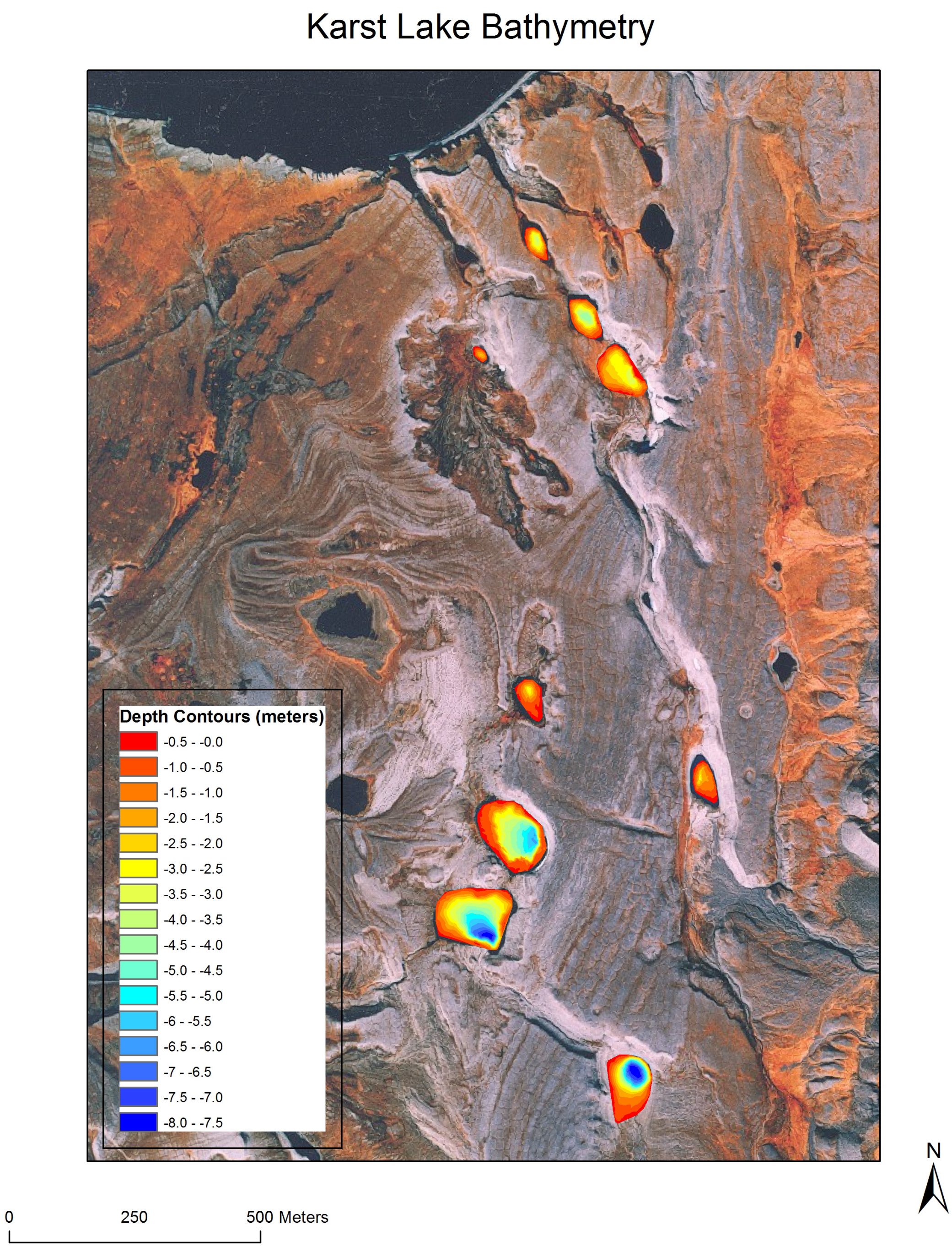


Figure 3.9: Bathymetric data collected for all the "karst lakes" in the Vardeborgsletta region (Figure S. Cohen, photo Norsk Polarinstitutt).

Lake 4 Bathymetry

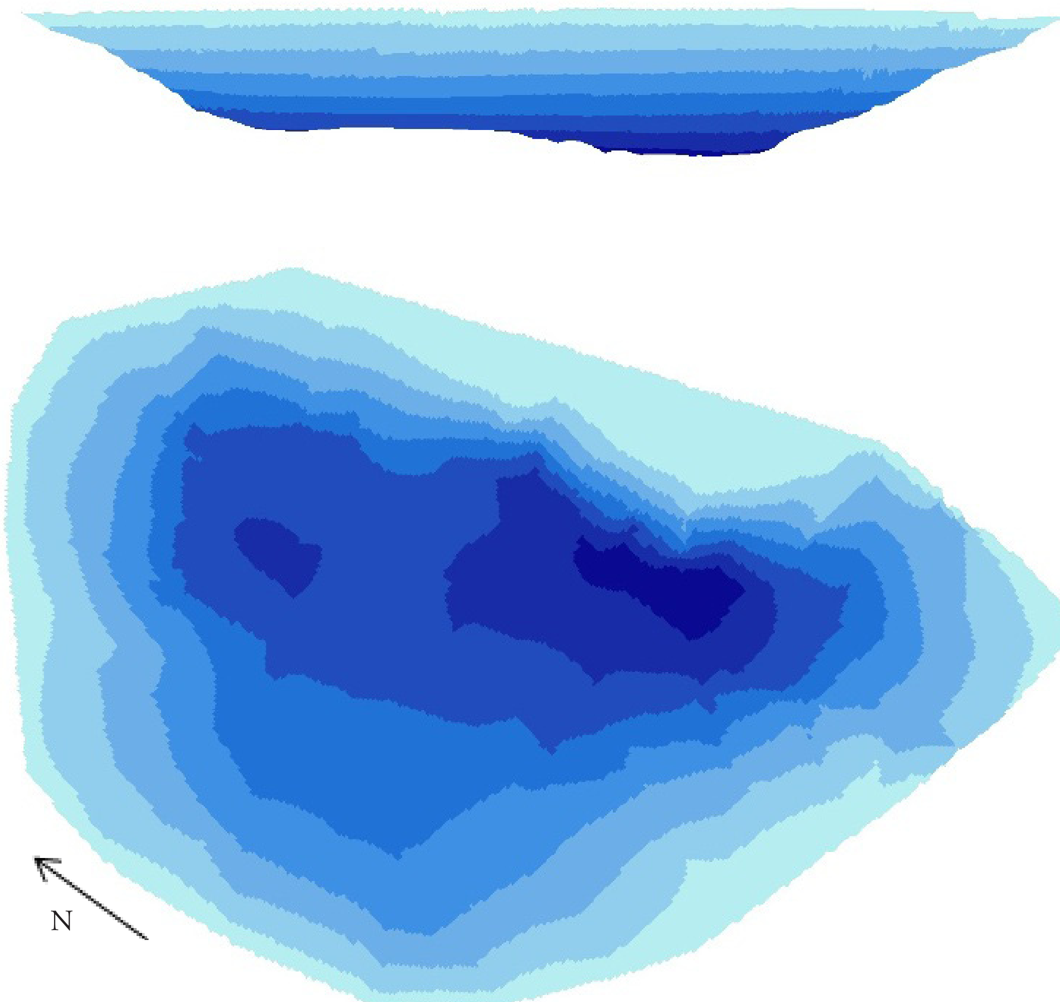


Figure 3.10: Lake 4 bathymetry is plotted in one-dimensional and three-dimensional view with depth contours in 0.5 m intervals.

The altitude of Lake 4 is 20.8 m above sea level. The maximum depth measured during the bathymetric profiling was 3.6 m and the total area and volume calculated for Lake 4 is 8,063 m^2 and 11,430 m^3 respectively. Each isobath represent depth increments of 50 cm, and the depth is 5 times exaggerated. The darker the color the deeper the sections of the lake. The deepest point in the lake (dark blue) is relatively close to the steep eastern slope. The surrounding land area near the lake is made up of fairly shallow steeping and stable stopes to the north and the west and to the south there is a very flat oscilating delta fan that is constantly accreting sediment layers.

Lake 7 Bathymetry

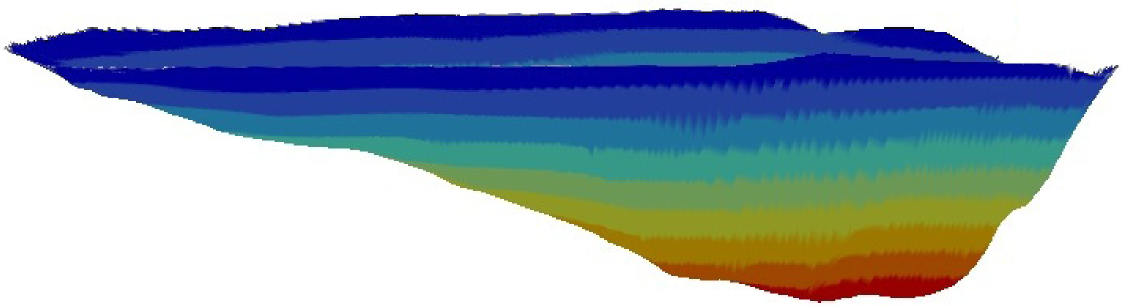


Figure 3.11: The bathymetric for Lake 7 is plotted in three-dimensional view and the isobars are in 1.0 m intervals.

The bathymetric map of Lake 7, provided by Hanna Axen and Elin Roalkvan, was also created during the 2012 field season. The different color isobaths mark one meter intervals. The warmer color represents the deepest point. At the beginning of the field season the deepest point of the lake was measured to be 8 meters. The total area of Lake 7 was determined to be 17,900 m^2.

Water Column

Conductivity and temperature profiles were measured for all of the lakes in the Vardeborgsletta region. For the sake of this study, focus was directed towards the data from the Lake 4 and 7 watercolums.

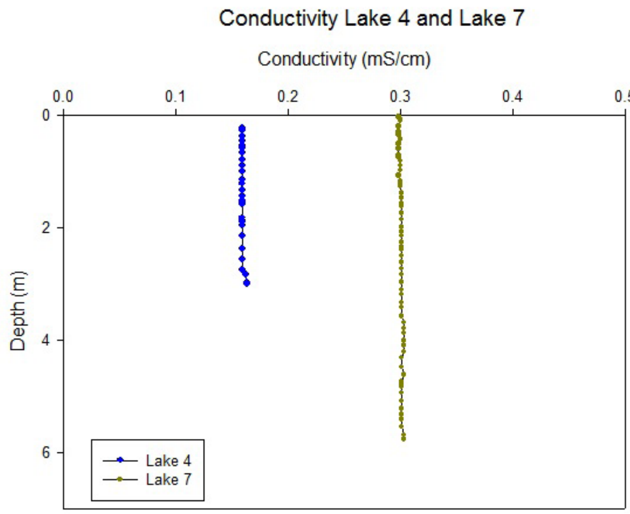


Figure 3.12: Conductivity profiles for both Lake 4 (blue) and Lake 7 (yellow).

The conductivity and temperature profile was measured with the Seacat CTD throughout the water column. The Lake 7 profile (yellow) was collected on the 27th of July, 2012 and the Lake 4 profile (blue) was later collected on the 29th of July. Low values for conductivity are seen in both lakes, Lake 4 reading fairly consistently 1.8 mS/cm while Lake 7 was around 0.3 mS/cm.

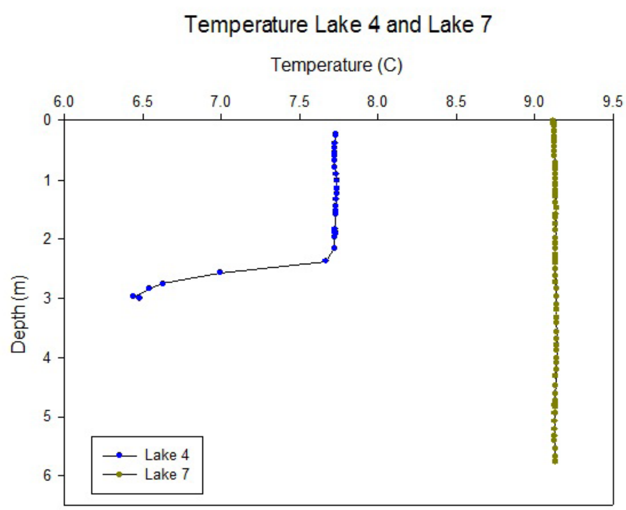


Figure 3.13: Temperature profiles for Lake 4 (blue) and Lake 7 (yellow) are plottetd against the depth of the watercolumn.

The lake temperatures did vary however. Lake 4 showed surface temperatures approximately 7.8°C and then at approximately 3 meters depth dropped closer to 6.5°C. Lake temperatures in 7 did not change from approximately 9.2°C throughout the entire water column.

Timescale Measurements

Measurement in and around Lake 4 and Lake 7 were not only done for specific days but were being collected throughout the entire season, from mid-July to early August.

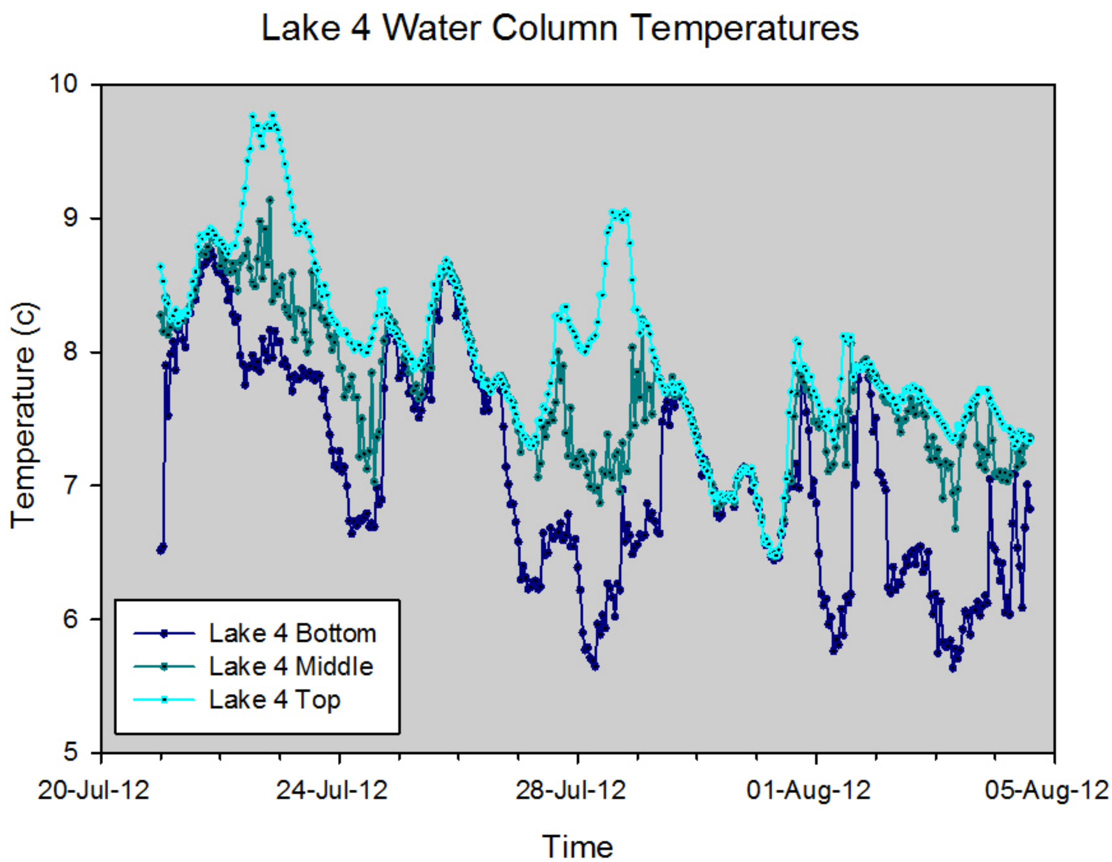


Figure 3.14: The Lake 4 water column data is shown for the 2012 summer field season. Temperatures are shown for the top (light blue), middle (green), and bottom (dark blue) sections of the water column.

Temperatures were logged at 10 cm below the water surface ("top"), 2 m below the water surface ("middle") and 3 m below the water surface ("bottom") (Figure 3.14). Temperatures in the Lake 4 water column vary up to 4 degrees at any given time. The coldest temperatures are seen at the bottom of the lake at approximately 5.5°C. These could be a result of meltwater sinking to the bottom of the lake from the snowpack. The warmest temperatures are measured in the surface waters and typically range between 9.5°C and 8.5°C.

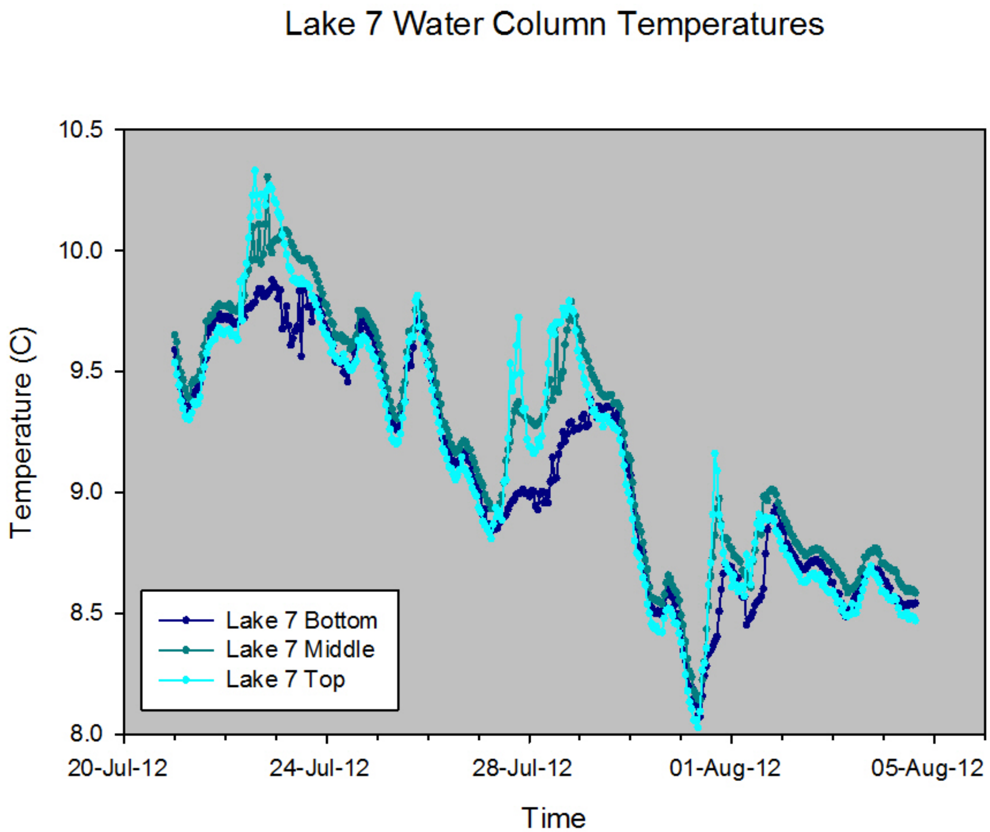


Figure 3.15: Water column temperatures were also collected throughout the field season in Lake 7 at the top (light blue), middle (green), and bottom (blue) sections of lake.

The temperature logger was deployed at 8 m depth and temperatures were logged at 50 cm, 3.5 m, and 8 m below the water depth (Figure 3.15). The Lake 7 water column shows little to no variation in temperature with depth. The highest temperatures measure to be around 10.5°C and are measured on both the top and middle temperature logger. The coldest temperature is approximately 8.0°C, around the 1st of August, and is also seen on the top, middle, and bottom logger. Lake temperature has an overall decreasing trend thoughout the field season.

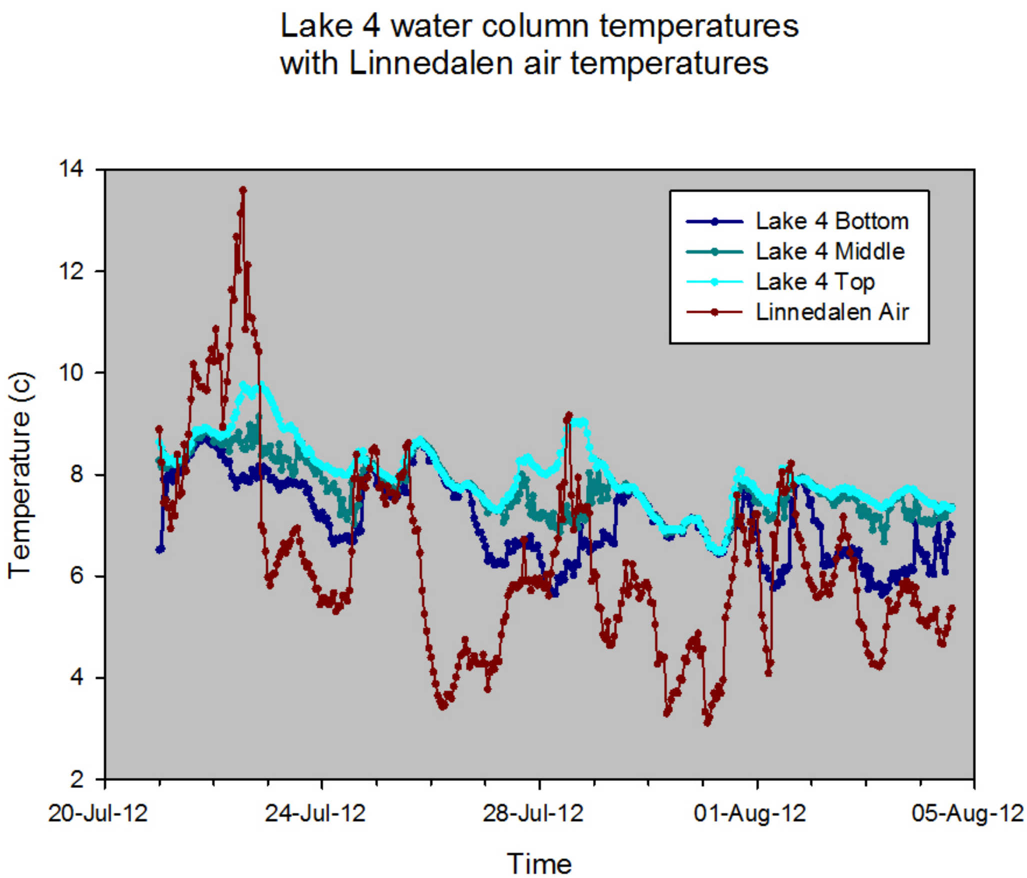


Figure 3.16: Linnédalen air temperatures, from the REU weather station, are plotted with Lake 4 water column temperatures.

Air temperature from the REU Linnédalen weather station is plotted against the watercolumn temperatures for Lake 4 to show the impact change in air temperature has on the lakes. Similarities in peaks in warm and cold temperatures are seen in both air and water temperatures. Both also show an overall decrease in temperature measured throughout the field season. The Linnédalen air temperature is plotted in red and lake temperatures are seen in light blue (top), green (middle), and dark blue (bottom).

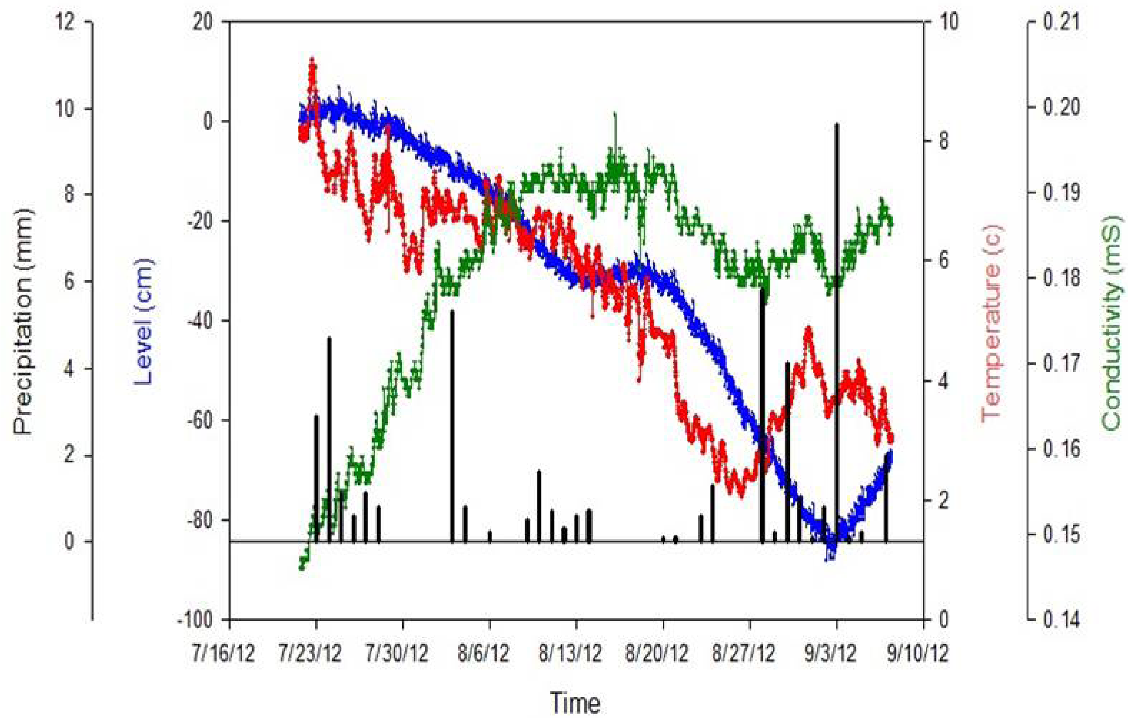


Figure 3.17: Conductivity (green), water temperature (red), relative lake level change (blue) from Lake 4 are plotted with precipitation (black) for the 2012 summer field season.

A temperature, conductivity, and level logger was deployed in Lake 4 at 1.3 m depth on the 21st of July, 2012. Conductivity is shown in green, water temperature in red, and relative level change in blue. The logger data was plotted with the precipitation data from the Longyearbyen airport (approximately 50 km away). As seen in the data from the thermistor strings, there is an overall decrease in temperature throughout the monitoring period. Conductivity, on the other hand, increases throughout the summer season. This could be a function of the decrease in volume of Lake 4. The relative lake level shows an overall decreasing trend as well as an 80 cm drop in lake level over the course of the monitoring period. The lake level decreases despite the peaks in precipitation especially seen between August 27th and September 3rd.

Ground Temperatures

Monitoring of ground temperatures around Lake 4 has been carried out for more then a ten years (H. Christiansen, pers. comm.). The continuous collection of data around Svalbard is shared on the Norwegian Permaforst Database (NORPERM). Ground tempereature loggers have been installed in the southern slope by Lake 4, near the sinkhole, and to the west in the karst plateau (Figure 3.5)

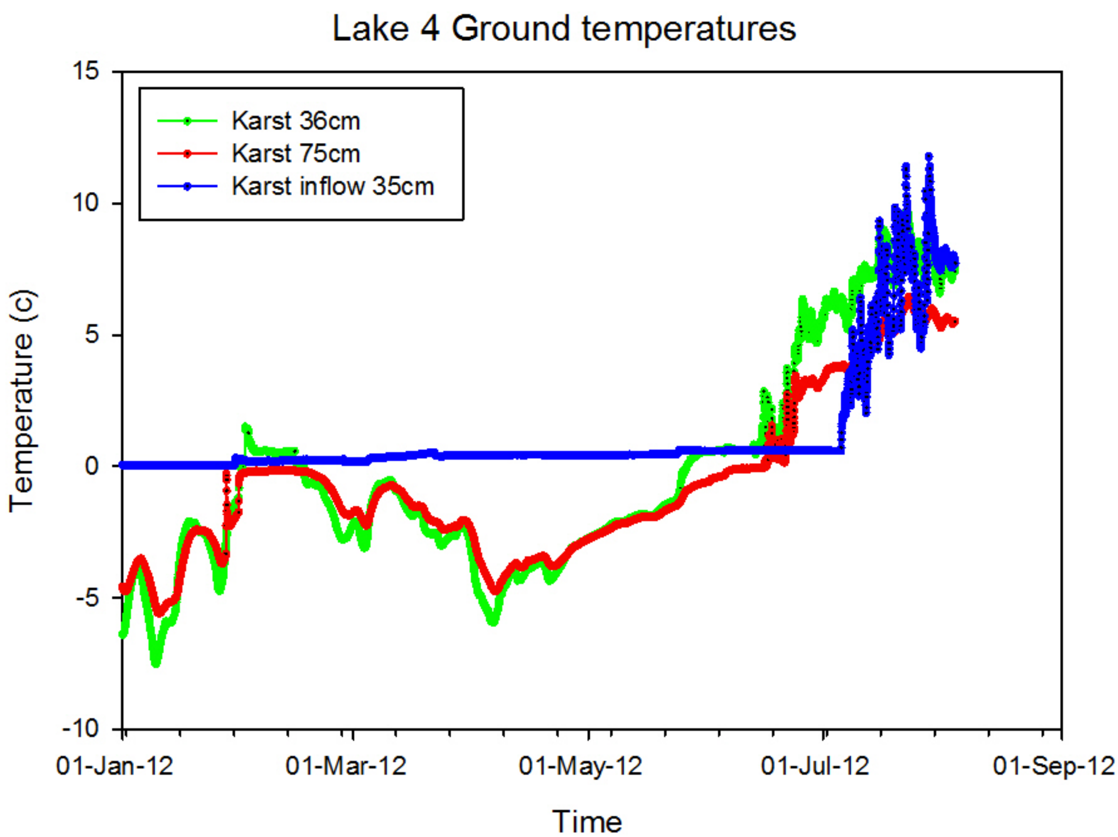


Figure 3.18: Temperature loggers proximal to Lake 4 are installed at 36 cm (green) and 75 cm (red) depth and near the sinkhole at 35 cm depth (blue). Temperatures plotted are from the beginning of January through early August 2012.

Around Lake 4 ground temperature loggers were installed by Prof. H. Christiansen in the southern slope as well as in the western plateau. This study will only focus on the beginning of 2012 leading up to the summer field season. These temperatures loggers collected data throughout the previous winter and received maintenance periodically. The ground temperatures installed at 75 cm (red) and 36 cm (green) depth show freezing temperatures up until late June often reaching temperatures as cold as -8°C. In July, August, and September, ground temperatures increase to 10°C . The temperature history from the logger installed at 35 cm depth (blue), just below the south slope, near the sinkhole does not follow the trend of nearby loggers. Temperatures do not measure below freezing the entire winter and in July the increase to temperatures near 13°C.

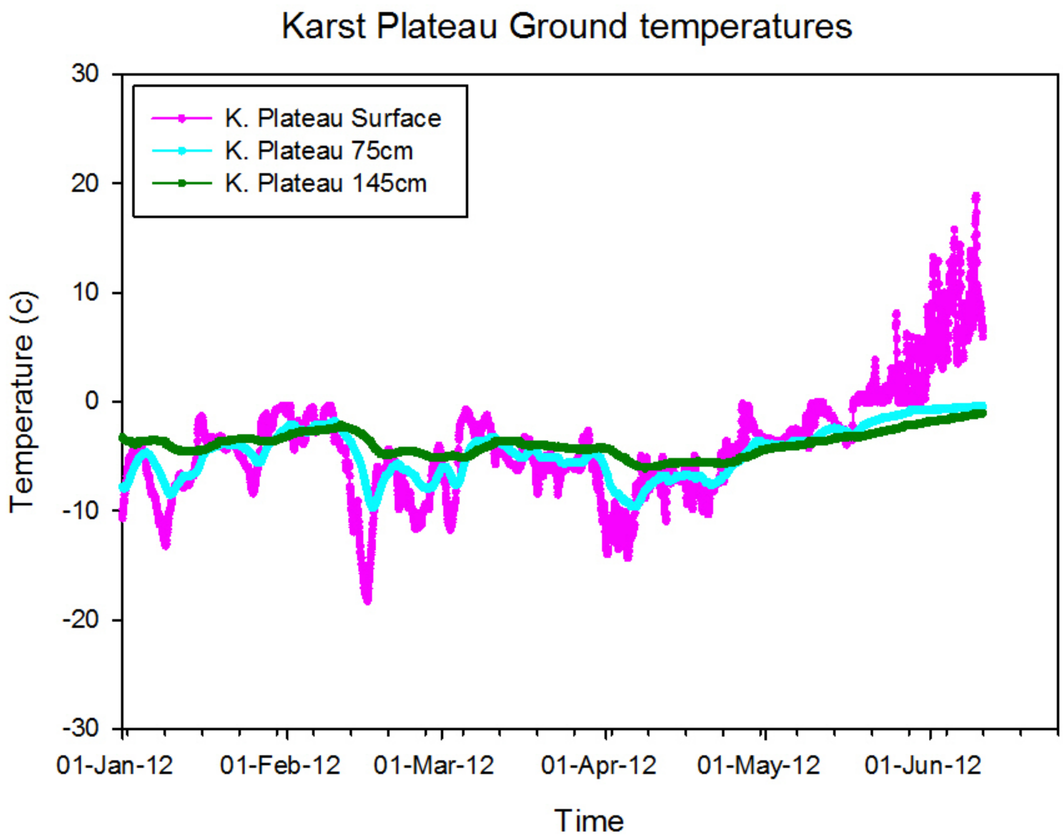


Figure 3.19: The Lake 4 distal temperature loggers are installed into the western karst plateau (Figure 3.5) on the surface (pink), at 75 cm (blue) depth, and 145 cm (green) depth.

Ground temperatures that are being logged in a more distal location to Lake 4 show an overall warming trend from January to July 2012. The surface temperature logger (pink) exhibits both the coldest measured temperature (-19^{o}C) and and the warmest (19^{o}C). The loggers at 75 cm (blue) and 145 cm depth (green) remain below freezing for the majority of the monitoring period.

Sediment Cores

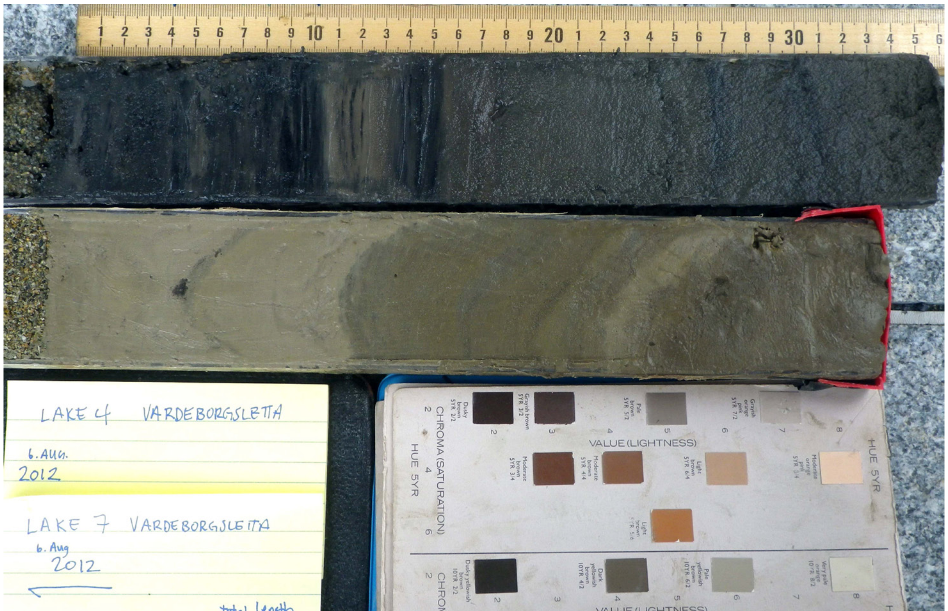


Figure 3.20: The Lake 7 core is 35 cm in length (top) and is an overall dark gray/black. The Lake 4 core is 32 cm in length (bottom) and is lighter grey and brown (Photo, M. Retelle).

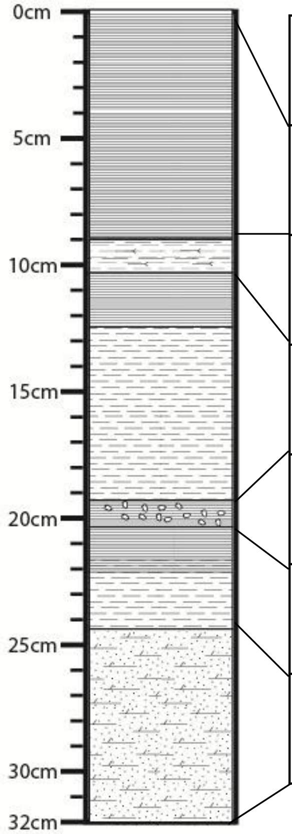
The Lake 4 core is comprised of terrigenous sediment from reworking fine-grained Holocene-age marine sediments in the watershed with alternating coarse and fine layers of inorganic fine and sandy silt and clayey silt. The upper section of the Lake 4 core is heavily laminated between clay and silt layers and silt and fine-grain sand layers. The bottom 8 cm is a silt massive with a 1 cc angular clast at the base.

The bottom 15 cm of the Lake 7 core is an organic-rich silt massive with finely disseminated organic matter and the upper 20 cm contain alternating terrigenous sediment, similar to the above core, and has biogenic sediment similar to the basal unit. The upper section is laminated with changes between silt, clay, and organic-rich layers. The bottom 15 cm is entirely comprised of a silt organic-rich massive.

The values for percent loss on ignition measured in Lake 4 (Figure 3.23) ranged from roughly 2.5% to 3.5% and were much lower than those measured for Lake 7. Percent LOI in Lake 7 ranged from around 5% from the surface of the core until around halfway down where it increased to just below 30%. The bulk density values were compatible with the percent LOI for both lakes. Larger bulk densities were seen in Lake 4, ranging from 1.9 g to 2.4 g, and reflected the lower amount of organic material in the core. Lake 7, much richer in organic material almost consistently measured bulk densities to be around 1.0 grams with the exception of three locations near the top of the core the measured closer to 1.9 grams (Figure 3.24). In Lake 4 the trends in grain size measurements roughly corresponded with those for LOI. Values mainly measured between 10 and 15 microns but some peaks reached as high as 30 microns. Lake 7 grain size shows a strong relationship with the LOI values. The upper section of the core has values ranging from 10 to 35 microns. The lower 15 cm are around 8 microns, consistently downcore.

Detailed Descriptions of Cores

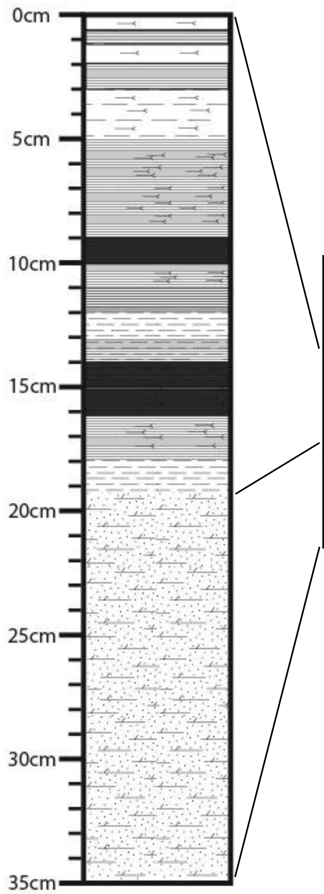
Lake 4



Units	Depth (cm)	Description (Munsell soil color chart 2.5)
A	0.0-0.9	light brown (5/3; 2.5/1; 4/2), finely laminated clay
B	9.0-10.3	dark grey (5/2; 4/2), silt lamina with organic fragment
C	10.3-19.2	light brown and grey (5/2; 4/2; 3/1) alternating clay and silt laminae
D	19.2-20.3	light brown (5/3), laminated clay with large clast entrained
E	20.3-24.4	light brown and grey (4/2; 5/4) alternating clay and silt laminae
F	24.4-32.0	dark brown (4/3) silt massive with large clasts (potentially a dropstone)

Figure 3.21: The Lake 4 core was classified into six different units (A-F) based on differing color, structure, texture, and accessories.

Lake 7



Units	Depth (cm)	Description (Munsell soil color chart 10YR and organic chart 5Y)
A	0.0-19.0	light brown (4/2; 5/2; 3/2; 4/3; 5/6), dark brown (2/1; 3/1;), laminated clay and silt with organic rich layers
B	19.0-35	light grey/brown (2.5/1), massive silt organic rich

Figure 3.22: The core from Lake 7 was divided into two units (A and B).

Loss-on-ignition, Bulk Density, and Grain Size

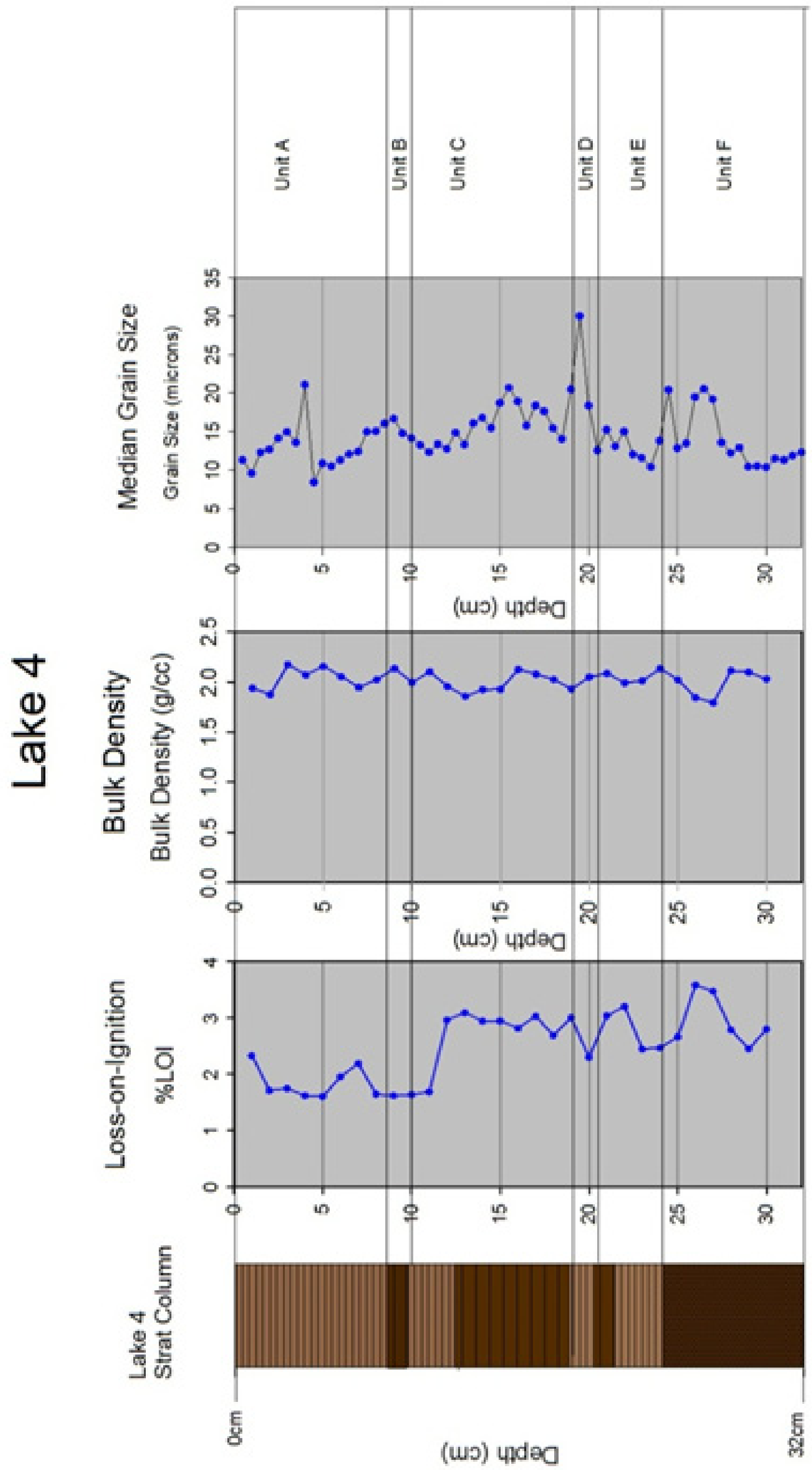


Figure 3.23: Results for LOI, bulk density, and grain size provided supporting information to divide the core into sub-units based on stratigraphy.

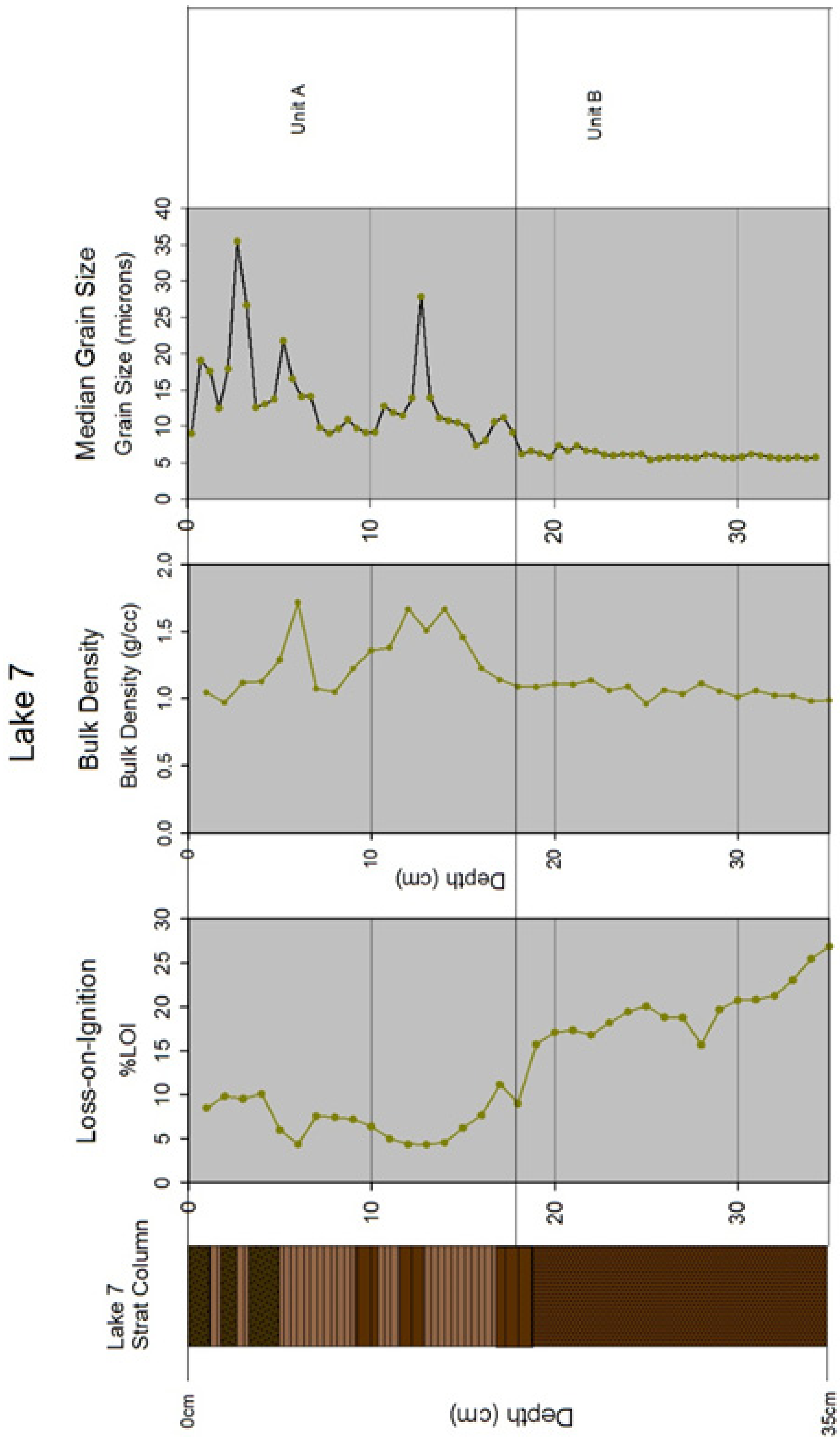


Figure 3.24: Laboratory analyses conducted on the Lake 7 core include LOI, bulk density, and grain size and these results provided supportive data to divide the core into different stratigraphic units.

GEOTEK MSCL

Lake 7

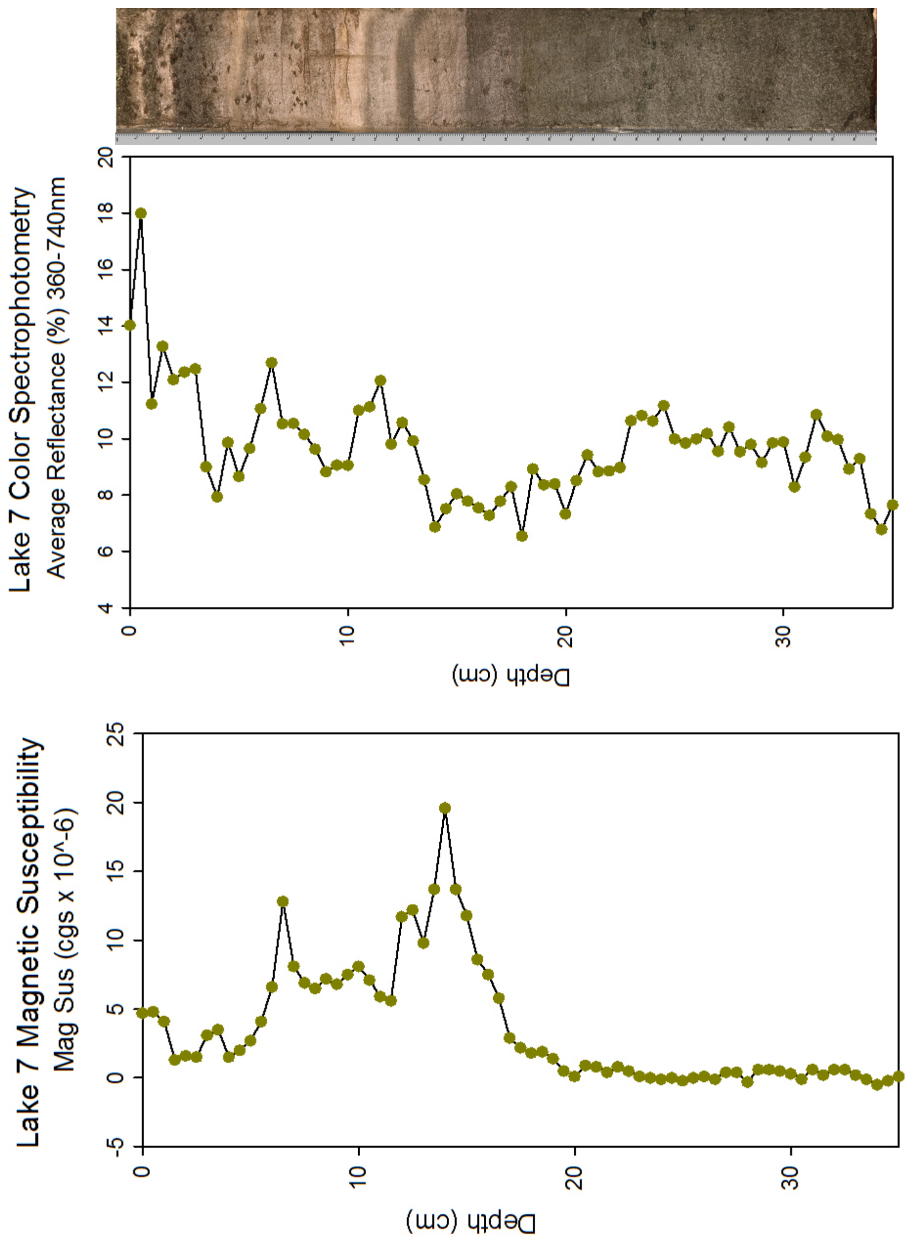


Figure 3.25: The GEOTEK core scanner provided a high-resolution photo of the Lake 7 core, magnetic stratigraphy down core as well as a full spectral color reflectance data, average reflectance is show here.

The bottom 15 cm show values for magnetic susceptibility ranging between 1 and 5. Similar values are seen in the first 5 cm of the core. There are peaks around 7 cm depth and 15 cm depth. These show values of roughly 15 and 21. The average reflectance shows an overall decreasing trend downcore, starting with values around 14 and 18 percent then dropping to roughly 6%.

Lake 4

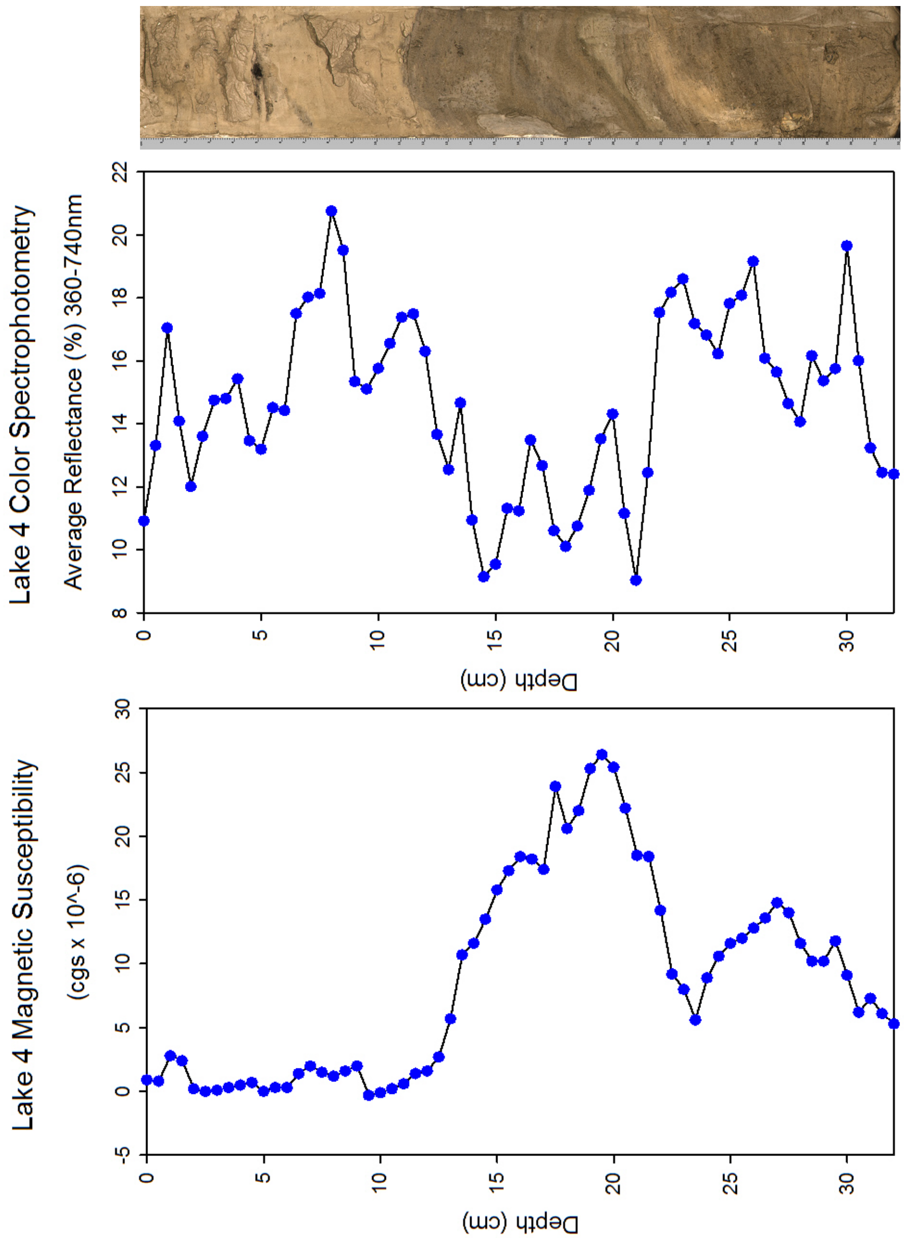


Figure 3.26: A high-resolution photo was produced for the Lake 4 core and changes in grain size in the scan is seen in the magnetic susceptibility values as well as changes in average color reflectance.

The magnetic susceptibility in the Lake 4 core had no apparent trend. There was low magnetic susceptibility in the first 13 cm, all falling below the value of 5. At the middle of the core, between 14 cm and 22 cm depth there is an increase in values running as high as 26. In the last 10 cm there is a decreasing trend in the magnetic susceptibility values. Average reflectance values range from 11% to 21%.

Analysis of Organic Matter

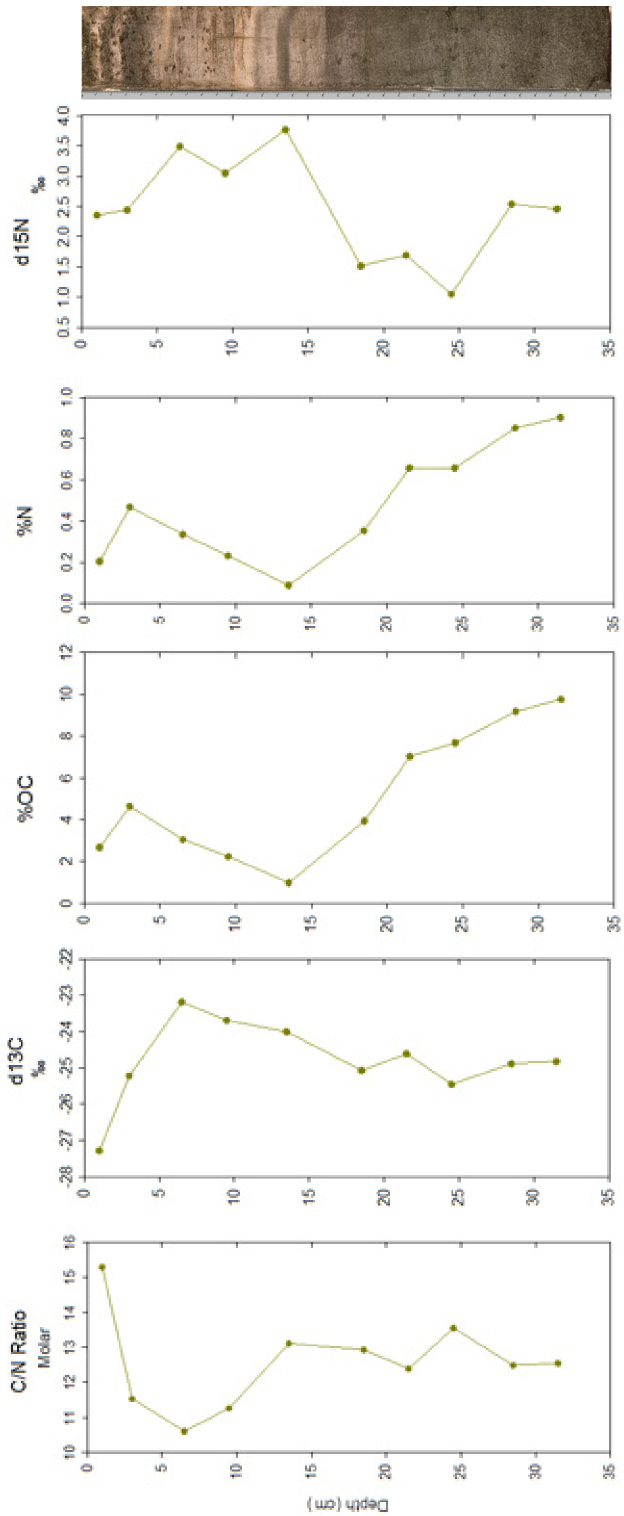


Figure 3.26: Percent organic carbon, percent nitrogen, delta ^{15}N, delta ^{13}C, and carbon to nitrogen ratios were measured for ten samples downcore for the Lake 7 core.

The C/N ratio values stay around 13% from the base until 13.5 cm depth. The top 10 cm have lower values between 10.5 and 11.5 and the top of the core has a peak just over 15%. The delta ^{13}C values are roughly -25 for the bottom 15 cm of the core. Values increase between 18.5 and 9 cm depth from -25 to -23. The upper 5 cm decrease to -27 at the top of the core. There are no apparent trends in the delta ^{15}N plot. Values at the bottom of the core are within the same 2.0-2.5 range as the top of the core. Between 24.5 and 18.5 cm depth the values are no larger than 1.7. Values increase between 13.5 and 6.5 almost as high as 4.0. The percent organic carbon and percent nitrogen show similar trends for overall concentrations. Percent organic carbon increases from 2% to around 10% downcore with a decreased value, 0.9%, at 13.5 cm depth. The same trend is seen for the percent nitrogen with upper core values around 0.2% increasing to just below 1.0% at the base of the core.

Plutonium:

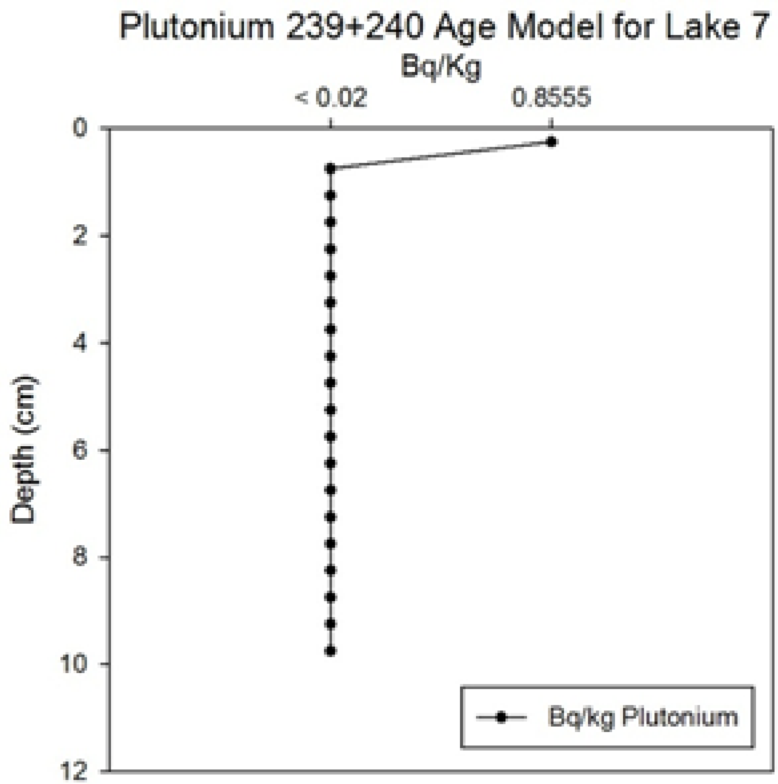


Figure 3.27 : A plutonium age model was attempted for the Lake 7 core but the highest values did not measure above 1.0 Bq/Kg.

The plutonium age determination was done for the upper 10 cm of the Lake 7 core. Results show on increase in plutonium in only the first 0.5 cm of the core, with a change from 0.02 Bq/kg to 0.8555.

Discussion

Geomorphology

The geomorphological mapping in the Vardeborgsletta region between the Lake 4 and Lake 7 watersheds exposes significant differences in the surface cover, features, and the processes surrounding both lakes.

There is little current sediment input into Lake 7 because of the minor inflow from Lake 8. Any movement of suspended sediment in the inflow is filtered by moss and other organics present in the channel between the lakes. The movement of water is minor at present resulting in little to no transport of the sediment from the inflow and outflow channels. In addition, the slopes that surround the lake are not very steep and are relatively stable. There is only evidence of slow mass-wasting (solifluction), reworked by waves, to contribute sediment to the lake.

Sorted and unsorted periglacial features are able to maintain their form as they migrate downslope into Lake 7. These features form with the annual freeze and thaw action in the active layer but because the lake's talik is not substantial enough to function as a heat source, there is no interference with the formation of periglacial features proximal to the lake. This presence of periglacial features around Lake 7 differs largely from the area surrounding Lake 4.

The only periglacial features found around Lake 4 are less distinctive and are located distal to the lake on the higher eastern and western plateaus. The slopes surrounding the lake are steep and provide an almost constant supply of sediment into the lake. The annual snowpack acts as a source of moisture to the slopes as well as a consistent inflow of summer snowmelt into the lake. Sedimentation in the lake increases over the course of the summer. The melt out from beneath the snowpack forms the small delta fan at the base of the southeastern slope. At the same time the thawing of the active layer loosens the sediment and the slope becomes more susceptible to rapid mass wasting (active layer failures) increasing the supply of sediment into the lake.

Åckerman (2005) undertook over thirty years of research at Kapp Linné studying the relationships between slope processes, active-layer thickness and climate controls. He demonstrated a positive correlation between temperature and downslope movement of sediment (Figure 4.1). This ultimately provides more sediment input into different catchments. Åckerman focused especially on large solifluction sheets that are developing below coalescing talus cones (2005). The west-facing slopes of Griegaksla, (west of Linnédalen) have sheets with lobate fronts that flow over flat surfaces of raised-beach ridges and marine terraces (Åckerman, 2005). The grey squares (Figure 4.1) show the surface movement of solifluction lobes in centimeters per year.

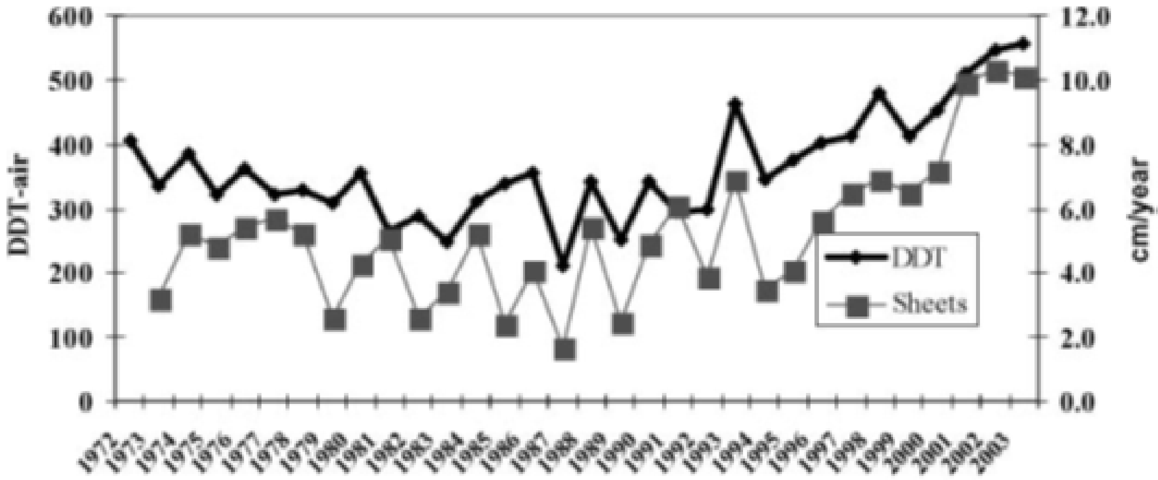


Figure 4.1: Summer temperatures shown as degree days thaw (DDT) plotted with the surface movement of solifluction lobes (Sheets). Increase in temperature shows an increase in surficial movement (from Åckerman, 2005)

Salvigsen (1985) describes the slopes in the Vardeborgsletta area as having very active solifluction processes that bring considerable amounts of sediment into the bottom of the basins. These observations were made in 1985 and observations made during the 2012 field season continue to find that the slopes surrounding Lake 4 and other "karst lakes" are very active. If Åckerman's calculations are accurate, the observed slope activity is increasing with temperature and time resulting in more sediment moving from the slopes into the catchment below. Salvigsen (1985) noted that the presence of periglacial features indicates normal permafrost conditions and concludes unfrozen boundaries within the continuous permafrost with pit excavation and temperature profiling. Because Lake 7 is surrounded by significant periglacial features it can be concluded that it is in an area of normal permafrost whereas Lake 4 is lacking defined periglacial features and experiences more slope instability and mass wasting events. This is surficial evidence of irregular permafrost.

Ground Temperatures

The stratigraphy and temperature profiles from the pits excavated around Lake 4 provide information from which the extent and influence of the lake on the ground thermal regime could be extrapolated. Pit # 7 was excavated 22 m from the southeast slope of Lake 4 and temperatures measured -0.1°C at the base (140 cm) of the pit. Pit #4 had a similar temperature profile to pit #7 because it also was excavated in the delta fan near the southeast slope. The other pits excavated proximal to the lake, however, did not show temperatures any colder than 5°C (Figure 3.5 and 3.7). This suggests that potentially the shade, snowpack, and wind-protected area of the southeastern end of the lake may have a less extensive talik beneath it, and with that less groundwater movement. The consistent accumulation of sediment from the slope in the small delta fan could also have an impact on the ground temperatures. This may be the only area proximal to Lake 4 where neither lake talik nor karst drainage has an influence on the ground thermal regime and less of an impact on the depth of the frost table.

The other pits excavated better reflect the influence of the lake talik and subterraneous water movement. Pit #1, found halfway between Lake 4 and Lake 3 (Figure 3.5), had water at the base and temperatures remained relatively warm due to groundwater flow between lakes. The pit on the western shore was well within the lake talik boundary maintaining a warmer temperature from below as well as absorbing heat in the thick insulating moss cover. A deeper pit, #8, was excavated in the delta fan 8 m from the water's edge in the dried up outflow channel to the sinkhole. This pit had the second warmest temperature at depth, measuring around 6°C at 160 cm depth and may be a reflection of its proximity to the water as well as in the flow path of the drainage to the sinkhole. The pit near the sinkhole (#6) had the warmest surface temperature and base temperature, never measuring below 8°C even at 130 cm depth. The warmer temperatures found closer to the sinkhole may be evidence of the islands and connecting channels of unfrozen ground through which lake water potentially percolates, drains, and flows during lake level changing events.

Soil pits excavated during Salvigsen's research in Vardeborgsletta (1985) were much deeper than those excavated during the 2012 field season and in different locations but both temperature profiles show dramatic temperature differences. Pit "A", excavated adjacent to Lake 1, does not show temperatures below 10°C in a 3.5 m deep pit. Pit "B" was similarly deep but temperatures were cooler. This pit was excavated near Lake 5. Pit "C" and "D" were excavated further up slope of Lake 1 in more normal periglacial features to act as control pits (Figure 4.2). Salvigsen concluded that there are permafrost free areas that exist closely within and connected by the large-scale depressions and trough features (1985). These areas free of permafrost can be seen in pits excavated that show no strong change in temperature down the profile.

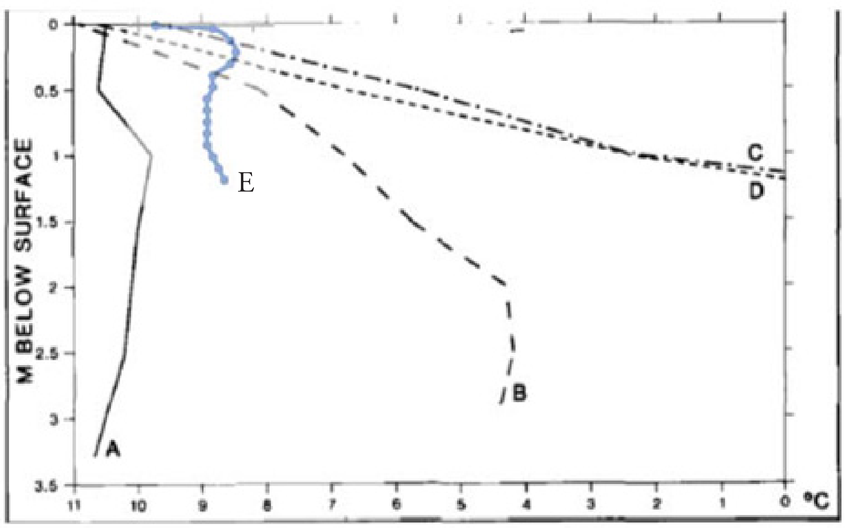


Figure 4.2: Temperature profiles taken close to Lake 1 (A), Lake 5 (B), and distal to Lake 1 (C and D) are those measured by Salvigsen (1985), plotted with these profiles is a shallower profile of a pit proximal to Lake 1 excavated during the 2012 field season (E).

Large-scale surficial evidence of irregular permafrost and karst terrain is seen throughout Linnédalen. One of the most distinct features is the trough-like feature running from Lake 5 north towards Isfjorden. Lake 4 is the lowest elevation found in the channel and outflow from all the lakes within the channel flow down to Lake 4. Very distinct geomorphological features are found next to lakes and within this trough-like feature. Previous shorelines are clearly etched into the channel walls (Figure 4.3) and large collapses and sinkholes are seen along the edge of Lake 6 (Figure 4.4) as well as near Lake 4 and further along the western side of Lake 3. These features are mainly found near lakes that exhibit rapid level changes and also tend to form in the areas that recorded warmer ground temperatures. In addition to the surficial karst features seen in the eastern part of Vardeborgsletta, a larger-scale feature is seen in the Norsk Polar Institutt aerial photographs (Figure 4.5). The slope processes and headward erosion seen at the southern end of Lake 1 are a result of active karst ground water movement. The pre-existing, late-Holocene raised beaches are truncated by the karst topography.

Figure 4.3: Former high-stand shorelines next to Lake 5 in the large-scale trough feature.

Figure 4.4: Collapse features seen proximal to Lake 6, from Salvigsen, 1985.

Figure 4.5: This aerial photograph of Vardeborgsletta clearly shows truncation of the raised beaches by karst features and topography. The headward erosion by Lake 1 is reworking the marine sediment from the raised beaches (Norsk Polarinstitutt).

Lake level Changes

The trends in the pit temperature profiles somewhat delineate areas of groundwater movement and lake drainage. This extent of groundwater flow affects the depth of frost table and potentially enhances the thaw of the active layer. Additionally, the consistent warm temperatures near the sinkhole simultaneously occurring with lake level changes through percolation of lake floor sediments strongly reflects a superior source heat, to that of a lake talik, more accurately explained to be a subterraneous karst drainage system.

The summer field season observations are reinforced by the ground temperatures logging in the steep southern slope show freezing temperatures in the winter months while the temperature logger near the sinkhole does not measure temperatures below freezing presumably maintaining groundwater movement throughout the year (Figure 3.18). The absence of frozen ground near Lake 4 was also observed in March 2012 when coring of Lake 4 was attempted but upon arrival at the lake, there was only a mosaic of ice on the lake floor (Figure 4.6). This ice may have formed but then a subsequent draining event caused the level to drop dramatically, leaving the surface ice, broken in mosaic form on the bottom of the lake. These draining events appear to happen sporadically throughout the year. Precipitation seems to have little to no impact on lake levels and the changes are probably entirely a reflection of the karst drainage system.

Figure 4.6: March 2012, a mosaic of lake ice seen on the lake floor after draining event (photo: M. Retelle)

Incongruences in the otherwise continuous permafrost are not only reflected in temperature profiles but also in the stratigraphy observed to depth in the pits. The sedimentological record of slope erosion and sediment input and lake level fluctuation is surficial and stratigraphic evidence of karst drainage and processes. The stratigraphic column seen in Pit #7 reflects a previously active south slope of Lake 4 with the cobbles at the base (Figure 3.6). The layer of organic matter on top of the cobbles could reflect more stable conditions in the lake or the surrounding area. The finer-grained terrigenous sediment the makes up the upper part of the pit coarsens upward and closely reflects both the high levels of sedimentation from thawing of snowpack and surrounding saturated slopes as well as the subsequent reworking of this sediment during lake drainages and level changing events.

The organic material found at the base of Pit #7 may potentially be from the reworking of the moss-rich shoreline cover and could have been suspended, detached, and floated to that site during a lake high-stand and then buried by delta fan sediment. The organics may have also just been carried in with the inflow when it was more substantial (Figure 3.6).

The "modern" ^{14}C age determined for the plant macrofossils at the 140 cm depth in pit #7 reflects rapid sedimentation in this periglacial karst terrain. The modern ^{14}C age presents all stratigraphy above the organic layer (130 cm depth) to have accumulated subsequent to the 1950's, 1960's bomb testing. Given the rapid sedimentation rate in the Lake 4 catchment the depth of sediment sampled in the Lake 4 core may be similarly recent and relatively young in age. The rapid input of sediment from the steep eastern slopes does not only form the small delta fan at its base but also continues into Lake 4 accumulating on the lake floor in alternating layers of fine sediment. This laminated section of the core may also reflect snowpack melting events, active layer thaw, and lake level changes. There may not be any direct correlation between the pit stratigraphy and the core stratigraphy because during lake draining events, coarser grained sediment from the lake edge are reworked into deeper sections of the lake, therefore showing no evidence of contemporaneous sedimentation layers grading from coarse to fine, from the delta to the middle of the lake.

In nearby Kongressvatnet similar lake level changes are seen in seasonal photographic monitoring and level logger data. In late winter and early spring, evidence of groundwater movement between the springs is seen as icings lower in the valley (pers comm. M. Retelle). Kongressvatnet is found within the same carbonate bedrock unit as in the Vardeborgsletta region and therefore could be connected to the broad karst drainage system. The REU team has collected bathymetric data from Kongressvatnet (Figure 4.7) and photographed level changes and previous shorelines on a seasonal basis. The deep sinkhole bathymetry, lack of a substantial outflow and bathtub rings (Figure 4.8) are evidence of drainage occurring through the sediments at the bottom of the lake.

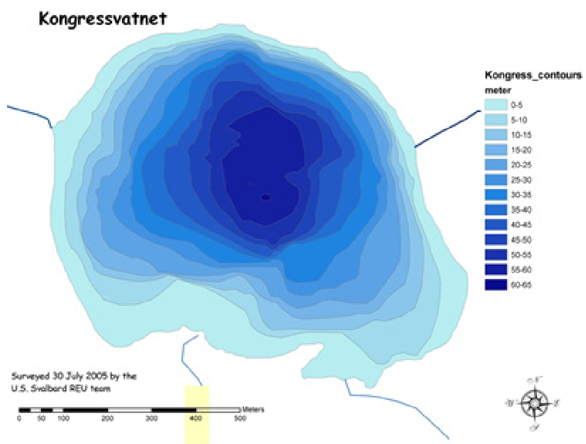


Figure 4.7: Bathymetric map for Kongressvatnet shows several inflows into the lake but depending on lake level has no clear outflow. Isobars are in 0.5 m intervals (REU Team)

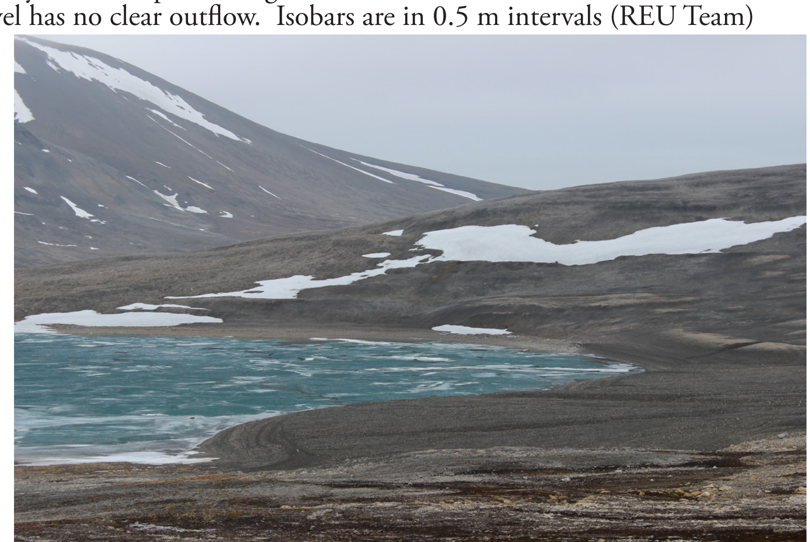


Figure 4.8: Bathtub rings marking previous shorelines are signs fluctuating and lowering lake levels.

Cores stratigraphies

The stratigraphies in both cores from Vardeborgsletta reflect distinct changes in hydrological and limnological regimes and changing lake level. The massive organic-rich silt that contains finely disseminated organic matter in the basal unit of the Lake 7 core reflects a period of stability and relatively quiet waters with autochthonous biogenic sedimentation. The upper unit of the core contains alternating terrigenous sediment from re-working of the Holocene-age marine sediments previously transported by periglacial processes. The plutonium age determination is not a reliable age model because either the "core top being blown off" during the coring process potentially due to a loose sediment water interface or the uppermost sediments in the lake had recently been eroded or reworked with lake level change. The insignificantly low levels of plutonium in the top 10 cm of the core until the top 0.5 cm could present the sediment to be relatively old, i.e. at the base of a typical $^{239+240}Pu$ profile, is at or prior to 1952 A.D. (Ketterer et al. 2004). In any case, the upper laminations in this core alternating between clay and silty organic layers could reflect seasonal sedimentation in the lake or reworking of different sediment sources with changes in air temperature. The clay layer could potentially mark periods when sediment is being reworked from periglacial features, when there is little to no lake ice. The dark silty and organic-rich layers settle and accumulate when there is less mobilization of terrigenous sediment in the lake and more productivity.

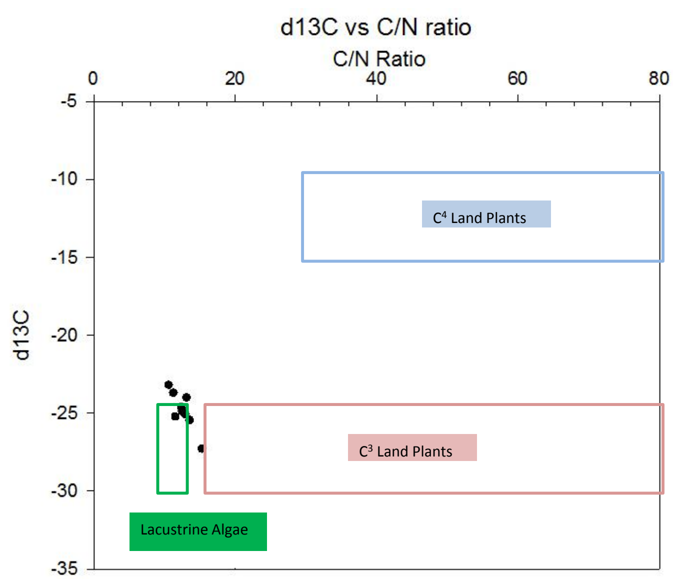


Figure 4.9: The analysis of the organic matter provided information about the source of organic material in the Lake 7 catchment.

When the C/N ratios are plotted against the $d^{13}C$ values, the Lake 7 samples clustered in between the lacustrine algae and C^3 Land plant parameters determined by Meyers (2003). This explains the current stable conditions of the lake allowing for organic production, but also recognizes the continuous input of sediment and organics from the increasing downslope movement of periglacial features. The basal unit of the Lake 7 core may consist only of lacustrine algae and could represent a period when there was a more established lake talik beneath the lake. This would affect the formation of periglacial features proximal to the lakes edge, therefore limiting the terrigenous source of sediment to the lake (Figure 3.25)

Based on the "modern" ^{14}C age for the pit organics, the slopes and sedimentation into Lake 4 is much more active than Lake 7. The sediment in the upper section of the core is allochthonous and the laminations in this unit closely reflection lake draining events. These events however are temporally sporadic and inconsistent volumes of water are lost with each draining event. This makes it difficult to reconstruct the timing of draining events from the sediment layer accumulation. The massive at the base of the pit may have accumulated during a more substantial melting or more significant sediment reworking event (Figure 3.26).

Karst in the periglacial regime in Svalbard

These karst systems are rare in areas of continuous permafrost because karst formation depends upon the solubility of calcium carbonate and groundwater interaction with the bedrock and this is would not be expected where the ground in always temporally and spatially frozen. The microclimate of Kapp Linné, however, is unique for Svalbard because of its maritime temperature climate. The combination of the carbonate bedrock and the high levels of precipitation and water availability may enhance the chemical weathering and dissolution of the carbonate bedrock and different karst drainages in this region.

Salvigsen (1983) has done research in other regions in Svalbard with flat lying limestone and evaporates that are highly susceptible to chemical weathering due to the tectonic formation of fissures and cracks. Observations have been made of other surficial karst features in raised beach sediments in Mathiesondalen, eastern Spitsbergen (1983). Earlier stages of karstification were discovered here as well as evidence of previously active karst systems. Salvigsen also found "fossil sinkholes" which are large depressions reaching 100 m in diameter, and some were found 70 m above sea level. There was evidence of surface stream flow but only when there was a surplus of water, otherwise in late-summer the ponds showed no visible surficial drainage (1983). These larger karst features could represent more active karst which forms geomorphological features of grater magnitude.

These active karst features may more extensive than what is observed in the Vardeborgsletta region today, but the large trough feature in Vardeborgsletta may represent a previously more active karst system that could be driven by different climate permafrost conditions. Salvigsen noted that the lowest lying depression in the study site had evidence of fresh slides in unconsolidated material there was no exposed bedrock. Similarly, there is no exposed bedrock near Lake 4 and the unconsolidated sediment is thick and the slopes are very active whereas there is exposed bedrock near the outflow and inflow of Lake 7 and the slopes remain relatively stable throughout the year. Proximity to bedrock outcrops and the depth of unconsolidated sediments may impact how much the active layer thaws during warm season as well as how much unconsolidated sediment is reworked from rapid and slow mass wasting events.

As seen in Linnédalen (Figure 4.5), the raised beach sediments in the Mathiesondalen region also appear to be truncated by karst features. Salvigsen describes the sinkholes as forming within the unconsolidated marine sediments above collapsed subsurface caves and tunnels and these tunnels and caves were formed when there was downward solution of the bedrock (1983). The strandlines seen between Kapp Linné and at the north end of Linnédalen and in Mathiesondalen have been formed almost continuously from 11,000 yr B.P. to the present which would make the surficial karst features Holocene age (Salvigsen, 1983). However, it may be possible that the modern geomorphic features are evidence of a relict karst system, reactivated at some time in the Holocene. The larger tunnels and caves resulting from chemical weathering during or before the accumulation of unconsolidated sediment may have just been preserved during colder periods and reactivated with an increase in mean annual ground and air temperatures.

Conclusion

The geomorphological evidence in the Vardeborgsletta region shows signs of previously active and currently active karst systems. The Holocene age marine sediments are truncated by various erosional features surrounding studied lakes that reveal the timing of the recent karst system activity as subsequent to Holocene marine sedimentation in Linnédalen. Periods of permafrost development, for instance during the Neoglacial or Little Ice Age, may have prevented or delayed drainage in the karst system.

The cores from Lake 4 and Lake 7 provide sedimentological records for active and inactive karst lake catchments. High sedimentation rates around Lake 4 reflect the continuously active surrounding slopes as well as the sporadic lake level changes through the lake talik connecting the surface waters to the groundwater moving through the karst system. Lake 7 reflects a more stable lake environment containing an overall organic-rich sediment record with pulses of terrigenous sediment coming from the sustained advancement of the surrounding periglacial features into the lake waters.

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