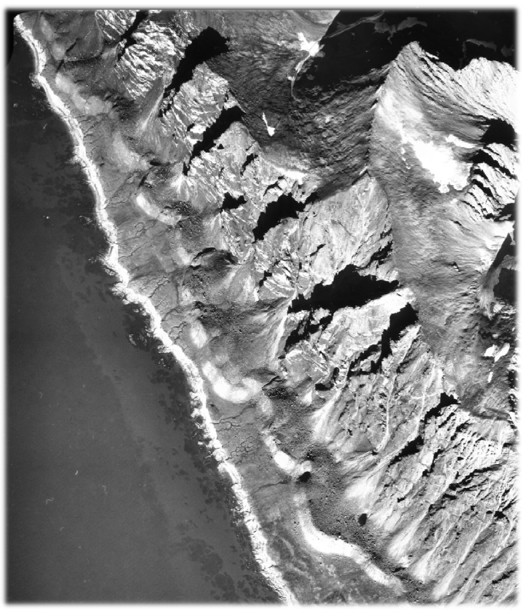
Sorted circles on Prins Karl's Forland and Kvadehuksletta

A comparison of a bird cliff environment and an old strand flat in western Spitsbergen

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Pictures on the front page

Left:
Aerial photo showing bird cliffs, rock glaciers and
strand flat near Fuglehuken on NW part of Prins Karl's Forland

Right:
Photo of sorted circles on the strandflat Kvadehuksletta,
near Geopol. Picture is taken facing north..

Preface

This work is part of the CAPP-dyn project (Dynamics of Carbon Pools in High Arctic Permafrost) at the Faculty of Geography at NTNU. Field work was conducted on western Svalbard over a span of two weeks in August 2010. Sites included the NW coast of Prins Karl's Forland, near the radio tower at Fuglehuken, and the second on Kvadehuksletta on Brøggerhalvøya near Ny-Ålesund. This thesis is written as a part of my Masters degree in Geography at the Norwegian University of Science and Technology (NTNU). The paper consists of a scientific article and a complementary text. The article will present the study as a whole, while the latter will highlight some aspects concerning scientific uncertainties as well as describing the theory in greater detail.

Many master students have probably experienced the euphoria of having endless possibilities when choosing a subject for the master thesis, just to be confronted with unforeseen challenges and things not working out the way they were supposed to do. In my case I had originally chosen to focus on the influence of detritus from bird cliffs in relation to the occurrence of sorted stone patterns and ice wedge polygons on the strand flat below on Prins Karl's Forland. Alternatively, I had thought about writing a thesis on whether ice wedge polygons found on Fuglehuken could be succeeding sorted patterns when the accumulation of organic matter was great enough. My supervisor could only advise on parts of these subjects and I had therefore hoped to get additional help from an external supervisor. This proved to be difficult as he was constantly busy. After a long time in a situation of uncertainty (I was almost two semesters overdue at that time) I decided that the best thing would be to change the topic of my thesis. For a while I wondered whether a simple description of the sorted circle examined on Fuglehuken would do, but I felt that I lacked data to do that. In the end I decided to compare the sorted circle at Fuglehuken with the one investigated on Kvadehuksletta.

Working on this thesis has given me an extraordinary opportunity to experience field work in Svalbard, and to learn methods directly from experienced researchers. At the same time I have run into a number of personal and practical challenges after returning from field work. I have experienced how rewarding it is to take a chance on something but at the same time how frustrating it is when hanging in thin air, being unable to decide whether to keep following the same course hoping it will get sorted out, or make a change. Undoubtedly, I have learned a lot about myself; how I handle difficulties and situations full of uncertainties, how I react when things do not go my way and what I have to do in order to change the course.

Acknowledgements

I would like to thank my supervisor Ivar Berthling at the Norwegian University of Science and Technology (NTNU) for his patience and support and for all his helpful comments. I am grateful for his positive attitude and for always being there to answer my questions, however far-fetched and strange they might have been. Many a time he provided me with a new perspective when I got stuck on one track, and made me focus on the important factors rather than the details. Likewise, I would like to thank Ronald S. Sletten from Washington University (USA) for the knowledge he shared during field work. While conducting research on Svalbard, he was my inspirational mentor and taught me most of the methods I used in the field, as well as broadened my knowledge about arctic soils and vegetation. I would like to thank Bernard Hallet, also from Washington University (USA), for all the things I have learned from him during our stay in Svalbard, as well as Mufak Naoroz from the University in Oslo for his help during the SOC analysis. I would like to also thank the Norwegian Polar institute (NP) which allowed me to use their aerial photos from Fuglehuken.

I would also like to extend my thanks to family and friends for standing by me when I was down, when I kept running into obstacles, and for supporting and pushing me on during the finishing stage of writing my thesis. I would like to thank my mother for pushing me onwards when I felt I would never finish, and my friend for her mental support and for dragging me away on trips when I needed a change of scenery. Thanks to my brother and father for their curiosity and for making me rethink things related to the subject, and also a big thank you to my boyfriend who supported me and kept me fed during intensive working periods. And lastly, I would very much like to thank my friend in Oslo for always welcoming me into her house and inspiring me to keep on working.

Summary (article abstract?)

Sorted circles may pose an important cryoturbation feature in the sequestering of organic C in Arctic areas. Trenches were dug through two sorted circles in Kvadehuken and Fuglehuken.

Contents

Table of figures (complementary text)

Abbreviations

BP	Before Present
C	Carbon
CAPP-dyn	Dynamics of Carbon Pools in High Arctic Permafrost
CRA	Conventional Radiocarbon Age
DFH	Differential Frost Heave
IC	Inorganic Carbon
m.a.s.l.	Meters above sea level
NE	North East
NW	North West
OC	Organic Carbon
TIC	Total Inorganic Carbon
TOC	Total Organic Carbon
SE	South East
SOC	Soil Organic Carbon
SW	South West

1 Introduction

This paper consists of an article and a supplying text depicting selected aspects of the study in greater detail. Main focus of this paper is on the article (chapter 3) presenting the study, methods, the site and the results with interpretations. It is meant to be read as a lone standing scientific article. The frame text deals with the theory of a self-organizing free convection model for sorted circles in chapter 2, and whereas this introductory chapter deals with important concepts, scientific considerations and data quality, as well as the necessity of this study and presenting the CAPP-dyn project.

Uncertainties attached to the results in this paper are mainly connected to sampling and because some of the original samples went missing before they could be fully analyzed in the lab. In regard to the fact that the sites, sampling and methods in the field were originally chosen with a different hypothesis in mind, the amount of samples from Fuglehuken were too few and not fully comparable compared with the samples from Kvadehuken. Another factor contributing to data uncertainty is that the amount of time used to write this thesis was longer than anticipated, making it difficult to keep track of all the loose ends and keep in mind information which was not noted down during field and lab work.

Though the data used in this paper is mostly of good quality and representative of the soil in the sorted circles, the sampling selection is not as good as it could have been. In addition, some of the original samples from Kvadehuken went missing during storage. For the grain size analysis, some of the results were therefore based on subsamples which were sampled before the originals disappeared. Because of the smaller sample size they are not as representative as the original.

The Capp-dyn project & relevance of this study

There are large variations of estimated Carbon stored in Arctic regions. One estimate made by Anisimov (2007) is that arctic soils contain approximately 455 Gt of Carbon, or 14% of the global soil carbon, of which about 50 Gt C are accumulated in the Arctic wetlands (Anisimov, 2007), whereas Burnham and Sletten (2010) estimate that the High Arctic contains 12 Pg SOC. Preliminary calculations done by Nybø and colleagues (2009) estimate that 0,2 million tons CO_2 is sequestered in vegetation on Svalbard every year, making vegetation a net sink of Carbon.

This value is more than 5 times greater than what was previously estimated, and points to a large underestimation of SOC in the High Arctic, as supported by several researchers (e.g. Bockheim, 2007; Gorham, 1991). The largest underestimations were typically done in barren areas categorized as polar desert (Burnham & Sletten, 2010). These estimations are important in relation to research on feedback effects on global climate.

As climate change becomes an ever more important focus for scientific research because of a greater awareness of how humans influence the climate, investigating soil organic carbon (SOC) and dynamic processes in permafrost become valuable assets in understanding feedbacks on global climate. In order to improve our understanding of the impact from permafrost regions on climate, it becomes more important to understand and quantify our knowledge about cryogenic processes burying organic carbon in these regions. The *Dynamics of Carbon Pools in High Arctic Permafrost* (CAPP-dyn) project in Svalbard is such a research project, focusing on cryoturbation as an important dynamic of sequestering C, as well as on improving our understanding the dynamics creating landforms in permafrost regions. The CAPP-dyn project is in collaboration between the Geographical Institute at the Norwegian University of Science and Technology (NTNU), the Institute of Geosciences at the University in Oslo (UiO), and the Institute of Geosciences at the University of Washington (UW). The CAPP-dyn project is financed by Norges Forskningsråd (NFR) and the POLRES-program, and is under the supervision of Ivar Berthling at NTNU.

Concepts

There are many concepts concerning permafrost regions and the landforms found here which have been used and defined in different ways by different researchers. Such terms need therefore to be defined in order to clarify what is meant when they are used in this text.

Sorted circles are periglacial landforms, a type of weathering landforms. The term periglacial refers to landforms created by intense freeze-thaw action, and are found at high latitudes, high altitudes and near alpine or continental glaciers (Pidwirny & Jones, 2009b). Patterned ground is used to collectively describe surface features in periglacial environments, and refer to a number of surface features including circles, stripes, steps, polygons and nets found here (Pidwirny & Jones, 2009b). Sorted and non-sorted circles are referred to with a variety of names, which may be confusing. Non-sorted formations may be called mud boils, frost boils, frost scars, mud circles, mud hammocks, frost medallion (Boike, Ippisch, Overduin, Hagedom, & Roth, 2008; Walker et al., 2004). Sorted circles are mostly called only this, but are sometimes also referred to as stone rings (Washburn, 1956).

Uncertainties and data quality

Scientific regards and research ethics

Starting off this chapter on a philosophical note - the idea that landscapes and landforms were the result of slow weathering processes was gaining importance in geosciences from the 18th Century and onwards. This concept, called Uniformitarianism, opposed the predominantly view that the world was created through catastrophic events like those described in the bible. From this concept springs the idea that everything around us can be described through the processes we can observe today, that these processes can explain the geomorphic and geologic history of the Earth, and that we can predict possible future changes by building on this knowledge (Pidwirny & Jones, 2009a).

The self-organization approach made by Kessler and Werner (2003) to modeling patterned ground (described in further detail in chapter 3), represents a paradigm shift in the field of geomorphology, moving from a reductionism approach towards concepts like universality and self-organization (Mann, 2003). These features can only be understood when examining effects of different mechanisms at scales greater than individual grains of sand. Examining properties of individual particles within a sorted circle has long been preferred (a typically reductionist approach), and will give an understanding of the physics affecting small, fast processes. These small scale processes, however, are slaved by larger, slower ones. Predictions made on the basis of examining the interactions of the fundamental particles within the circle therefore cannot satisfactory predict emergent properties of the circle as a whole (Mann, 2003).

In regard to the scientific data analysis and quality safeguard, it is important to be aware of the two mistakes in pattern recognition; to find patterns where there are none, and not to find patterns which actually exist. Francis Bacon formulated this concept, as part of his method, as the three tables of discovery: The table of presence, of absence and of degree, meaning the presence of two variables, only one and the proportional variation between the two (Fritz, Levi, C.S.B., Stroll, & Wolin, 2011). In the case of this paper it means finding the underlying processes and factors which are important in creating sorted circles, and excluding those which have no influence.

When it comes to research carried through in nature, the ethical principle is to respect the environment and, in so far it's possible, to avoid disrupting ecological and natural systems (NFK, 2009). In regard to excavating the two sorted circles in the fragile arctic environments on Svalbard, this principle was ensured by trying to reconstruct the circle structure after finishing research, thereby disrupting as little as possible and leaving the site in a state where the natural processes can easily correct this interference.

Data quality

Data were gathered through observations and measurements in the field, and lab analyses of soil samples. Supplementary information includes studies of maps, aerial photos and photos made during the field trip in August 2010.

There will always be a degree of uncertainty regarding quality of data, either due to methods used e.g. sampling and lab analysis, or because of uncertainties linked to the handling of samples, data calculation. As in all scientific research, results will have an unavoidable degree of uncertainty and falsehood. Main sources of uncertainties in results presented in this article include loss and gain of mass during sifting and handling, and C^{14} dating. As there were no large wooden chips or similar in the samples used for TC analysis, the note about removing bigger, biologically inactive organic pieces from the subsample, as voiced in Schumacher (2002) does not apply here. This principle might however be transferred to the inorganic part of the sample, as there is a large range in particle sizes in some of the samples, making it hard to pick a representative subsample. It was chosen to take a subsample showing the range of the smaller sized particles In hindsight it might have been better to sift the samples not taken in peat before subsampling.

Figures 1 and 2 shows an attempt to quantify the amount lost or gained through sifting, using samples taken Kvadehuksletta in western Svalbard in the same period of time as samples were taken in Fuglehuken. The sieve shaker used to determine the grain size distribution is far from tight enough to prevent small sized particles from escaping. Through the constant movement of the soil in the sieve shaker, small particles disappear into the air outside the shaker. Logically, the finer the particles are, the more likely they are to become airborne and disappear. In addition, particles will remain in, or loosen from, some of sifts during shaking (mainly sift sizes between 2 and 0,125 mm), causing the sample to either gain or lose weight. An extreme example of a sample gaining weight during sifting can be seen in figures 1 and 2. One sample shows a dramatic increase of 10 g. In comparison, the two other samples gaining weight only gained about 3 g.

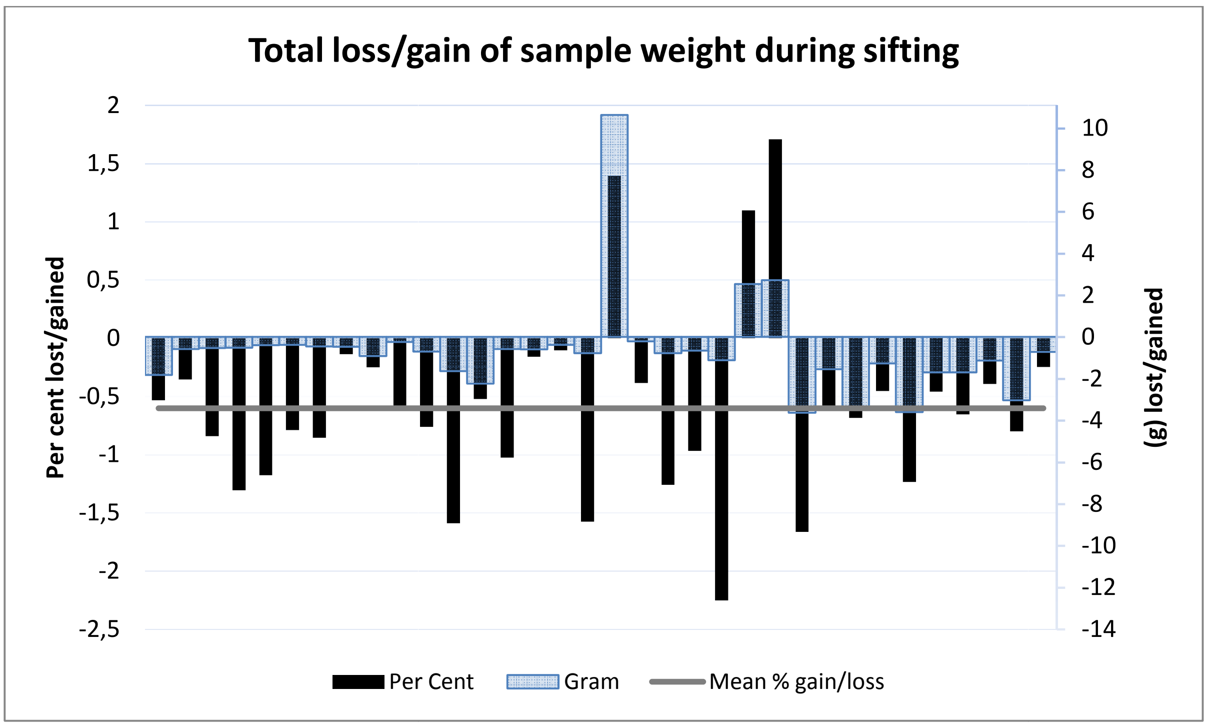


Figure 1: Per cent difference in total sample mass before and after sifting. The line indicates a general loss of 0,6 % of total sample weight. Samples presented here are from both Kvadehuken and Fuglehuken.

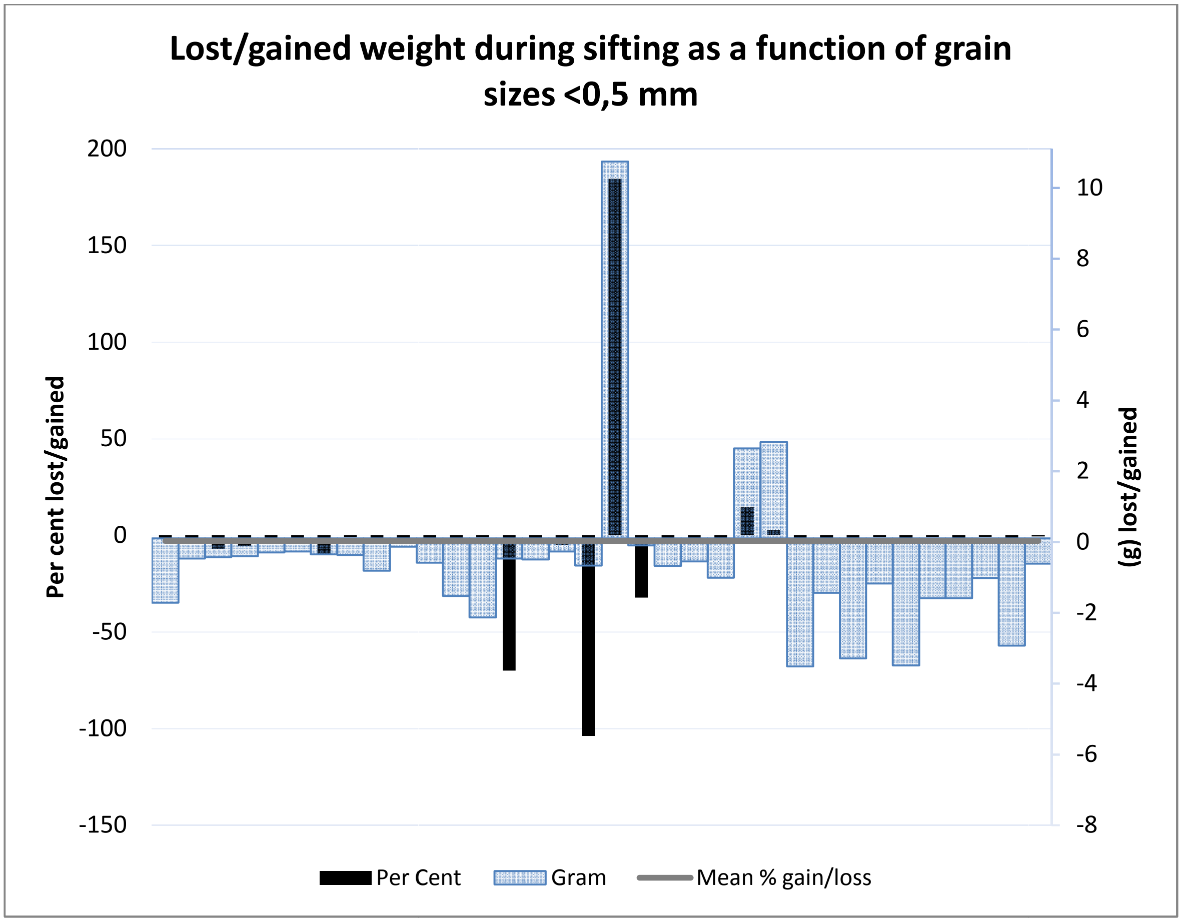


Figure 2: Per cent difference in mass before and after sifting of grain sizes smaller than 0,5 mm. The line indicates a loss of about 3 % from these smaller particle sizes. Samples presented here are from both Kvadehuken and Fuglehuken.

As a general rule, the smaller the particles, the easier they stay in the air and are transported away with the air. The amount lost was found to be between 0.6 and 1.8 grams, or 0.3 – 0.5 per cent of the total sample. However, some samples had increased their total weight after sifting which would point to the additions of small stones stuck and then coming loose from the sifts. Since these small stones have to come from some of the other samples this would account for the peaks of material loss in some of the samples.

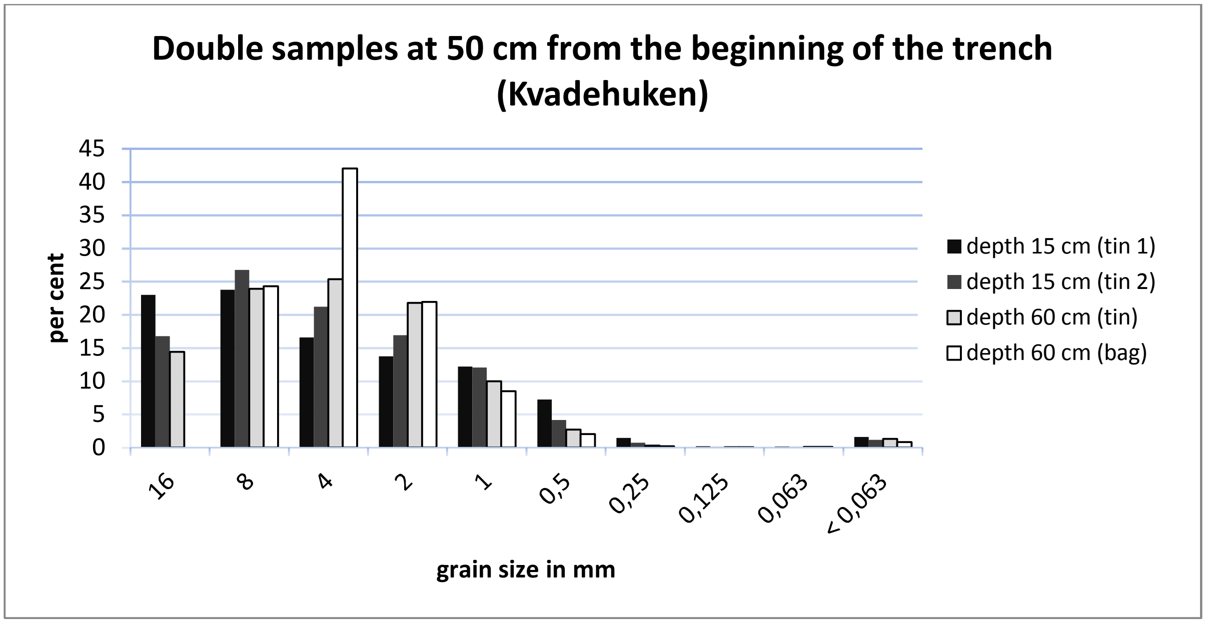


Figure 3: Grain size distribution from two sets of double samples taken at the same depth. Both sets are sampled from the coarse border, at 50 cm from the beginning of the trench dug through the sorted circle in Kvadehuken.
-> why is there a sudden peak at 4mm instead of at 8mm?

Figure 3 presents grain size distribution of samples at the same point in the profile, two of which are sampled at a depth of 15 cm and two at 60 cm. In general, they have similar size distributions but there are a few exceptions. Comparing the sample sets, there is a pronounced difference in grain size bigger than 16 mm. This is most likely the result of the parent material being non-homogenous, making it difficult to take representative samples. The differences in the size group 4 – 8 mm between the samples taken at 60 cm depth shows large differences. This might again be the result of sampling in non-homogenous materials, but could also indicate that samples were taken from two different patches of soil. Through constant cryoturbation, patches of soil are pushed up or down, creating a mosaic of soil patches with different properties, which might or might not look the same.

Hypothesis

Sorted circles were chosen to be the focus of this paper because they have the potential to bury large amounts of carbon through cryoturbation and because they, along side other sorted periglacial features are covering relatively large areas in permafrost regions. Cryoturbation is an important process burying organic matter in arctic soils because of the supposed convection movement burying organic matter present on its surface. In addition, their dependency on water for their development cause these land forms to occupy areas which have the potential for plant growth (Humlum, Instanes, & Sollid, 2003; Washburn, 1989). Sorted circles are one example of land forms in the Arctic which has the potential to sequester large amounts of organic Carbon (C). In order to improve estimations of organic C in Arctic soils, it is of interest to better our understanding of the dynamics of sorted circles, the rate of organic matter sequestering and the age of the organic matter present in these circles.

As a part of the project, this paper investigates the dynamics and the organic content of two sorted circle on Prins Karl's Forland on the west coast of Spitsbergen. Because of its closeness to bird cliffs and the ocean, the site at Fuglehuken is characterized by high input of nutrients and a relatively stable climate, creating a highly productive arctic area in regard to vegetation growth and C sequestering. Kvadehuken on the other hand, is situated in a polar desert. As Burnham and Sletten (2010) proposed, organic pools in such barren areas is greatly underestimated. Circles in both areas are therefore of strong interest when investigating cryoturbation and C sequestration in the Arctic. Mapping and understanding the structure, soil movements, the amount and the age of organic matter in these circles are therefore the focus of this thesis.

2 Theory

This chapter presents conceptual models of how sorted circles in cold climates are formed. The dominant process driving these subsurface soil movements are directly linked to the freeze-thaw cycle and are dependent on the temporally available soil moisture, resulting in differential frost heave (DFH), soil circulation due to variations in water and soil density, and frost sorting (Hallet, 1998; Kessler & Werner, 2003; Matsuoka, Abe, & Ijiri, 2003). Secondary processes (in no particular order) have by different authors been mentioned as the upfreezing of stones, surface displacement of stones caused by gravity, squeezing of stone domains, lateral sorting, particle sorting, cryoturbation, soil deformation, soil creep, frost cracking, mass displacement, temperature induced soil contraction and expansion (e.g. French, 2007; Horwath, Sletten, Hagedorn, & Hallet, 2008; Kessler & Werner, 2003; Peterson, 2011; Walker, et al., 2004; Washburn, 1956, 1980) These processes and feedback mechanisms result in separating and accumulation of fine grained material in the central domain and stones in the surrounding border. The influence of these processes and feedback mechanisms over large periods of time (often hundreds to thousands of years) will cause the development of sorted features such as circles, stripes, polygons and nets (Kessler & Werner, 2003).

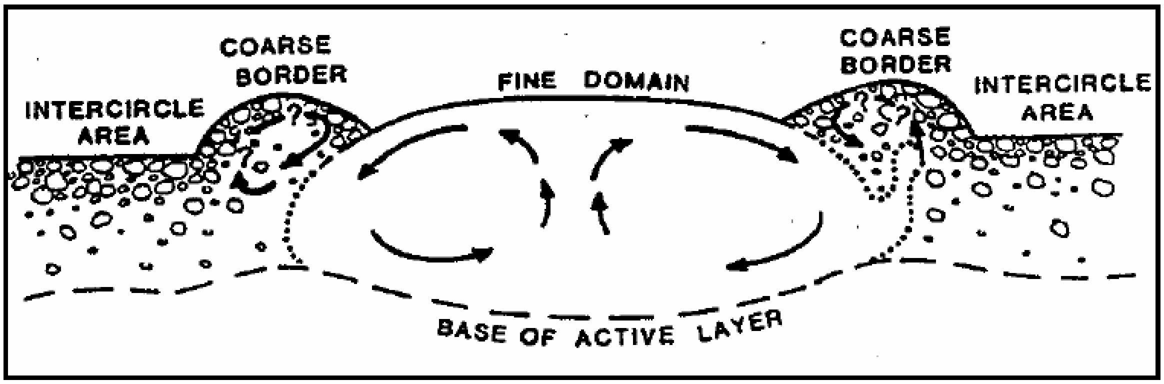
Sorted circles are distinctive landscape features in the Arctic, consisting of a circle of coarse stones surrounding a fine grained center which is often covered by low vegetation. They are active layer phenomena, normally measuring between 2 and 10 m in diameter (Humlum, et al., 2003). Sorted circles are widespread periglacial land forms and are mainly found in flat, well drained soils like Lithosols, Regosols, Arctic Brown soils, and in upland tundra (Washburn, 1956). They are therefore found on many mountain plateaus and coastal flats (Humlum, et al., 2003). According to Matsuoka and colleagues (2003), they form in sedimentary rock regions dominated by fine materials, and sporadically on crystalline rocks where the surface is dominated by blocks. Sorted circles are characterized by a center of fine grained mineral material surrounded by a coarse border of stone and boulder sized rock fragments. The inter-circle area consists of the parent, poorly sorted rock material. A schematic representation of a sorted circle is shown in figure 4.

Sorted patterned ground has a clearly sorted grain size distribution with an outer coarse border and an inner area of finer material (Washburn, 1956). Typically, the center is composed of soil which is both fine-grained and frost-susceptible (French, 2007). Frost heave and thaw settlement in the active layer are the main processes creating soil sorting. The upward movement of stones in heterogeneous unconsolidated soil is called upfreezing and is a typical sign of frost sorting, comprised of the hypothesis of a “frost-push” and a “frost-pull” mechanism. Frost-pull is the process in which the top of a pebble or stone is gripped by the advancing freezing pane, pulling it along upwards and away from the enclosing soil. The hypothesis of frost-push is based on the differences in thermal conductivity between solid objects and unconsolidated material. This creates ice around and beneath the stone or pebble, pushing it upwards. Common for both hypotheses is that during thaw, the pebble is unable to return to its original position because the space is filled up with materials pushed in through volume changes during freezing, and therefore ends up closer to the surface than before. Silt caps found on the edge of stones pointing towards the surface is an indication of such an upfreezing effect (French, 2007).

Common for all these formations is the presence of fine unconsolidated materials in the center. Etzelmüller and Sollid (1991) therefore state that the presence of silty and fine-grained material is a precondition for the development of sorted circles. However, this fine grained material does not necessarily have to be there originally, but may instead be the result of in situ weathering. Based on published studies of field work, laboratory work and other data, they propose that the fine grained material found on Kvadehuken on Svalbard is a dissolution product of the dolomite bedrock as shown in laboratory experiments (Sletten, 1993). The material accumulates in terrain depressions and at the bottom of slopes. Chemical and biological weathering, as well as pedogenetic processes (especially the translocation of silt), are prerequisites for cryogenetic processes. Frost sorting and cryoturbation are two such processes important for the development of sorted patterns. Etzelmüller and Sollid (1991) therefore conclude that the composition of bedrock and surface materials is an important control factor for these processes.

Hallet and Prestrud (1986) proposed a buoyancy-driven convective model that is due to changes in moisture content with depth. This theory was developed further by Krantz and his coworkers (Krantz, 1990) into a predictive computer model named the free convection model. The theory is based on the self-organization of poorly sorted, temporally water-laden sediments through repeated freeze-thaw cycles, resulting in a convection movement within the soil (Kessler & Werner, 2003; Washburn, 1980), as can be seen in figure 4.

Similar sorted features are also found in non-periglacial regions like in continental Europe, but are formed because of other mechanisms than those found in permafrost regions (Ahnert, 1994; Francou, Le Mehaute, & Jomelli, 2001; Mann, 2003).



Figur 2. Konveksjonsmodellen (etter Hallet et al. 1989).

Figure 4: Schematics of a well-developed sorted circle, showing the fine grained domain in the center and the adjacent coarse borders and inter-circle areas left and right. Figure is based on Hallet and Prestrud (1986). Source: (Motrøen, Eide, & Nordahl, 2005)

Although a number of field observations, lab experiments and theoretical calculations have been conducted (e.g. Etzelmüller & Sollid, 1991; Hallet, 1998; Kessler & Werner, 2003; Kling, 1997; Krantz, 1990; Matsuoka, et al., 2003), there has not yet emerged a general explanation of the development of sorted features. In part, this might be caused by practical and technical challenges studying these slow moving processes, both in the field and simulating these processes in the lab or as computer simulations (Haugland, 2006; Mann, 2003). However, these studies have managed to validate many of the underlying mechanisms forming patterned ground development in cold regions, but there are still processes which are poorly understood (Mann, 2003). For example, researchers have in many cases focused on small scale studies of grain properties and physics affecting individual particles found in the patterned feature. This approach has not worked very well in regard to patterned ground, because such smaller and faster processes are slaved by larger, slower ones within the sorted circle as a whole (Mann, 2003).

The contribution of differential frost heave and soil circulation has been highlighted in recent studies. DFH is a term used for the differentiated volume increase in non-homogenous soils during freezing, and the resulting variations in soil movements. The difference in heave amount varies between fine grained and coarser materials in the soil. In combination with the time lag between heave and settlement of patches of soil dominated by different grain sizes, this effect contributes to particle sorting. It is not dependent on soil saturation, as frost heave is fed by the unfrozen subsoil water, and is an active process everywhere soil may freeze. It is therefore neither dependent on permafrost nor deep seasonal frost. The second process highlighted in recent research, is soil circulation. This process happens due to the variability in water and/or soil density, that is, when buoyancy exceeds a critical value. This process is active during periods of super-saturation of soils, either in the active layer above permafrost or when temporary water storage emerges during thawing in non-permafrost soils. At any specific site, DFH and soil circulation may operate separately or together (Matsuoka, et al., 2003).

Kessler and Werner (2003) propose a simple computer model for explaining the mechanisms forming patterned ground. Based on a self-organized and self-maintaining approach and taking into account greater spatial and temporal scales, they simulate the subsurface movements of thousands of individual stones and grains of sand. Following the results from this model, sorted patterns are formed by the interaction of two mechanisms: Lateral sorting and squeezing of stone domains. The latter causes stones to move within and lengthen existing lines where stone concentration is high, while lateral sorting causes soil to move towards higher soil concentrations and stones move towards higher stone concentration (Kessler & Werner, 2003). This is similar to Washburn's (1956) prediction that a general explanation of patterned ground would include the upfreezing of stones resulting in sorting, and the second is the compression of stone domains caused by expanding soils during freezing. According to Kessler and Werner (2003), the emerging pattern is determined by the relative strength of these two mechanisms in combination with ground incline and the ratio of stones to soil.

3 [Article] Sorted circles on Prins Karl's Forland and Kvadehuksletta. A comparison of a bird cliff environment and an old strand flat in western Spitsbergen

4 Abstract

Sorted circles may pose an important cryoturbation feature in the sequestering of organic C in Arctic areas. Trenches were dug through two sorted circles in Kvadehuken and Fuglehuken.

5 Introduction

Preliminary calculations estimate that 0,2 million tons CO_2 is sequestered in vegetation on Svalbard every year, and that vegetation is a net sink of Carbon (Nybø et al., 2009). Burnham and Sletten (2010) estimated that the High Arctic contains 12 Pg SOC. This value is more than 5 times greater than what was previously estimated, and points to a large underestimation of SOC in the High Arctic. The largest underestimations were typically done in barren areas categorized as polar desert (Burnham & Sletten, 2010).

Sorted circles are distinctive periglacial landscape features in the Arctic, consisting of a circle of coarse stones surrounding a fine grained center which is often covered by a layer of vegetation. They are active layer phenomena, normally measuring between 2 and 10 m in diameter (Humlum, Instanes, & Sollid, 2003). Sorted circles are widespread periglacial land forms and are mainly found in flat, well drained soils like Lithosols, Regosols, Arctic Brown soils, and in upland tundra (Washburn, 1956). They are therefore found on many mountain plateaus and coastal flats (Humlum, et al., 2003).

The most commonly accepted theory of how sorted circles in cold climates are formed was proposed by Hallet and Prestrud (1986). The theory is based on the idea of self-organization in poorly sorted, temporally water-laden sediments through repeated freeze-thaw cycles, resulting in convection movements within the fine grained center and the border (Kessler & Werner, 2003; Washburn, 1980). The theory is further developed by Krantz and his coworkers into a predictive computer model called the free convection model (Krantz, 1990).

Sorted circles were chosen to be the focus of this paper because they have the potential to bury large amounts of carbon through cryoturbation and because they, along side other sorted periglacial features are covering relatively large areas throughout permafrost regions. Cryoturbation is an important process burying organic matter in arctic soils because of the supposed convection movement burying organic matter present on its surface. In addition, their dependency on water for their development cause these land forms to occupy areas which have the potential for plant growth (Humlum, et al., 2003; Washburn, 1989).

Svalbard was chosen because of its accessibility for doing research as well as because of its exceptionally well developed sorted circles. The sorted circles around Ny-Ålesund on western

Svalbard are well developed and are logistically well suited for the study, as well as there is available information on climate, geomorphology, Quaternary landscape development and pedology (Hallet, 1998). The two sites were chosen because they represent two distinct, but quite common natural environments in the arctic – the bird cliffs and bare stony ground. The strand flat Kvadehuksletta on Brøggerhalvøya has been investigated in a number of studies and is therefore of interest for investigating changes as well as to conduct new studies. This is also the case for Fuglehuken on Prins Karl's Forland (?).

Because of its closeness to bird cliffs and the ocean, the site at Fuglehuken is characterized by high input of nutrients and a relatively stable climate, creating a highly productive arctic area in regard to vegetation growth and C sequestering (Möller, 1999). Kvadehuken on the other hand, is situated in a polar desert. As Burnham and Sletten (2010) proposed, organic pools in such barren areas is greatly underestimated. Circles in both areas are therefore of strong interest when investigating cryoturbation and C sequestration in the Arctic. Mapping and understanding the structure, soil movements, the amount and the age of organic matter in these circles are therefore the focus of this thesis.

6 Site description

The geology of Svalbard is diverse both in age and types of bedrock. It differs from tertiary to Precambrian bedrock, consisting both of sandstone and schist. Based on the bedrock map Svalbard and Jan Mayen (Wisnes, 1983)

Based on measurements carried out in front of the glacier Austre Brøggerbreen about 10 km south of Kvadehuksletta, permafrost depth in the area is estimated to be about 200 m deep (Etzelmüller & Sollid, 1991).

Weather in the Arctic is semi-permanent, i.e. characterized by a pattern of high and low pressures. In winter, Svalbard is strongly influenced by the Siberian High: An intense, cold anticyclone forming over eastern Siberia, resulting in strong cooling in especially cold Siberian winters (Humlum, et al., 2003). Climate in the area of the two sites is categorized as high Arctic with marine influence. Ny-Ålesund, situated about 10 km SE from Kvadehuksletta at the end of Kongsfjorden, has an annual mean air temperature of -6.1°C and mean precipitation is 373 mm. Kvadehuksletta and Fuglehuken are presumed to have more precipitation and slightly lower summer temperatures than in Ny-Ålesund (Etzelmüller & Sollid, 1991).

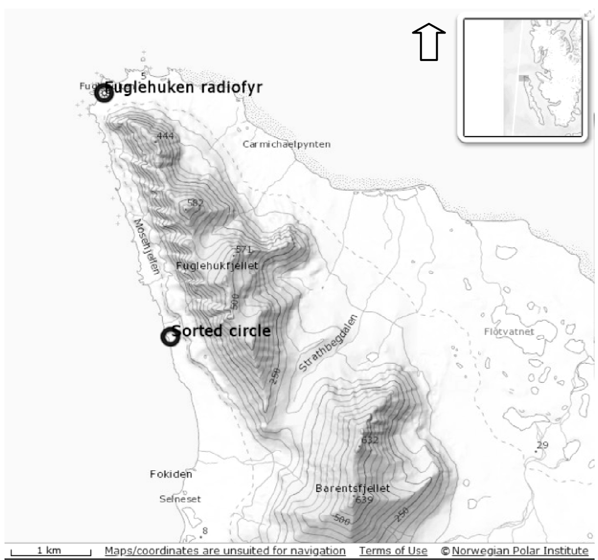
The investigated site Fuglehuken is situated on the northern tip of the island Prins Karl's Forland. On the peninsula Brøggerhalvøya about 20 km across Forlandsundet lays the second site: Kvadehuksletta.

Fuglehuken

Prins Karl's Forland is divided by a fault line stretching from the northernmost tip following the mountain ridge to the southern tip. The western part is dominated by Precambrian bedrock of sandstone and shale which is much older than the tertiary sandstone and schist bedrock of the NE coast and slightly older than the Cambrian shale bedrock in the SE part. This divide results not only in a geological divide between the eastern and western coast of the island but also in different conditions for landscape and vegetation development.

The investigated area on Fuglehuken is situated west on the northernmost part of Prins Karl's Forland in western Svalbard. The northern tip of Prins Karl's Forland is called Fuglehuken. The area below these cliffs are dominated by mires and rock glaciers covered in thick moss. The topographic map (figure 4) shows a very steep gradient from the mountain ridge down to the western coast, creating perfect breeding places for migrating sea birds. These colonies create highly productive ecosystems because of their nutrient rich guano, compared to arctic areas without these colonies._In the vegetation map of Svalbard the flat area around Fuglehuken is categorized into the Dryas octopetala zone (Brattbakk, 1986). This kind of tundra is referred to as ornithogen tundra because of their influence from bird colonies (Möller, 1999).

The study area on Fuglehuken is situated on the strand flat about 1 km south of Fuglehuken radiofyr (see figure 1). The strand flat consists of wet bog with scattered stones and boulders. Patterned features found here include sorted circles, sorted nets, and polygonal ice wedges. The strand flat is situated below Mosehjellen; a shelf formation approximately 2.5 km long. The shelf is made out of 21 - 23 lobate rock glaciers fed by rocks falling down from the cliffs above and are prominent features in the landscape. They have been the subject of several studies made by Berthling and colleagues (Berthling, Etzelmuller, Eiken, & Sollid, 1998; Berthling, Etzelmuller, Isaksen, & Sollid, 2000).



Site	m.a.s.l.	Coordinates
Sorted circle	11 *	N78 52.093 E10 31.068
Fuglehuken radiofyr	4	N78 52.093 E10 31.068

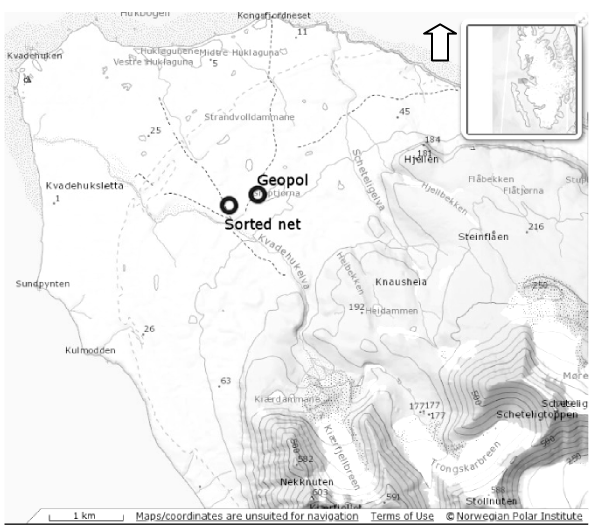
*Likely a measurement error; m.a.s.l. should be about 4-5 m

Figure 1: Sites investigated near Fuglehuken on Prins Karl's Forland. Fuglehuken is situated at the northernmost tip of the island. Study sites are situated on the strand flat below Mosehjellen on the NW coast of the island. From the northern tip: Collapsed ice wedges no. and 2, soil pit dug near an active ice wedge, and the sorted circle. The distance from ice wedge 1 and the sorted circle is a little less than 2 km. Map source: http://toposvalbard.npolar.no/ 8th of May 2013

Patterned ground features on the strand flat of Fuglehuken include active, relict and collapsed ice wedges, sorted circles, non-sorted mudboils and sorted stripes. Active ice wedges are mainly found as a net close to the soil pit and the sorted circle marked in figure 1. There are also some ice wedges scattered on the strand flat in a northwards direction. Sorted circles are found in scattered areas close to the shore line. Some of them are fairly active while some are almost wholly covered by vegetation. Some of the circles seem to be mudboils, i.e. non-sorted circles. Highest density of circles is found near the sorted circle which was excavated (see figure 1). The area in front of the rock glacier seen furthest south in figure 1 is characterized by a net of sorted lines following the front of the glacier towards the shore line.

Kvadehuksletta

Kvadehuksletta is covered by several raised beach ridges. The most preserved ridges are found below 45 m.a.s.l, and are dated to the late Weichsel (about 13.5 ka). There are several ridges from here up to 74 m.a.s.l, where the uppermost layer could be of pre-Weichsel age (130 – 290 ka). Thickness of the marine sediment deposits varies from several meters at the beach ridges to almost nothing in some interridge areas. In these interridge areas one can find weathered bedrock, fluvial reworked material and patches of vegetated tundra. The hydrological regime is controlled by permafrost with a thick active layer and the beach ridges, resulting in an arid soil regime. Because of this, water saturated sediments are found only in terrain depressions (Etzelmüller & Sollid, 1991).



Site	m.a.s.l.	Coordinates
Sorted net	40	N78 56.963 E11 27.481
Geopol	55	N78 57.057 E11 28.539

Figure 2: Site investigated on Kvadehuksletta close by Ny-Ålesund. The site is situated close to Geopol, the hut normally used to live in during research and a land mark on the strand flat.
Map source: http://toposvalbard.npolar.no/ 8th of November 2013

Bedrock geology is reflected in the mineral composition of the bedrock geology on site. Sediments are dominated by carbonates: About 80% dolomitic limestone, 5% other carbonates, and 15% is a mix of sandstones, conglomerates and metamorphic pebbles (Etzelmüller & Sollid, 1991). South and southeast of these raised strand flats is a mountain ridge, below which are found several rock glaciers.

The map (figure 3) shows the investigation site on Kvadehuksletta at an elevation of 40 m.a.s.l.It is situated near Geolpol.

Vegetation is sparse and present mainly in depressions and in the fine grained circles of sorted features. Vegetation consists mainly of cryptogam and some vascular species.

7 Methods

The circle on Fuglehuken was chosen because it was one of a limited few still active circles, and is situated near an area of thick peat and ice wedges, indicating an area of active soil movements. This circle is highly influenced by organic matter. On Kvadehuksletta, the circle was chosen because it was deemed representative of the circles in the area in regard to size, form, activity, drainage and plant cover.

2 meter long trenches were dug through the sorted circles at both sites in order to examine their subsurface structure and to gather soil samples for further analysis. Exposed parts of the fine grained center, the coarse border and in the case of Fuglehuken parts of the inter-circle area were sampled and described. Sampling and schematics of these circles can be seen in figures 3 and 4.

Soil properties were described through observation of soil color, soil properties such as the presence of silt caps and cracks in the fine left by ice lenses, and the amount of plant roots and visible plant parts.

To gain additional information about the area surrounding the circle on Fuglehuken, a collapsed ice wedge was examined and sampled. This was done in order to measure peat depth and to carbon date the oldest organic material. This site was chosen because the collapsed ice wedges greatly simplified the access to soil at depth in frozen soil normally difficult to access. In addition, the active layer was measured using a metal rod.

In the lab, soil samples were dried at 60°C for 21 days in a Termaks drying cabinet. Samples were weighed before and after drying with an Ohaus precision standard scale. The resulting difference in weight shows the amount of water present in the soil sample. None of the samples had free water in the container when weighed before drying. To determine particle size distribution, dry samples were placed in a sieve shaker (Octagon digital) and sifted through a total of nine sifts, ranging from 16 mm to 63 µm. The Gradistat program version 8.0 (Blott, 2010) was used to characterize soil particles into the categories gravel, sand and silt & clay. In one case, particles smaller than 63 µm were extrapolated using Gradistat. This was not done for other samples because the samples were too big. The calculation error increases with larger quantities of the sediment being of the smallest size (Blott, 2010). In other samples, soil particles smaller than 63 µm were moistened and determined by feel (Holden, 2005).

At the university in Oslo (UiO), total Carbon (TC) content in sampled soil was analyzed through dry combustion at 1350°C. The dry sample was pulverized and two subsamples of approximately 0.35 gram were prepared. One of the subsamples was left as it was while the other was treated with hydrochloric acid (HCl) in order to remove carbonates (e.g. calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$]) so that it would be possible to determine the percentage of total organic (TOC) and inorganic Carbon (TIC). The pretreated sample was dried on a heating plate. Then, the acidic reaction products remaining in the sample were washed out using condensed water. They were then dried in a hot closet at 80°C for two hours. Lastly, both the pretreated and untreated samples were analyzed using the LECO Carbon Analyzer (model CR-412).

Key samples from both study sites were dated at the Beta Analytic lab in 2012, using the accelerator mass spectrometry (AMS) method. Details on these methods can be found on the homepage of Beta Analytics (2013a). The age referred to in this article is the conventional radiocarbon age (CRA), which is the age corrected for stable ^{13}C and ^{12}C isotopes. All organic sediment samples were pretreated with acid washes, whereas the two peat samples from Fuglehuken were pretreated using the acid/alkali/acid (AAA) method (Beta, 2013b).

8 Results

Sorted circles found on Kvadehuken and Forlandet are similar in that they are both situated on strand flats created either during or after the last ice age. The strand flat on Kvadehuken, with a higher elevation, are older than the one on Fuglehuken. The two strand flats are, on the other hand, quite dissimilar when it comes to the occurrence, distribution, activity and size of sorted circles and other patterned land forms. Near Fuglehuken, sorted circles are mainly circular and small (from about 1 to 5 Meters measured from outside the coarse border). They are relatively inactive: 80 – 100 per cent of their total surface is covered with vegetation and cryptogam, including both the border and the fine grained center. Sorted circles here are only found close to the shore line. The strand flat is dominated by thick peat and ice wedges, with a gradual transition to sorted lines further south. On Kvadehuken, sorted circles, nets and lines are the dominant patterned features. Sizes of the closed sorted circles range from relatively small (about 3 Meters including the border) to very large in the case of oblong circles (10 Meters or more). Activity of these features ranges from fairly active to very active, as could be seen by the crevice created top of many coarse borders because fresh material is erupting towards the surface. The fine grained center of most features is covered by cryptogam and other plant species, covering between 40 – 90 per cent of the surface.

General descriprion

The circle on Kvadehuksletta is an oblong, closed circle in an area of similar circles and sorted lines. The fine grained center in the middle was investigated by placing a net with squares of 10 cm^2. Results from this analysis is that the center surface is covered by 65 % cryptogam, 18 % cryptogam and Saxifraga oppositifolia, 2 % other plants and 15 % bare surface. Surface near the subduction area (see fig. 3), cryptogam and vegetation cover gradually covered more of the surface and became thicker than in the center, showing a folded structure when reaching the coarse border. After digging the trench, a zone consisting of light brown colored mineral soil was found beneath this area.

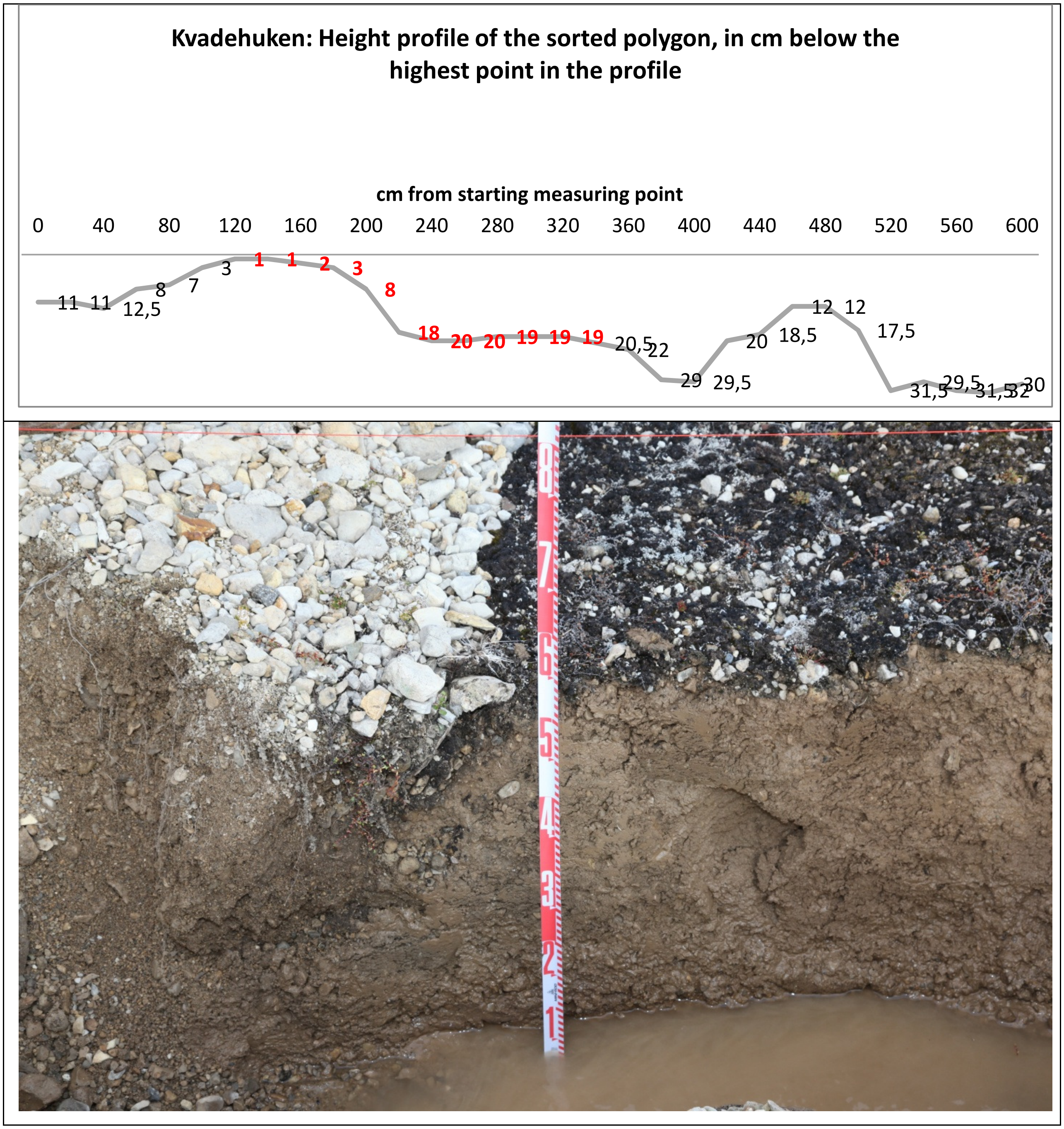


Figure 3: Surface profile of the polygon net in Kvadehuksletta. Height is shown in cm relative to the highest point in the circle. Profile includes some of the surrounding, non-sorted surface. Highlighted numbers show the profile of the trench.

Soil properties range from purely organic to chiefly mineral horizons, and from silty loam to coarse gravel and boulders in size. Total carbon content range from 35,7 % to as little as 0,47 %, consisting in some cases of both carbonates (IC) and organic carbon (OC) and in other cases only of one of the types.

Active layer depth was found to be 30 cm ± 1 cm at the two ice wedge sites and 36 cm ± 1 cm in the soil pit. The 10 cm organic layer overlaying the inter-circle area was thawed all the way through. These measurements were made on the 10^{th} of August, and the active layer is therefore expected to reach grater maximum thawing depth.

At the two ice wedge sites there is clear evidence for cryoturbation. In the area close to where the ice wedge was and the existing permafrost, small patches of peat with different soil classifications are distributed randomly throughout the soil horizon. In contrast, the active layer investigated on top of one of the polygons showed a homogeneous soil layer. This indicates that the area near the former ice wedge is not constantly frozen.

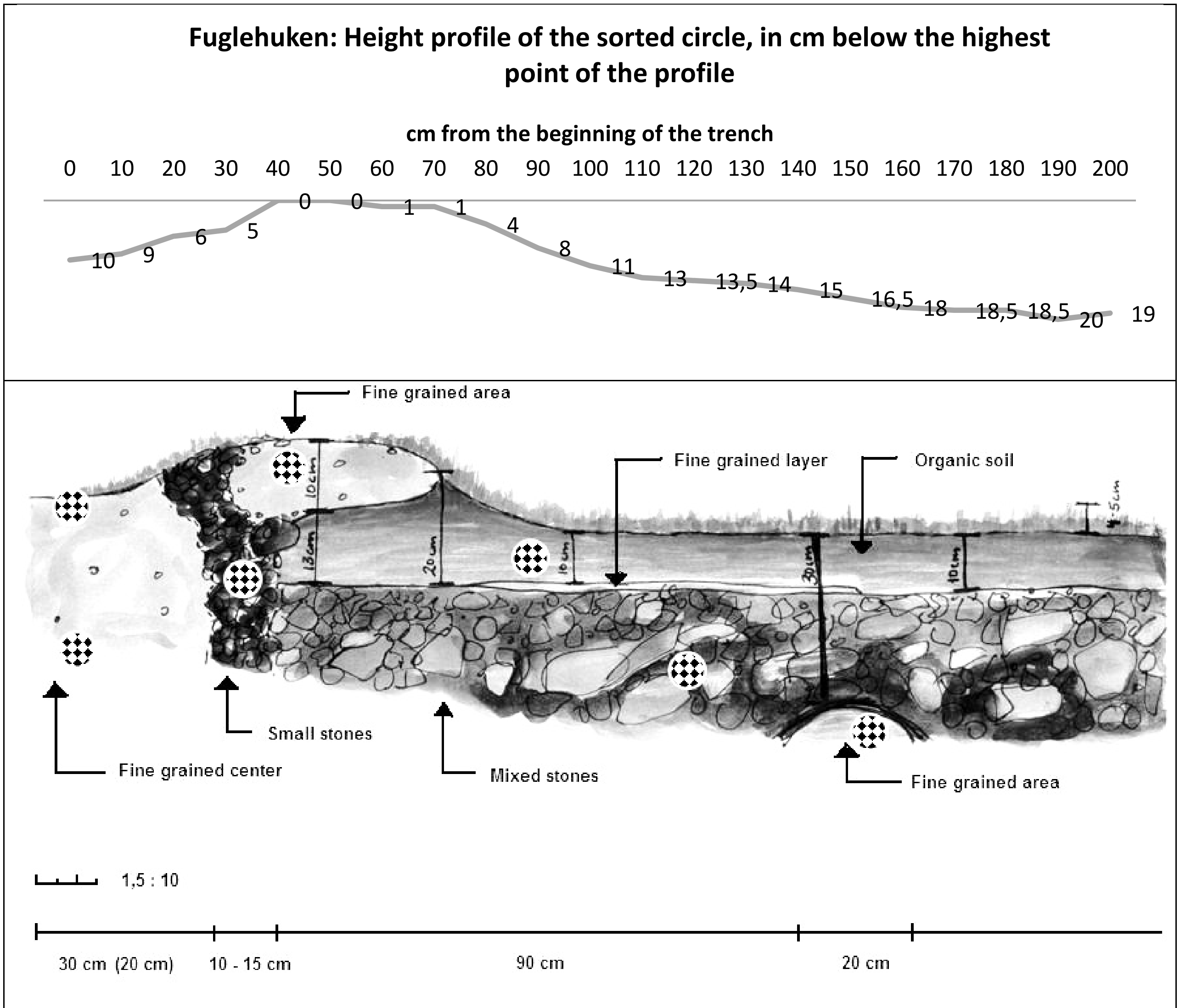


Figure 4: Schematics of the trench dug through a sorted circle. To the far left the center point of the circle is shown, following the trench dug through the border into the area outside the circle. Points in the profile marked with a checkered pattern show where soil was sampled. The line on top of the schematics shows the measured surface profile relative to the highest point of the border

The circle on Prins Karl's Forland is situated approximately 10 Meters inland from the shoreline at a height of 4 m.a.s.l. Diameter of the circle is between 2,5 and 3,5 meters, as it is neither uniformly round nor with a consistently even border. The center is approximately 2 m across and the uneven border ranges between 30 cm to 1 m in width. Vegetation cover is found in sporadic patches throughout the center and the subduction area between the border and the center, while comprising of thick vegetation patches covering most of the border.

Plant species in the vegetation mat in the center consists of grass, vascular plants, moss, and cryptogam. About 40 % of the surface in the fine grained center is covered by a fine gravel matrix. Mineral soil contains massive clasts of silt. Color is light grey to light brown and contains a weak, millimeter thick plate structure. Silt caps are found on top of many of the stones and roots are found up to 20 cm below the surface. When the trench was dug water percolated out of the soil.

The border area is about 50 cm wide and consists of a fine grained, light brown soil. Between this fine area and the circle center is a line of coarse to fine gravel, of which many are angular. At a depth of 11 cm the soil is categorized as C horizon and is an abundant with fine and very fine roots. This layer seems to be very biologically very active area based on the amount of roots and soil color. Superseding the C horizon at a depth from 11 to 26 cm is an A horizon. Below 26 cm a partly fractured, open beach gravel matrix was found.

Surrounding the area around the circle is a vegetation mat on top of a 10-12 cm thick organic

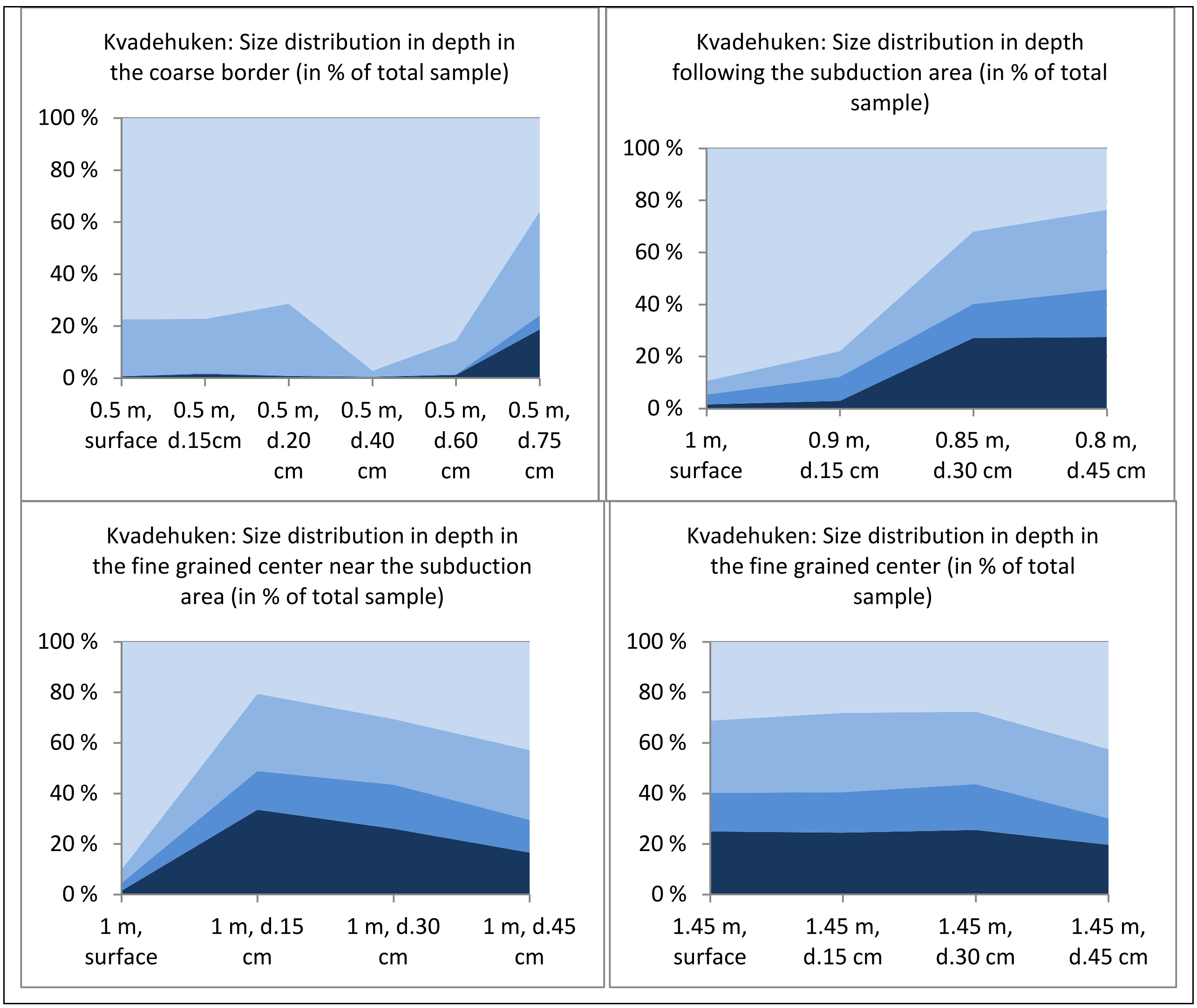
Table 1: Fuglehuken. Statistics of grain sizes between 16 mm and 63 µm calculated in Gradistat. Except for the sample taken from the coarse gravel and boulder area outside the circle, percentages of the sample smaller than 63 µm were too high to be extrapolated in the Gradistat program.

		Center surface	Center 20-25 cm	Border surface	Outside 20-25 cm	Outside 30-35 cm
SAMPLE TYPE:		Bimodal	Unimodal	Unimodal	Unimodal	Unimodal
TEXTURAL GROUP:		Sandy Gravel	Sandy Gravel	Gravel	Gravel	Sandy Gravel
SEDIMENT NAME:		Sandy Medium Gravel	Sandy Coarse Gravel	Coarse Gravel	Coarse Gravel	Sandy Coarse Gravel
FOLK AND WARD METHOD (Description)	MEAN:	Very Coarse Sand	Very Fine Gravel	Medium Gravel	Coarse Gravel	Very Fine Gravel
	SORTING:	Very Poorly Sorted	Very Poorly Sorted	Poorly Sorted	Very Well Sorted	Very Poorly Sorted
	SKEWNESS:	Symmetrical	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed
	KURTOSIS:	Very Platykurtic	Platykurtic	Leptokurtic	Very Leptokurtic	Platykurtic

layer. In addition there is a cm thin line of fine grained material situated below parts of the organic layer (see figure 4). Just outside the border and 12-31 cm below the surface is a matrix of clean, open gravel consisting of both angular and rounded rocks in various sizes. This layer contains a lot of long roots.

Surface height from the center point of the sorted circle to the end of the trench is shown in figure 2.

Grain size distribution and porosity



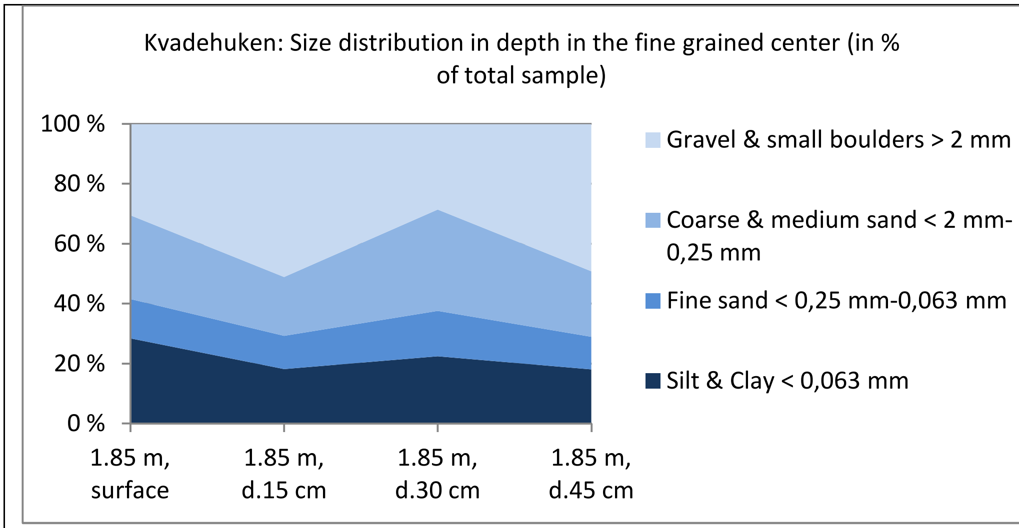


Figure 5: Kvadehuken: Size distribution at different points in the section, following the soil profile from the surface and down. The sizes of gravel, sand, slit and clay are shown in percentage of the total sample.

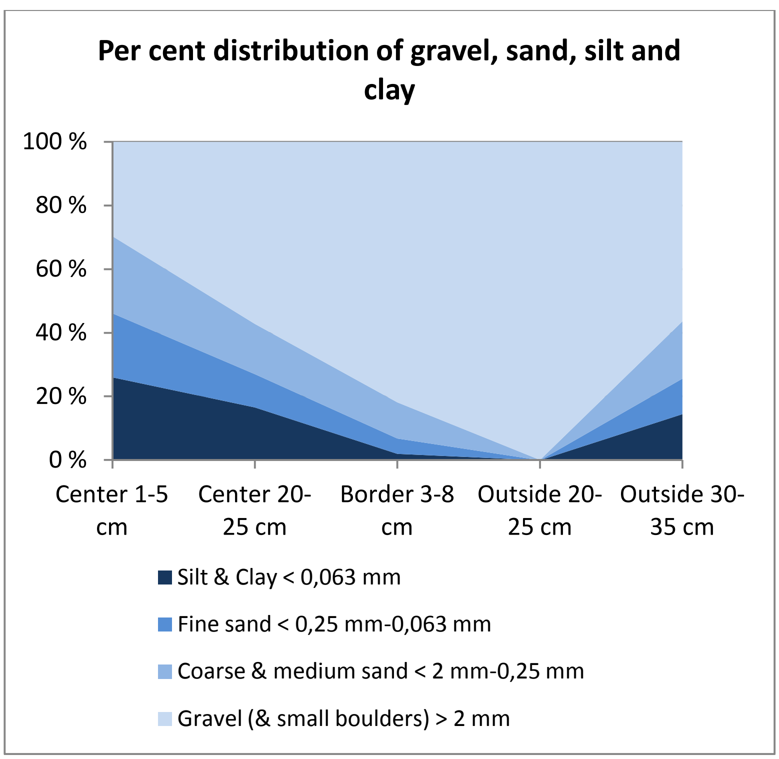


Figure 6: Grain size distribution in Fuglehuken.

Grain size distribution in soil samples from the sorted circle In Fuglehuken was analyzed in order to describe soil properties of the center, the border, the area outside the circle, and to determine whether the grain size distribution could explain its dynamics. Table 1 shows characteristics of the sand and gravel share of the sample, showing a sediment range from sandy medium gravel to coarse gravel. Particle size distribution between 16 mm and 63 µm were analyzed using the GRADISTAT program (Blott, 2010) rendering the following qualitative results in table 1.

Because of unforeseen circumstances only three samples were analyzed further by feel in order to determine whether particle sizes smaller than 63 µm are dominated by silt or clay. The sample taken at 20 cm below the surface in the circle center and the soil sampled from the fine grained area found 30 cm below the surface outside the circle are both dominated by clay. The sample from outside the circle has a little silt as well, as indicated by the crunching sound when chewed. Sampled soil from the fine grained area on top of the border is dominated by silt but with a fair amount of clay, indicated by the possibility roll it into a 1 mm thick, very easily breaking string. The soil does not absorb water easily which may be because of its high organic matter content.

Four samples were taken in order to determine the bulk density of the soil in Kvadehuken, one of the surface layer, one from the coarse border, and two from the center.

Carbon and water content

Figure 5 seems to confirm the field observation of the border as a very biologically productive area. The percentage of TOC is as high in the sample taken from the border as in the peat layer right outside the circle. The small increase in TIC in the border points to more carbonates and might therefore point to more chemical weathering and more leaching than in the other places. Compared to the rest of the samples, these two stand out as organic rich C areas.

9 Discussion

Because of permafrost, drainage only happens on the surface and within the active layer. This is because the sub-zero temperature in the frozen ground will freeze any water reaching it, effectively preventing water from draining trough this layer. The shore line is situated a few meters below the strand flat, influencing the temperature gradient in the transition area between the active shore line and the strand flat. Drainage properties in the ground close to the shore are therefore different than on the strand flat itself. That in itself might explain why sorted features are only found near the shore and not on the flat area behind it.

Particle sizes

Particle size distribution determines soil properties related to its water holding capacity, permeability, cation exchange capacity and rate of mineral weathering (Holden, 2005).

Water content is highly dependent on the combined surface area of the soil. Small particles such as silt, clay and humus have a large surface when compared to their weight. In addition, humus can absorb and store more water compared to mineral particles of equal size. Figure 3 clearly shows that water content in the samples is governed by their organic matter content and only to some degree by the amount of small mineral particles.

Based on data analysis of particle sizes down to 63 µm in gradistat, only the sample at the surface in the center shows a bimodal size distribution. This result is expected when following the model of advection movement upwards in the center, following the surface towards the border. Coarse material is pushed and pulled up to the surface through freezing and thawing, giving the surface area a sorting into the smallest and the largest grain sizes. When looking at figure 23 though, this seems to be the case only down to 63 µm, after which the percentage of fine particles decreases. This indicates a wash out of the finest particles, leaving the surface with a dominating size distribution of very fine sand and medium gravel (see table 2 in (Blott, 2010)).

Taking the particles smaller than 63 µm in account there are two more exceptions from this unimodal distribution, both from fine mineral material. One is from 20 – 25 cm below the surface in the center and one from the possibly developing circle at 30 – 35 cm below the surface outside the excavated circle.

Weak ice lens structures were found in the silty center meaning ice lenses form during winter and that the circle is susceptible to frost heave and sorting. The fact that these lenses are not very distinct could indicate little DFH activity.

Adding information from the remaining soil in the bottom pan after sifting which is smaller than 63 µm (figure 3), the grain size distribution analysis from the silty center and parts of the border shows a distinctive dominance of either small particles (smaller than 250 µm) or larger grain sizes (from 4 mm and larger). Figure 7 also shows that the bimodal size distribution of the center surface sample calculated with gradistat (table 1) is exaggerated. That is, the small increase in the per cent of particle size 63 µm does not reflect the actual trend as there is a decrease in the amount smaller than 63 µm. Soil taken 20-25 cm below the surface in the center area fits the description above better because figure 7 shows a strong increase in the smallest particle sizes. The fine grained area sampled outside the circle also has a slight bimodal distribution.

As can also be seen in figure 3, none of the soil samples showed any large percentage of the grain sizes in between one of the two extremes. Soil properties such as its water holding capacity and plasticity relevant to the dynamics of sorted circles largely depend on their size distribution of particles smaller than 500 µm. Figure 7 shows their percentage distribution of sizes from 250 µm and smaller. There is a significant difference between the border on one hand, and the center and fine grained area found outside the sorted circle. Size distribution in the border shows a percentage decrease with smaller sizes whereas it is the opposite in the other samples.

Figure 3 shows a correlation between the amount of water and per cent organic matter (represented as TC) rather than with the amount of fine grained particles.

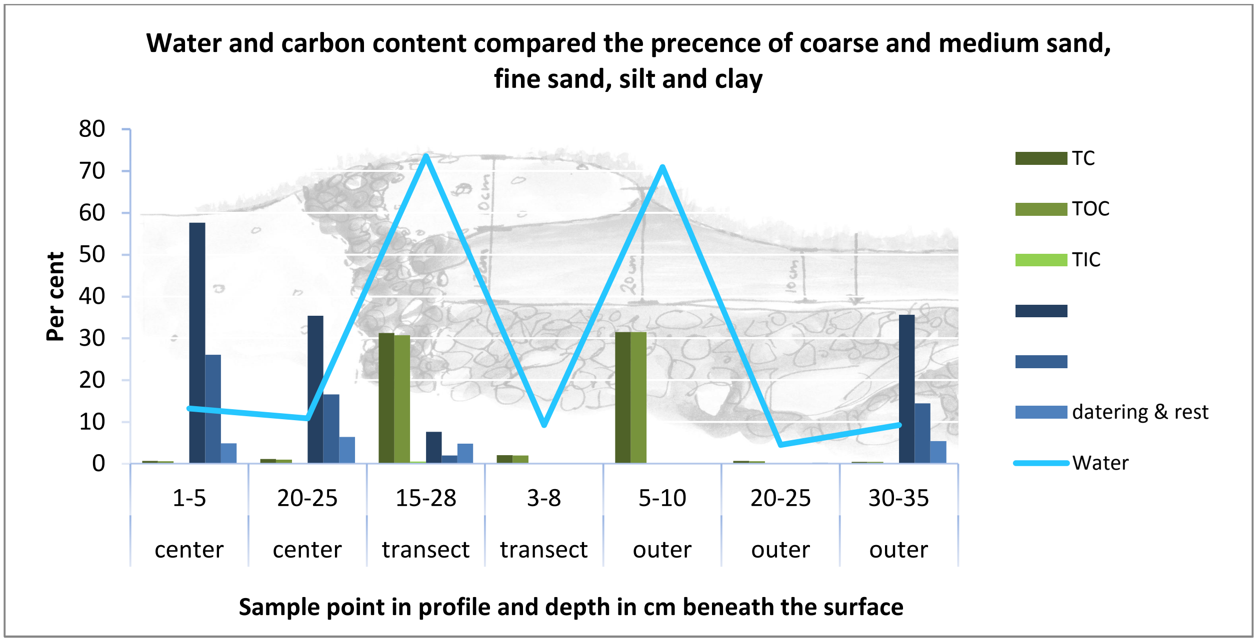


Figure 7: Per cent content of carbon and water related to particle size distribution in soil samples taken from the sorted circle. Grain sizes are grouped into coarse and medium sand (1-0,126 mm), fine sand (0,125-0,064 mm), and silt and clay (smaller than 0,063 mm). The sequence shows (from left) the fine grained center, the coarse border and the area outside the circle.

Figure 7 shows a correlation between the amount of water and the organic C content in the sample. On the other hand, particle sizes in the lower end of the spectrum seem to follow the opposite trend. Both the trench at 15 cm depth and the outer area right below the surface consist purely of organic matter.

Organic content

The high amount of organic Carbon in the lower border, and also in the upper 10 cm of the outer area, might be the result of the same micro climate effect as found on top of and around palser. The drier conditions on top of the border and the draining properties of the stony ground beneath the peat in the surrounding area may create more favorable growing conditions in summer than the surrounding wet mire.

Dating

Table 2: C14 Dating results from the sorted circle on Kvadehuksletta and Fuglehuken.

Fuglehuken	Sample depth	Soil type	Conventional Radiocarbon age	Range of uncertainty (in years)
Sorted circle, center	20 – 25 cm	Organic sediment	3730 BP	+/- 30
Sorted circle, fine border	3 – 8 cm	Organic sediment	670 BP	+/- 30
Sorted circle, border	15 – 28 cm	Peat	80 BP	+/- 30
Ice wedge 2	170 cm	Peat	6750 BP	+/- 40

Kvadehuken, Point in profile	Sample depth	Soil type	Conventional Radiocarbon age	Range of uncertainty (in years)
Center, 186 cm	0-5 cm	Organic sediment	9 470 BP	+/- 50
Center, 186 cm	15 cm	Organic sediment	8 940 BP	+/- 40
Center, 186 cm	30 cm	Organic sediment	9 670 BP	+/- 40
Center, 186 cm	45 cm	Organic sediment	9 700 BP	+/- 50
Center, 143 cm	0-5 cm	Organic sediment	6 550 BP	+/- 40
Center, 143 cm	15 cm	Organic sediment	10 550 BP	+/- 50
Center, 143 cm	30 cm	Organic sediment	10 160 BP	+/- 50
Center, 143 cm	45 cm	Organic sediment	6 900 BP	+/- 40
Center, 100 cm	0-5 cm	Organic sediment	310 BP	+/- 30
Center, 100 cm	15 cm	Organic sediment	8 570 BP	+/- 50
Center, 100 cm	45 cm	Organic sediment	10 130 BP	+/- 50
Subduction area, 90 cm	15 cm	Organic sediment	1 100 BP	+/- 30
Subduction area, 85 cm	30 cm	Organic sediment	5 100 BP	+/- 40
Subduction area, 80 cm	45 cm	Organic sediment	4 430 BP	+/- 40
Sorted border, 50 cm	15 cm	Organic sediment	1 470 BP	+/- 30
Sorted border, 50 cm	40 cm	Organic sediment	2 020 BP	+/- 30
Sorted border, 50 cm	60 cm	Organic sediment	1 520 BP	+/- 30
Sorted border, 50 cm	75 cm	Organic sediment	3 040 BP	+/- 40

10 Conclusion & Acknowledgements

Sorted circles may pose an important cryoturbation feature in the sequestering of organic C in Arctic areas. The amount of organic matter found in the circle on Fuglehuken show that such features in bird cliff environments are most effective. The age of C in Kvadehuken show that sorted circles will keep sequestered C buried for a long time

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