A Karst Lake System in the High Arctic: A Case Study at Linnédalen, Svalbard

AG-212 Holocene and Modern Climate Change in the High Arctic

Term Report 2010 - University Centre in Svalbard

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Introduction

The island of Spitsbergen, which makes up the largest portion of the Svalbard archipelago, is located in the high arctic, between 74° and 81° north. This high latitude Arctic environment provides the means for widespread permafrost formation. Currently, Svalbard is 60% glaciated, leaving 40% and approximately 25,000km as a permafrost and periglacial environment (Humlum, 2003: 199). Glaciers, permafrost, and periglacial features can all be widely observed on Svalbard. This study will look at a system of karst lakes found in an active and continuous permafrost zone on Svalbard. Karst is a globally spread phenomena which commonly occurs in regions consisting of carbonate rocks and evaporites when weathering and erosion occurs (Ritter et al, 2006: 407).

Although karst is found in every region on earth, it is mostly found in temperate or tropical climates, because moderate temperatures, humidity, high precipitation, free flowing water, and high vegetation levels are all seen as favorable factors for formation (Ritter et al, 2006: 412). Karst is not nearly as frequently found in Arctic climates, due to the typical Arctic conditions of extremely low temperature, low precipitation, frozen water, and low vegetation being unfavorable for the formation of karst features. There have been relatively few studies of karst features occurring in High-Arctic environments. These studies have been mostly concentrated in Canada, the United States, Russia, and Svalbard. It was originally thought that only thermokarst features could form in the arctic, and true karst could not exist, because the chemical weathering needed to form karst was prevented by permafrost (French, 2007: 69). Thermokarst is not related to karst, and has nothing to do with the solubility and weathering of limestone or evaporites. The relationship of the two names can be explained, because the thaw of permafrost leads to thermokarst features, including the collapse, subsidence, erosion, and instability of the ground surface, which would appear similar to the results of true karst (French, 2007: 186.). It is now known that true karst can exist in the High-Arctic. Studies by D. C. Ford have resulted in the development of a model for karst existing in permafrost zones, with the groundwater circulation and solution being limited to the active-layer, allowing for shallow karst terrain (French, 2007: 69).

The previous studies of karst systems in the High-Arctic have been done on karst systems in Svalbard, the United States, Canada, and Russia. In a study done by I. D. Clark and B. Lauriol at the Firth river basin, in the Yukon, Canada, the drainage of water from karst systems is proven to flow through taliks, and then resurface in the growth of an aufeis. In Svalbard, Northeast of the study area, a karst system has been studied by O. Salvigsen, Ø. Lauritzen, and J Mangerud. Here, the authors have only been able to conclude that the water must drain below the active layer of two meters, but cannot determine the mechanisms which make this drainage possible. A study by O. Salvigsen and A. Elgersma in Svalbard focuses on the same area as this study. They were able to determine that the lakes in the study area were true karst, but did not attempt to date the formation of the karst. They did, however, try to determine how the water drained through the karst system, by performing dye tests and digging pits in the area, but were unsuccessful.

In order to further the understanding of karst systems in High-Arctic climates consisting of active permafrost zones, this report will take a comprehensive look at a karst lake system located in Linnédalen, Svalbard. The report will include a geomorphological map created after a month long period of observations in the study area which aims to catalogue the periglacial features and processes occurring in the area. The report will also attempt to come up with an explanation of when and under what conditions the karst lake system was formed. Finally, the report will include an interpretation of how the water in the lakes drains vertically through the permafrost. This report is meant to be the first part of a continuing study of the karst lakes in Linnédalen. At the end of the report there will be a plan for the continuation of the study.

Study Area

Linnédalen is a valley located in Western Spitsbergen, the largest of the islands which comprise the Svalbard archipelago. The Svalbard archipelago is located between 74° and 81° North in the Barents Sea.

Figure 1

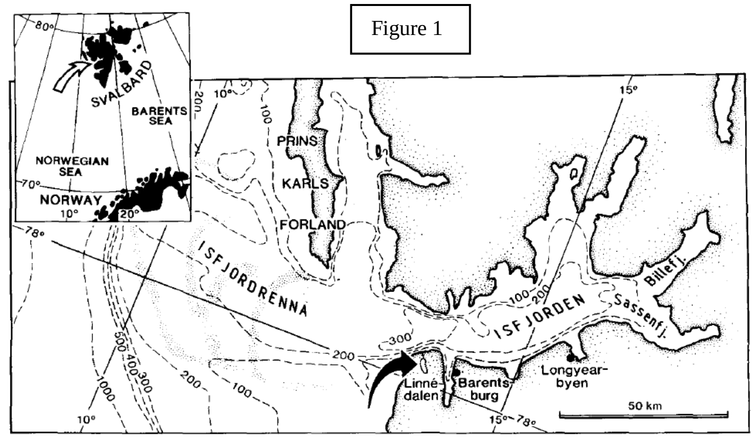
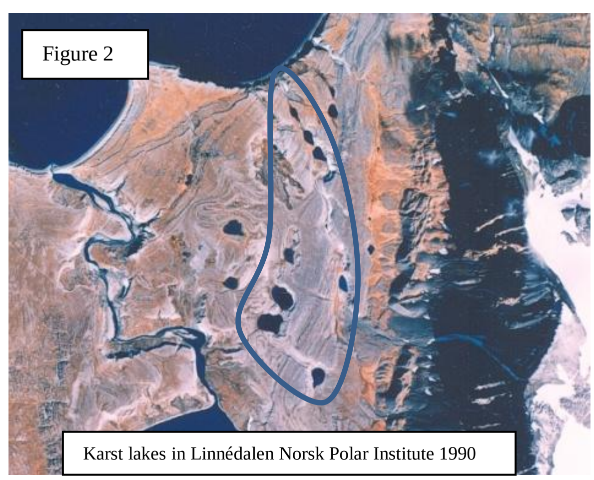


Fig. 1. The Isfjorden area on the west coast of Svalbard. Location of the Linnédalen valley is shown by the arrow. Possible submarine end moraines (shaded) after Ohta (1982). Bathymetry in metres (from Map 503, Norsk Polarinstitutt 1975).

The mean annual air temperature at Linnédalen, taken from air temperature records from Isfjord Radio (approximately 3.5km west) is -4.8°C from the period of 1912-1975. The annual precipitation is 400mm, taken from the same time period (Åkerman, 2005: 116). These conditions are not typical of locations abundant in karst landforms. Svalbard is located within the zone of continuous permafrost, with observed depths ranging from 75-450 meters (Salvigsen et al, 1985: 148). This location in Linnédalen has been the study site of many research projects over the years through the Svalbard REU program. Linnédalen contains a glacier-river-lake-river-ocean system. The karst lake system is located to the north of the glacier and main lake, Linnévatnet. It is close to the ocean, on the Vardeborgsletta plain, about 30 meters above sea level (Mangerud et al, 1990: 249). During the majority of the year, the ground in this area is completely frozen, and the lakes are also frozen. The short active-layer and thawing/melting season in Linnévatnet typically extends from June to August, with limited activity

Figure 2



Karst lakes in Linnédalen Norsk Polar Institute 1990 existing from the end of May to October (Åkerman, 2005: 123).

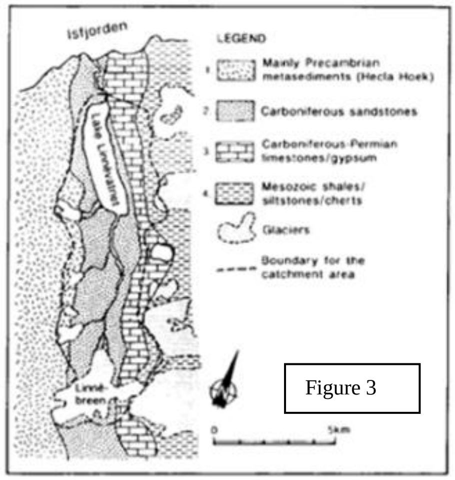


Figure 7 Simplified bedrock map of the study area (modified from Hjelle *et al.*, 1986). Note that Linnébreen erodes coal-bearing rocks.

Bedrock Map of Linnédalen (Svendsen et al, 1989)

Although the study area lies in a zone of continuous permafrost, the local geology of the area is suitable for the karst formation. In the eastern side of the valley, where the karst lakes are located, the observed underlying bedrock is limestone, gypsum, and dolomite, deposited during the Carboniferous and Permian, ranging from approximately 350-250 million years ago (see figure 3) (Svendsen et al, 1989: 157).

Background

Karst Formation

Karst is defined by Jennings (1985) as, "terrain with distinctive landforms and drainage arising from greater rock solubility in natural water than is found elsewhere." In a typical karst system, the most soluble rocks in the area will succumb to weathering and erosion and develop cavities. These cavities in the rock may become linked and cause the overlying ground to collapse. Surface water will seep through sinkholes to the cavities underground. This results in poorly developed surface drainage, with extensive underground drainage (Ritter, 2006: 407). Rocks with the highest level of carbonate material are the most susceptible to solution, and therefore will most often be the rock that karstification occurs in. Limestones or dolomites are often the rock which will be the most soluble in any given area (Ritter, 2006: 409). Porosity is also an important factor in karst formation. The amount of secondary porosity and permeability in rocks is what determines if the rock can hold water and allows the water to circulate. Zones of weakness, including fractures, faults and joints will encourage permeability and increase the chances of karstification (Ritter, 2006: 410).

Solution is the driving process of karstification. Mineral calcite is soluble in pure water, and in very simple terms, the more carbon dioxide dissolved in the water, the stronger the solution becomes. Water with high levels of dissolved carbon dioxide will attack the calcite and begin the process of creating the karst features. Because the water in the Arctic is generally frozen for the majority of the year and permafrost inhibits circulation, karstification is a rare phenomenon in the arctic, although not impossible (Ritter, 2006: 412). Solubility is not the limiting factor which prevents the widespread of karst in the Arctic. Calcium carbonate dissolves more readily in colder temperatures, so it could be concluded that solution activity would be greater in the Arctic. This has not been found to be true however. Since solubility is not the limiting factor, the aridity of Arctic climates is believed to prevent the development of karst (French, 2007: 69). If large areas of limestone with a high concentration of calcite exist and solution processes attack joints, bedding planes, and other weak areas, there is the opportunity for karst to develop in the Arctic (French, 2007: 69). Calcareous bedrock, as well as zones of weakness are both present at the study site, creating an area which is suitable for the formation of karst. The study site is also located in a coastal area, and has higher documented precipitation rates than many Arctic areas, making it less arid than the typical Arctic climate.

Frozen Ground Patterns

Frozen ground patterns are one of the defining features of periglacial and permafrost zones in Arctic and Subarctic climates. A. L. Washburn classifies and distinguishes the different patterns in his classic 1956 paper, which include sorted and nonsorted circles, polygons, stripes, nets and steps. Washburn gives two primary criteria for the classification of a frozen ground pattern, which are: (1) its geometric shape, and (2) whether the material composing the feature has been sorted. There have been many different theories on how these patterns develop. In 2003, Kessler et al published a paper in *Science* giving a theory to the development of these patterns. Kessler et al reasoned that these patterns arose because of freeze-thaw cycles which drive an interplay between two feedback mechanisms. The study stated that, "the formation of ice lenses in freezing soil first sorts stones and soil by displacing soil towards soil-rich domains and stones toward stone-rich domains. Second, stones are transported along the axis of elongate stone domains, which are squeezed and confined as freezing soil domains expand". The study developed numerical models which could produce outputs of the different shapes by changing the dominating force, and hillslope gradients.

The appearance of frozen ground patterns are an indicator of an active permafrost environment. In the study site, frozen ground patterns are present, and appear to be active, indicating that the karst lakes are draining in a zone of active permafrost.

Hillslope Processes

In permafrost environments, the mass wasting of slopes is a widespread phenomenon. On gentle slopes, the slow mass-wasting process, solifluction, commonly occurs. When pertaining to permafrost environments, solifluction is known as gelifluction (French, 2006: 225-228). Gelifluction generally occurs during the thaw period, and is usually restricted to the top half meter of the active layer (French, 2006: 228). The movement of sediment downslope is associated with frost creep. Frost creep occurs from either one-sided or two-sided freezing. Both scenarios have to do with the variables of the frequency of freeze-thaw cycles, angle of slope, moisture available for heave, and frost susceptibility of the soil (French, 2006: 227).

Permafrost Hydrology

Although there is quite a bit of literature regarding the surface hydrology of permafrost, little is known concerning how water drains vertically through permafrost. The impermeability of permafrost restricts water from moving through it, yet it has been documented in places that water does indeed travel through the permafrost. This movement is made possible by taliks, or unfrozen zones in the permafrost (French, 2006: 104). In the case of this study, either intra-permafrost or sub-permafrost taliks of some sort must exist in order for the water to drain through a karst system. Both open and closed taliks exist within continuous permafrost. Open taliks result from local heat sources, while closed taliks result from a change in thermal regime of permafrost (French, 2006: 105). There is no one model that exists to explain how water drains through permafrost in different regions, because in each specific location where this phenomena occurs, different variables exist which influence the creation of a drainage system. This leads for the need of individual investigation for each case. Figure 4 shows an interpretation of water draining through taliks in a continuous permafrost zone from Clark et al.

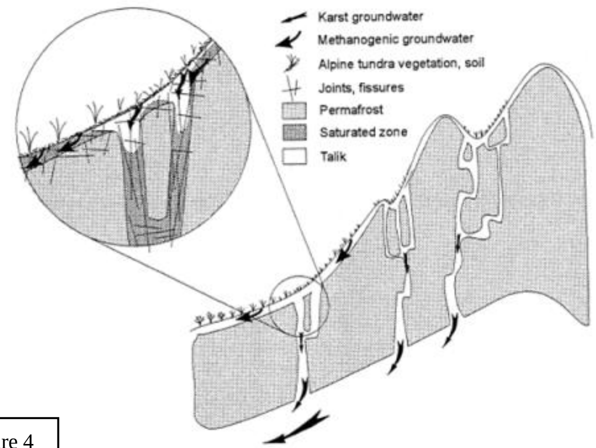


FIGURE 13. Schematic representation of recharge and circulation of methanogenic and karst groundwaters, and the growth of aufeis in the carbonate terrains of the northern Yukon. Diagram represents a hypothetical section across the upper Firth River valley (not to scale).

Figure 4

Interpretation of drainage through permafrost, figure modified from Clark et al, 1997

Methods

The methods for this study included one month of time spent in the Linnédalen area on the West coast of Spitsbergen. During this month, trips to the study site of the karst lakes were made on average of five times per week to observe and take note of the periglacial features and landforms in the area. Documentation of fluctuating lake levels was also noted by placing rock cairns on shorelines and observing changes during the month spent in the area. Notes were taken directly on maps of the area, and extensive photographs documenting the landscape and features were taken. The observations taken from the field were then transferred to a map, utilizing the programs Photoshop, and ArcMap to create the map. A basemap of the Vardeborgsletta plain in Linnédalen was used. The basemap uses the coordinate system WGS1984. The UTM Zone is 33N. The projection is Transverse Mercator. Observations from the study site were drawn on the .tiff (tagged image file format) file of the basemap package in Photoshop. It was then imported into ArcMap, where a 1990 aerial photograph of the area from the Norwegian Polar Institute was georeferenced on top of it.

Other field methods included surveying the karst lake area in order to get elevations of the lake surfaces relative to each other and to sea level. This was done using a TOPCON GTS-220 Series Total Station. The data from this will be used to create transects of the karst lake system. The data from that portion of the field collection is not available in this part of the report, but will be included in a follow-up portion.

An extensive examination of literature pertaining to past studies done at the study site was also completed. This was done in order to aid in the creation of hypotheses for the study. The first hypothesis is for the timing of formation of the karst lakes. The second hypothesis is for a possible drainage system for the water moving within the karst lake system.

Map

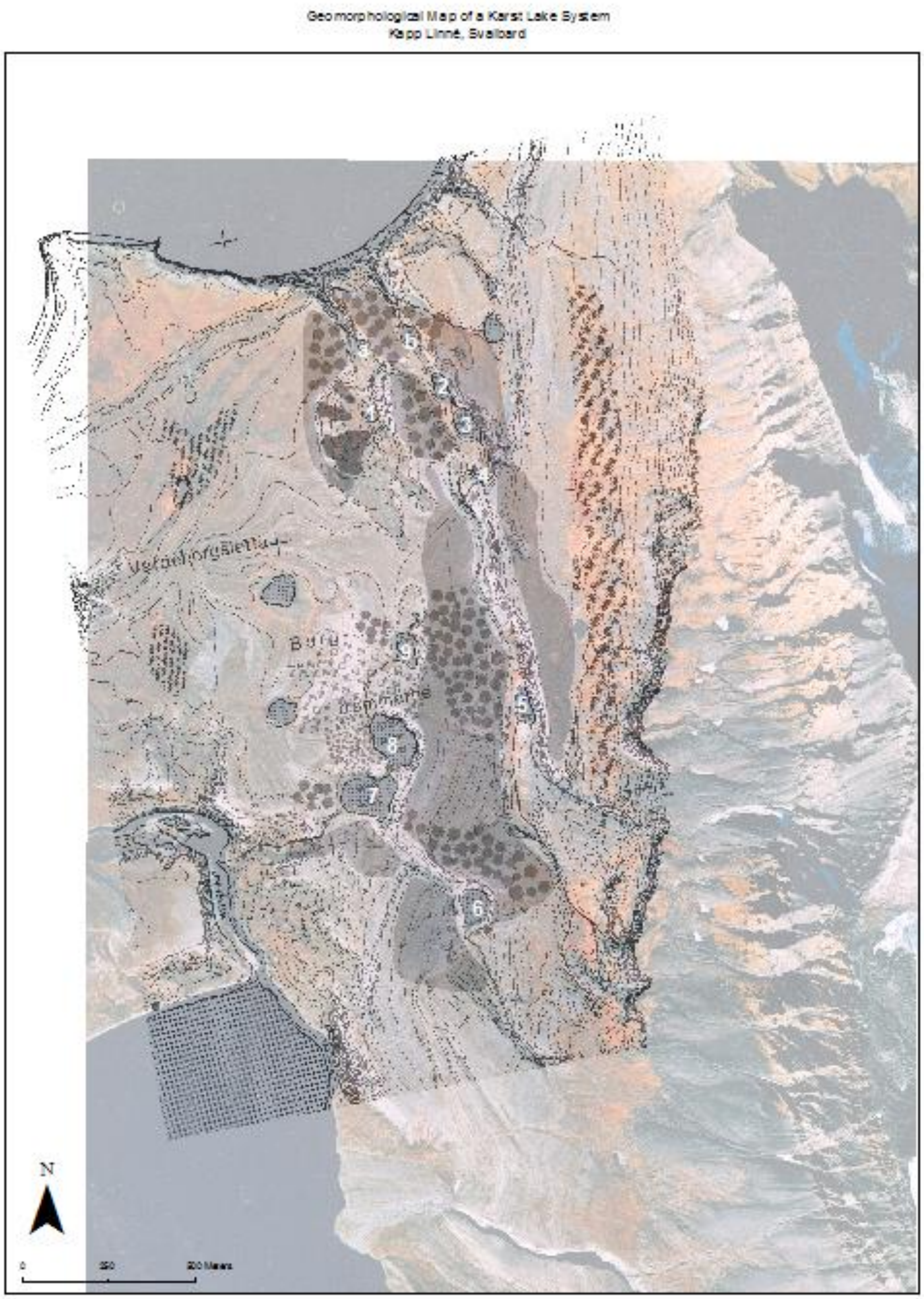
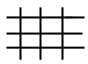
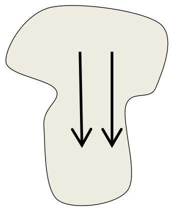


Figure 5: Map identifying processes occurring at the study site by the author

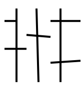
Key

Netting 

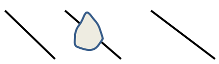
Downslope Sediment Transport 

Solifluction Lobe 

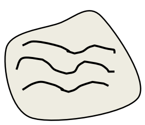
Relict Channel



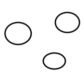
Active Channel



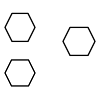
Lake



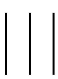
Sorted Circles



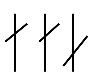
Ice Wedge Polygons



Sorted Stripes

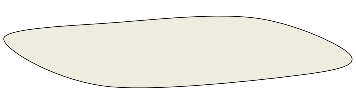


Unsorted Stripes



Relict Shorelines

Beach Terrace



Sinkhole

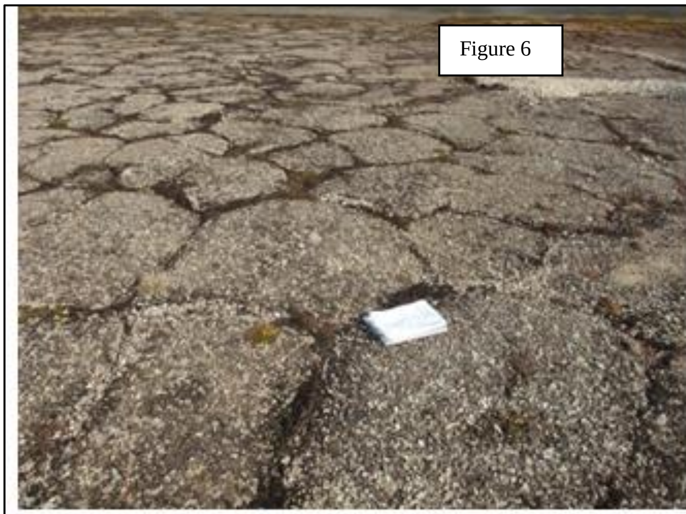
Analysis and Discussion

By analyzing the different processes occurring at the study site, it can be determined that the study site is an active permafrost zone. This section gives a catalogue of some of the observed processes.

Ice Wedge Polygons

Ice wedge polygons are unsorted polygons characterized by bordering ice wedges, and appear unsorted due to the lack of a border of stones (Washburn, 1956: 832). Ice wedge polygons were well distributed over the entire study site, appearing in varieties of different sizes. Some stretched up to five meters in diameter, while others were approximately a half meter in diameter. Some groups of the ice wedge polygons appeared to be active, with recently formed cracking visible (see figure 6). Additionally, other groups appeared to be relict from the heavy and well established amounts of vegetation appearing in the borders of the polygons (see figure 7). Because permafrost is always associated with ice wedge polygons (Washburn, 1956: 833), it can be assumed that the study site is an active permafrost zone.

Figure 6



Picture taken by author from close proximity to Lake 7

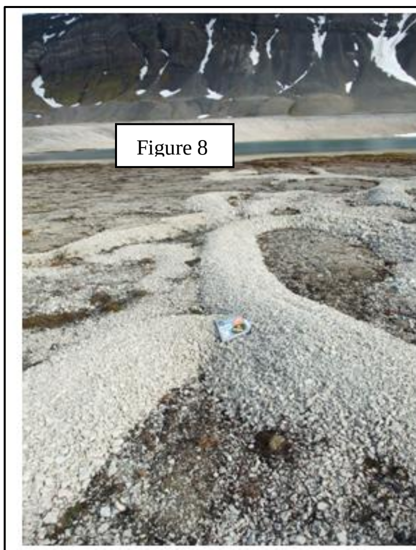
Figure 7

Picture taken by author between Lake 6 and Lake 7

Sorted Netting

Sorted nets appeared extensively over the site, especially close to Lakes 7 and 8. Nets are defined by Washburn, 1956, as, "patterned ground whose mesh is intermediate between that of a sorted circle and a

Figure 8

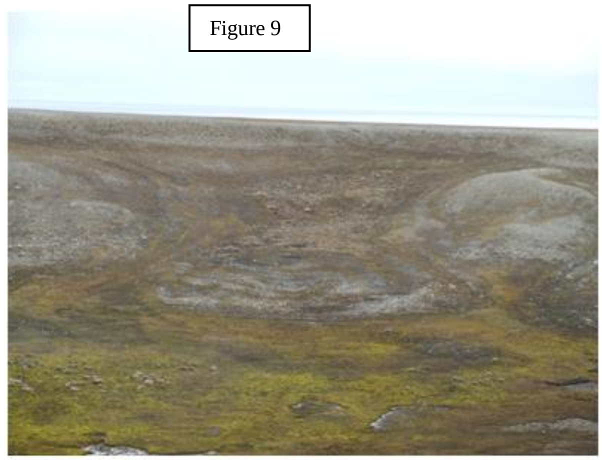


Picture taken by author close to Lake 3

sorted polygon and has a sorted appearance commonly due to a border of stones surrounding finer material". This patterned ground was classified as netting, because it appeared to be an intermediate between circles and polygons, and was on flat ground which discouraged the thought that it could possibly be categorized as sorted steps (see Figure 8). The stones that made up the netting were all of similar clast size, which were approximately 3-5cm in length. Most of the netting appeared to have formed on top of previously formed unsorted circles, leading to the thought that these patterns have been formed relatively recently compared to other frozen ground patterns at the study site.

Solifluction

Figure 9

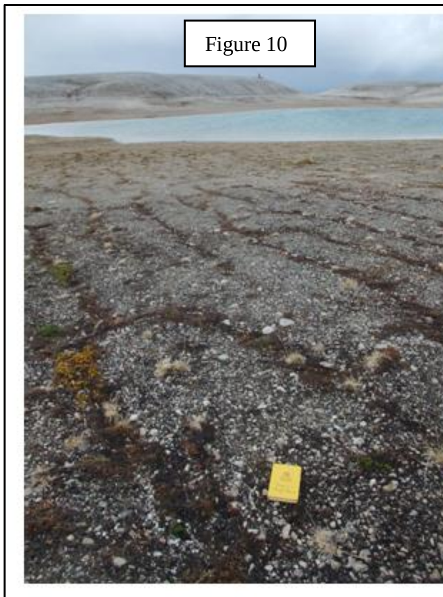


Picture taken by author at Lake 1

Solifluction lobes were a prominent feature on the west side of Lake 1 (see figure 9). Solifluction is categorized as a slow mass-wasting process, and described as "slow flowing from higher to lower ground of masses of waste saturated with water" (French, 2007: 225). Because the solifluction at the study site is assumed to be in a permafrost region, it is termed as gelifluction. The gelifluction lobes at the study site indicate that there are active freeze-thaw processes occurring which are associated with the thawing of the active layer during the melt season. When the active layer unthaws, water cannot penetrate more than a few meters down through the impermeable permafrost which underlies the active layer. This water saturates the soil and increases pore pressure which creates a loss of friction and cohesion and causes the soil to creep downslope (Ritter, 2006: 375). The presence of gelifluction lobes leads to the belief that water in the study site cannot drain vertically in most areas, and the presence of taliks is necessary for water to drain vertically beneath the karst lakes.

Unsorted Stripes

Figure 10



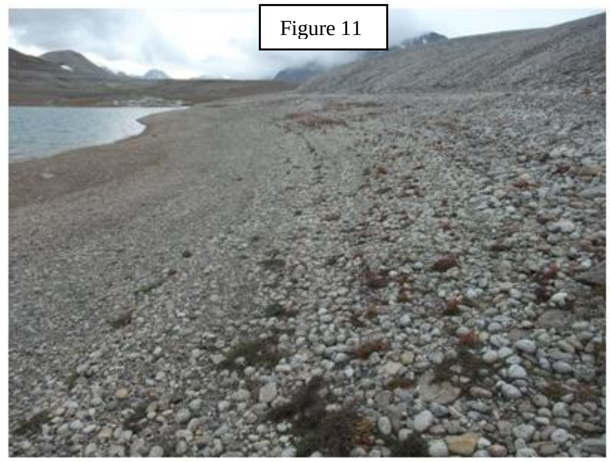
Picture taken by author at Lake 6

Unsorted stripes occurred close to many of the shorelines of the lakes and, especially in gentle sloping areas (see figure 10). According to Washburn, 1956, unsorted stripes are classified as, "patterned ground with a striped pattern and a nonsorted appearance due to parallel lines of vegetation-covered ground and intervening strips of relatively bare ground oriented down the steepest available slope". In many situations at the study site, unsorted stripes emerged out of other frozen ground patterns as the slope increased, which occurred most often moving towards the shorelines of the lake. Because unsorted stripes appeared in such close proximity to the shorelines, it leads to the belief that if taliks are present in the area for the draining of the karst lakes, they must be limited to small areas directly under the lakes, or deep down in the permafrost.

Relict Shorelines

Relict shorelines appeared at multiple lakes, and were especially prominent at Lakes 1 and 6 (see figure 11). They were well preserved on ground which was gently sloping or relatively flat. At Lake 6 there were ten different relict shorelines documented. Some of the shorelines looked as if they had not been reached by water in many years; certainly decades and possibly centuries in some places. Well established vegetation in the area of the relict shorelines (see figure 11) is an indicator for these long time periods of no water. Plant growth in the arctic is very slow due to a short growing season and harsh conditions, with millimeters of growth taking years in some cases, so the establishment of the vegetation would have taken a long time (Wager, 1938). The actual dating of plants would give a better idea of how long it has been since water has reached these relict shorelines. The development of a better drainage system for the karst lakes could be an explanation for the lower water levels.

Figure 11

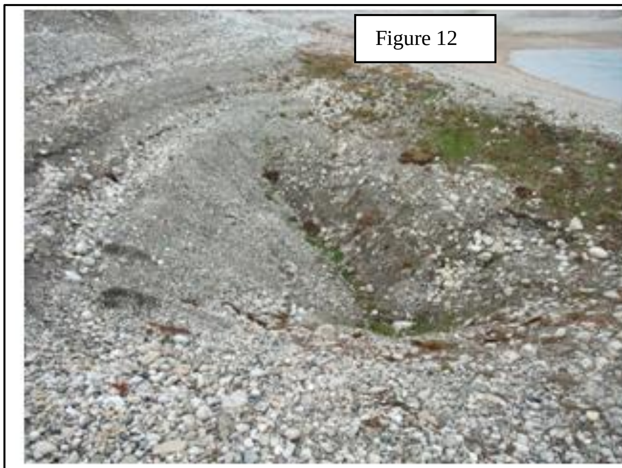


Picture taken by author at Lake 6

Sinkholes

Visible sinkholes, both dry (see figure 12) and containing water (see figure 13), were present at various locations around the study site, including Lake 6, Lake 4, and in the dried up river bed which runs between Lake 4 and Lake 5. Sinkholes, which are also known as dolines, form either by water infiltrating into joints and fissures and causing the enlargement of cracking, or by collapse from solution occurring beneath the surface (Ritter, 2006: 419, 421). Sinkholes are the most common karst landform, and a definite indicator of karst activity. Dry sinkholes at the study site (see figure 12) which are no longer reached by the lake water but

Figure 12



Picture taken by author at Lake 6

Figure 13

Picture taken by author at Lake 4

contain their own relict shorelines indicate that karst activity has been occurring at the study site for long periods of time. Sinkholes which still contain water and actively drain (see figure 13) are indicators that karst activity is presently occurring at the study site. Observed activity at the sinkholes still containing water included day-to-day lowering of the water level and water spiraling down into the sinkhole.

Fluctuating Water Levels

During the month spent at the karst lake system in Linnédalen, fluctuating water levels were observed. Cairns were setup (see figure 14) at each of the karst lakes during the first few days at the study site, and in most cases water level made significant decreases by the end of the study period. In a few cases water level went up, but this occurred at lakes which experienced significant snow melt during the study period. The only lakes which had outlet rivers which could have led to surface drainage were Lakes 7, 8, a, and b. None of the other lakes had river outlets and had no other means of surface drainage.

Figure 14

Picture taken by author at Lake 6

Hypothesis for the time period of formation of the karst lakes

The time period of formation of the karst lakes is not known. The estimate in this study comes not from using dating methods, but instead from reviewing the geologic history of the study site. The karst lakes are located in bedrock which was deposited during the Upper Carboniferous-Permian, 300-250 million years before present (Salvigsen et al, 1985: 146). Svalbard was located at around 40° N during this time period, and has been slowly moving towards the North Pole to its current location of 74°-81° north.

Preferable conditions for the solution of rock include zones of weakness such as joints and faults, which originate from tectonic activity (Ritter, 2006: 410). During the Tertiary, which dates from 65-1.8 million years before present, extreme deformation occurred on Svalbard due to tectonic activity. During the Paleocene and Eocene a major transform fault zone developed between Svalbard and Greenland with 1000 kilometers of dextral movement along the fault. In the western hinterland zone along the west coast of Svalbard there was a major strike-slip fault, which is a NNW striking lineament with a strike length greater than 60 kilometers. It consists of steeply dipping, intensely deformed slivers of Carboniferous through lower Permian strata within Caledonian basement rocks. On the Vardeborgsletta plain there is a low angle thrust ramp of two thrusts cut into the Kapp Starostin formation (Braathen et al, 2010). These Tertiary events would have created zones of weakness which could have encouraged the karstification of the bedrock.

The deformation was completed by the Oligocene which ended 23 million years ago (Braathen et al, 2010).

During the last interglacial period, Western Svalbard was often completely glaciated. The location of the karst lakes was completely deglaciated by 12,500 years ago, which is known by dating shells (Svendsen et al, 1991: 215). Although there were advancements of glaciers after this documented on Svalbard, Linnébreen, the glacier in Linnédalen, never reached the karst lake area (Svendsen et al, 1992: 216). After the area was deglaciated sea level was much higher than present and completely covered the current location of the karst lakes. It is thought that if the karst lake system was formed before this time period, the system would have been completely filled with sediments from this time of high sea level (Salvigsen et al, 1985: 152). When sea level went down in the early Holocene, Vardeborgsletta contained no permafrost (Salvigsen et al, 1985: 152). This indicates that the early Holocene would be a likely time for the karstification process to begin. From 10,000 to 8,000 years before present sea level dropped almost 40 meters on the Western coast of Svalbard (Landvik et al, 1987: 41). If the karst system did indeed begin to develop after the last glaciation of the Linnédalen area, it would have had to begin developing shortly after this drop in sea level, because the system appears to be quite developed and chemical weathering rates on Svalbard are estimated to be slow. Åkerman estimated the rate of chemical weathering to be 2.5mm/1000 years. Others have estimated the rate to be up to 15.75mm/1000 years (Svendsen et al, 1989: 164), but considering that the karst system may have not started to develop until 10,000 years ago, the development would need to have started immediately. During this window of time from 10,000 to 8,000 years before present, the Younger Dryas event occurred, causing Europe to become quite cold and lowering the ELA of glaciers. This event did not appear to have much effect on Svalbard. Temperatures were relatively similar to those today (Svendsen et al, 1991: 218), and the permafrost in this area was not well established yet (Salvigsen et al, 1985: 152), creating a possibly good environment for the establishment of a karst system. However, according to paleoclimate records, Svalbard was significantly more arid during this time period than at present, so not all conditions were perfectly ideal (Svendsen et al, 1991: 218).

Interpretation of the hydrology of the drainage system

There have been previous studies done to attempt to explain how the karst drainage system works in the permafrost conditions at this particular set of karst lakes. Salvigsen and Elgersma did a study of this karst lake system in 1985. They dug pits within close proximity to the lakes near the water level of the ponds but were met with dry permafrost conditions. They concluded that the water must be draining vertically down from the karst lakes through the sediments without horizontal movement (Salvigsen and Elgersma, 1985: 152). They also made an attempt to trace the water through the lakes by performing dye tests, but had no success.

In typical karst drainage systems, the water drains through karst aquifers in three ways, “(1) intergranular pores within the unfractured bedrock, (2) joints and bedding planes imparted to the strata following deposition and lithification, and (3) conduits that have been enlarged by aggressive solutions," (Ritter et al 2006: 414). The impermeability of the underlying permafrost in this area complicates the understood methods for karst system drainage.

A reasonable explanation for the drainage of the karst system would be an arrangement of taliks existing under the lakes and sinkholes in the area. The taliks would in all likelihood be both hydrothermal closed talik. Closed taliks result from a change in thermal regime of permafrost possibly from lake drainage and downward aggradation of permafrost. Hydrothermal taliks are non-cyrotic which maintain a temperature above 0° Celsius by heat supplied by groundwater flowing through the talik (French, 2007: 105). It is possible that there is some kind of network of narrow taliks stretching down possibly hundreds of meters into the permafrost which eventually allow the water to drain out to the ocean. There is also the possibility of some sort of weak geothermal heat source which is allowing for the heating up of the groundwater and the taliks, but does not have the strength to disrupt the continuous permafrost and associated features of the area. It has been documented that the ground temperatures in this area are high compared with usual permafrost temperatures, but no source of geothermal heat has been found (Salvigsen et al, 1985: 152). There are some documented springs in Svalbard (Liestøl, 1977: 8) but none are within close proximity of the karst lake system.

Further Studies

This initial report is hopefully only the first part of a comprehensive concerning the karst lakes in Linnédalen which will last for several years as a bachelor's and master's thesis. There are several ways to further this study. For the next few months the term project will be turned into a bachelor's thesis. One specific area of the project will be chosen to further for this project. The data is available to create transects of the lakes in order to show the relative heights of the lake surfaces, as well as the heights in connection to sea level. Lake level fluctuations throughout the month of study time will also hopefully be incorporated to show the actual drainage which occurred. Another version of the map with improved illustrations will also add to the study. This will either be done with a program other than Photoshop or with the furthered knowledge of Photoshop.

The longer term goal for the project and the master's thesis will include going back to the study site in the summer of 2011 to continue field work. There are a few ideas for the gathering of data to improve the understanding of the processes occurring at the karst lakes as well as the drainage of the karst lakes. One of the ideas is to set up a time lapse camera which looks down on the karst lakes in order to observe the changes occurring at the lakes during the entire melt season. Another idea is to dig pits around all of the lakes and sinkholes as well as on the beach terraces and install temperature loggers at several different depths to see what kind of temperature fluctuations are happening during the year, as well as establish a time period and depths for the active-layer. This data will be accumulated over the course of the entire year, and collected in the summer of 2012. Also during this time another intensive observation period will occur and places of interest identified by the temperature loggers will be investigated further. There is a lot of potential for the collection of data in this area, and hopefully a good understanding of how the drainage system works in a continuous permafrost area will be established as an end result. The knowledge in this area is limited, and optimistically the continuation of this project will lead to a better understanding of intra-permafrost hydrology.

Conclusion

The system of karst lakes which are located in Linnédalen at the West coast of Spitsbergen is an example of a unique drainage system in a continuous permafrost area. From the month of observation time spent in the area it can be concluded that active processes associated with permafrost are happening, which confirms that the area is underlain by continuous permafrost. It can also be confirmed that vertical drainage of water through the permafrost is occurring in the lakes. This was confirmed by lake levels dropping during the observation period with no possibility of surface drainage.

There is not conclusive evidence for the dating of formation of the karst lakes and sinkholes, but by doing extensive research, a hypothesis can be made that the processes which led to the formation of the lakes began 10,000 to 8,000 years before present. This was made possible by the deposition of calcareous bedrock during the upper Carboniferous and lower Permian and then tectonic deformation during the Tertiary. Sea level drop and unfrozen ground at the present location of the lakes during the Holocene made it possible for the initiation of the solution of the bedrock.

A rough interpretation of the processes going on in the permafrost which allows for the drainage of water is also possible. The current interpretation is that there is a network of narrow closed hydrothermal taliks directly underneath the lakes which allow for the drainage of the lakes in an impermeable permafrost area. Hopefully further investigations will take place in the future for a more complete understanding of how this drainage system occurs.

Literature

Åkerman, H. J. 2005: Relations between slope processes and active-layer thickness 1972-2002. Kapp Linné, Svalbard. *Norsk Geografisk Tidsskrift-Norwegian Journal of Geography* 59, 116-128. Oslo.

Braathen, A., Nøttvedt, A., and Olaussen, S. 2010: The tectonic and sedimentary history of Svalbard: UNIS field excursion guide. The University Centre in Svalbard, Longyearbyen, Svalbard.

Clark, I. D., and Lauriol, B. 1997: Aufeis of the Firth River Basin, Northern Yukon, Canada: Insights into Permafrost Hydrogeology and Karst. *Arctic and Alpine Research* 29(2), 240-252.

French, H. M. 2007: The Periglacial Environment. John Wiley & Sons Ltd, West Sussex, England. 458 pp.

Humlum, O., Instanes, A., and Sollid, J. A. 2003: Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. *Polar Research* 22(2), 191-215.

Ingólfsson, Ó. 2006: Guide to the quaternary geology of Western Svalbard. The University Centre in Svalbard, Longyearbyen, Svalbard.

Jennings, J. N. 1985: Karst geomorphology. Basil Blackwell Inc., New York.

Kessler, M. A., and Werner, B. T. 2003: Self-organization of sorted patterned ground. *Science* 299, 380-383.

Landvik, J. Y., Mangerud, J., and Salvigsen, O. 1987: The Late Weichselian and

Mangerud, J., and Svendsen, J. I. 1990: Deglaciation chronology inferred from marine sediments in a proglacial lake basin, western Spitsbergen, Svalbard. *Boreas* 19, 249-272.

Liestøl, O. 1977: Pingos, springs and permafrost in Spitsbergen. *Norsk Polarinstitutt Årbok*, 8-29.

Ritter, D. F., Kochel, R. C., and Miller, J. R. 2006: Process Geomorphology. Waveland Press Inc., Long Grove, Illinois. 560 pp.

Salvigsen, O., and Elgersma, A. 1985: Large-scale karst features and open taliks at Vardeborgsletta, outer Isfjorden, Svalbard. *Polar Research 3 n.s.*, 145-153.

Salvigsen, O., Lauritzen, Ø. and Mangerud, J. 1983: Karst and karstification in gypsiferous beds in Mathiesondalen, Central Spitsbergen, Svalbard. *Polar Research l n.s.*, 83-88. Oslo.

Svendsen, J. I., Mangerud, J., and Miller, G. H. 1989: Denudation rates in the Arctic estimated from lake sediments on Spitsbergen, Svalbard. *Palaeogeography, Palaeoclimatology, Palaeoecology* 76, 153-168.

Svendsen, J. I., and Mangerud, J. 1991: Paleoclimatic inferences from glacial fluctuations on Svalbard during the last 20,000 years. *Climate Dynamics* 6, 213-220.

Wager, H. G. 1938: Growth and survival of plants in the Arctic. *Journal of Ecology* 26(2), 390-410.

Washburn, A. L. 1956: Classification of patterned ground and review of suggested origins. *Bulletin of the Geological Society of America* 67, 823-866.