P-11-05

SKB studies of the periglacial environment – report from field studies in Kangerlussuaq, Greenland 2008 and 2010

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March 2011

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Contents

1 Introduction

In order to reduce uncertainties in safety assessments of the planned repository of spent nuclear fuel, SKB identified the need to increase the understanding of glacial and periglacial environments. In collaboration with Posiva OY (Finland) and NWMO (Canada), SKB started the Greenland Analogue Project (GAP) in order to study the effect of climate cooling and glaciation on repository safety. GAP chose an area northeast of Kangerlussuaq, West Greenland, to be studied as a present-day analogue of a future glacial environment in both Scandinavia and Canada. The GAP, planned to run from 2009 until 2012, conducts *in situ* investigations of some of the parameters and processes needed to achieve a realistic understanding of how an ice sheet may impact a deep repository. In addition, the GAP will provide measurements, observations and data that may significantly improve safety assessments and risk analyses of glaciation scenarios /SKB 2011/.

Issues regarding the periglacial surface environment are not included in GAP's primary focus, which has led SKB to initiate parallel activities in the same area. This new project is named The Greenland Analogue Surface Project (GRASP), and will conduct conceptual and numerical modelling of ecosystems, hydrology and near surface hydrogeology. Choosing the same investigation area for the two projects will facilitate common usage of base-line data and logistics in the field. Information from the GRASP will be applied for a better understanding of ecological and hydrological processes in a future periglacial environment in Forsmark. Annual and long-term dynamics of the permafrost are of special interest, as well as the impact of taliks on the transport of matter from the bedrock up towards the surface.

This report primarily describes findings from the field season of 2010, but does also report on field work conducted by SKB in 2008. The report provides some background information on the area, describes preliminary results and set-up for monitoring activities initiated during the field work in September 2010.

Field party of the 2008 and 2010 seasons consisted of the following members:

2008	2010
Sten Berglund, SKB	Sten Berglund, SKB
Lars Brydsten, Umeå university	Emma Bosson, SKB
Stefan Engels, Stockholm university	Lars Brydsten, Umeå university
Karin Helmens, Stockholm university	Anders Clarhäll, SKB
Birgitta Kalinowski, SKB	Tobias Lindborg, SKB
Ulrik Kautsky, SKB	Jens-Ove Näslund, SKB
Tobias Lindborg, SKB	
Anders Löfgren, EcoAnalytica	
Jens-Ove Näslund, SKB	
Björn Söderbäck, SKB	

2 Physical setting

GAP and GRASP field sites are set in the vicinity of Kangerlussuaq, located in an area of Greenland where environmental studies have been more extensive compared to other parts of the country. This is partly because the area provides easy access through Greenland's international air port, which is located in Kangerlussuaq. In addition, Kangerlussuaq houses the Kangerlussuaq International Science Support (KISS), which facilitates field research for several international research teams. This part of west Greenland is the most extensive ice free area of Greenland, which creates a diversified set of arctic environments, from the coast, through plains and a hilly terrain towards the ice sheet margin (Figure 2-1).

2.1 Bedrock geology

The Kangerlussuaq area is situated within the Nagssugtoqidian Orogen, which is a Palaeoproterozoic tectonic belt with a prominent eastnortheast-trending structural grain. This orogen is part of an extensive suite of Palaeoproterozoic organic belts stretching from Canada through Greenland and Scotland to the Baltic shield /Park 1994/. Similarities of rock types through this region are one of the reasons for the choice of location for the GAP and GRASP studies. Tonalitic to granodioritic gneisses are the rock types that dominate the local bedrock in the Kangerlussuaq region. Just north of the investigation area at Two Boat Lake is the eastnortheast-trending Ikertôq thrust zone, which is one of the most significant boundary zones within the Nagssugtoqidian Orogen. The Ikertôq thrust zone is characterized by numerous metasedimentary psammitic rock panels that parallel the thrust /van Gool et al. 1996/. Thrust zones and structural grain also leave an imprint on bedrock morphology with ridges and valleys generally following the eastnortheast direction. These, originally structural, valleys have been broadened and deepened by outlet-glaciers from the Greenland ice sheet, not just during the Holocene, but during numerous time periods preceding the last glacial maximum.

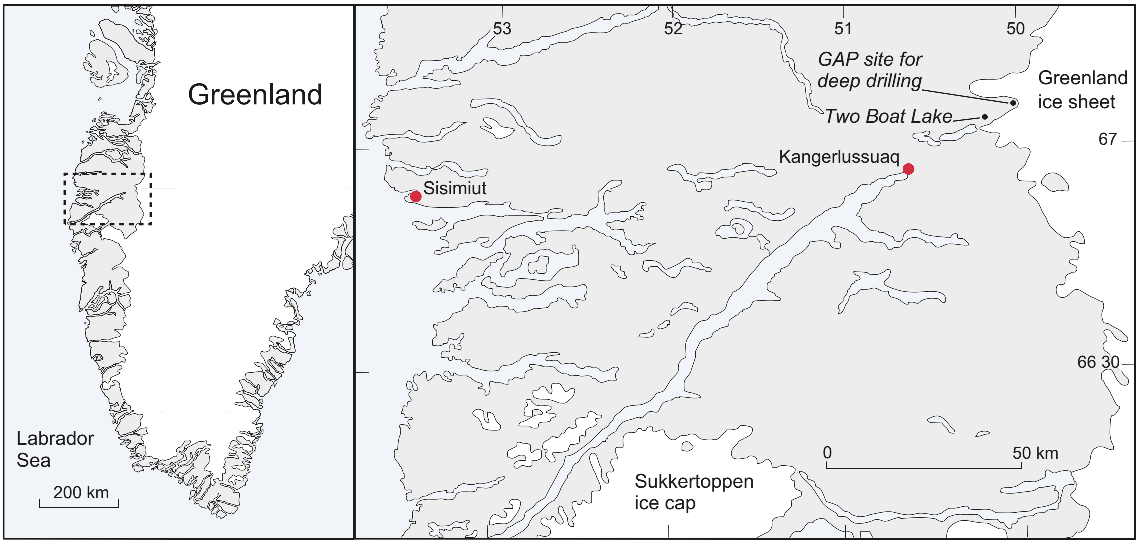

Figure 2-1. *Location of the study site at Two Boat Lake in relation to the ice sheet margin and the Greenland west coast. Leading up the town of Kangerlussuaq is the 190 km long Kangerlussuaq fiord.*

2.2 Glaciation history

History of the Greenland ice sheets has rendered great interest, not least because of the possibility to use the history as a key to the future. The future for the Greenland ice sheet is of major concern since a melting ice sheet could have great impact on global sea-levels and associated transgressing shore-lines. By using atmosphere-ocean general circulation models (AOGCMs) /Gregory et al. 2004/ predicted higher global air temperatures of 3°C might result in an irreversibly decreasing Greenland ice sheet. However, such a scenario can be questioned by taking into account findings of Eemian (previous interglacial before Weichsel glaciation) ice in basal layers of the ice sheet /Dansgaard et al. 1985/. The presence of Eemian ice in south and coastal Greenland implies that the ice sheet was essentially intact despite a climate of about 4 degrees warmer than today, and melting at that time could not have contributed more than 1 to 2 m to sea-level rise /Oerlemans et al. 2006/.

Recent studies from the basal layers of the Dye 3 ice core from southern Greenland show that at least 450,000 years have passed since southern Greenland was ice-free /Willerslev et al. 2007/. The basal layers of the ice contain DNA that can be attributed to a coniferous forest containing pine, yew and alder, corresponding to the type of vegetation that can be found in middle Sweden today. There are also traces of herbaceous plants belonging to families of *Asteraceae*, *Fabaceae* and *Poaceae* in the Dye 3 basal ice, which suggests an open forest allowing heliophytes to thrive /Willserlev et al. 2007/. The basal ice is dated using four different methods, which all suggest the ice predates the Eemian interglacial and have therefore survived one or several prolonged periods of temperatures higher than today.

The last glacial maximum is the time when the ice sheet reached its largest extension at the end of the last ice age, the Weichselian glaciation. The ice sheet in West Greenland reached its maximum at approximately 18,000 BP (before present), with its margin situated out on the continental shelf, in areas today submerged by the sea /Funder 1989, Bennike and Björck 2002/.

At about 10,000 BP, the ice sheet margin had retreated to a position of the present coast, and at about 6000 BP it had about the same position as the present ice margin /van Tatenhove et al. 1996/. It is not possible to determine the exact position of the minimum configuration of the Holocene ice sheet since the margin retreated beyond the current position of the ice sheet. However, /van Tatenhove et al. 1996/ extrapolated retreat velocities from dated moraine systems and concluded the margin probably reached about 10 km beyond its current position some time during the postglacial climatic optimum /Funder 1989/, which occurred prior to 4000 BP /Dahl-Jensen et al. 1998/. At this point, when the ice sheet had a more retreated marginal position, it most probably occupied drainage pathways for proglacial meltwater that were different from today. /Willemse et al. 2003/ studied the record of eolian silt deposits and found that deposition was considerably lower during a time period preceding 3400 BP. They interpreted the reduced silt depositions as due to rerouting of meltwater discharge following the mid Holocene ice sheet recession. At that time, meltwater was not flowing through the Sandflugtdalen and Ørkendalen valleys (Figure 3-10), which today serve as the main drainage routes of weltwater into the Kangerlussuaq fjord. Spatial and temporal variation in local eolian silt deposition is further described in Section 3.1.3.

2.3 Climate

The Kangerlussuaq region is climatically dominated by relatively stable high pressure cells over the ice sheet. The high pressures, further exaggerated by catabatic winds, cause easterly wind directions to dominate the regional wind patterns. Low-pressures and associated precipitation arrives from the Southwest, but a substantial portion of the moisture is precipitated over the Sukkertoppen Ice Cap (Figure 2-1), which thereby promotes a more continental climate at Kangerlussuaq, north of Sukkertoppen Ice Cap /Engels and Helmens 2010/. Mean annual precipitation (measured 1949–99) at Kangerlussuaq airport is only 149 mm and annual mean temperature is –5.7°C (measured 1973–99) /Cappelen et al. 2001/. These figures can be compared to Greenland's capital city Nuuk, which is situated south of Sukkertoppen. Nuuk has an average annual precipitation of 752 mm and the annual mean temperature is –1.4°C (measured 1961–90) /Cappelen et al. 2001/.

Annual precipitation decreases even further inland towards the ice sheet as a consequence of increased continental setting. Precipitation is also unevenly distributed over the year, with a strong summer maximum. The potential evapotranspiration could be as much as 300 mm /Hasholt and Søgaard 1978/, which means that the area can be regarded as a polar desert. A great portion of lakes and streams are only water-bearing during the period following snow melting, which is because the hydrological balance is dominated by evaporative losses throughout the open water period. Lakes usually lack surficial drainage later in the season and some of them are saline, which comes from the drying out by evaporation rather than drainage /Willemse et al. 2004/.

Windspeeds at the Kangerlussuaq weather station (Danish Meteorological Institute) is evenly distributed throughout the year, with an annually dominating wind direction from eastnortheast. But wind directions at the station are strongly determined by the topography and generally run parallel to the fjord /Hasholt and Søgaard 1978/, and thus probably deviates slightly from the wind patterns closer to the ice sheet. The area of the Two Boat Lake, situated in close vicinity to the ice sheet is more dominated by catabatic winds, which however decrease rapidly with increasing distance from the ice sheet margin. Based on directions of elongated sand dunes and ventifacts in Sandflugtdalen 5–10 km southwest from the Two Boat Lake, /Dijkmans and Törnqvist 1991/ measured the dominated wind direction to be from eastsoutheast.

3 Results of base-line studies 2008 and 2010

One of the purposes of the field studies of 2008 was to find a lake catchment that would be suitable for more detailed studies of a periglacial environment. The lake should be in close proximity to the ice sheet, but should not be affected by surface drainage of glacial meltwater. The catchment should be of a suitable size and be easily accessible from the only road in the area. When the SKB field party in 2008 visited the lake that later was chosen for expanded studies (Figure 3-1), there was another research group working on the lake at the same time. Each of the research groups had simultaneously their zodiac boats out on different parts of the lake. This unlikely coincidence gave rise to the working name Two Boat Lake. Since the lake does not have an official name, Two Boat Lake is used in this report when referring to the lake that became the focus of studies in 2010.

All maps and locations reproduced in this report are in the coordinate system of WGS 84 UTM zone 22N.

3.1 Surface geology

We conducted preliminary mapping of regolith by remote sensing techniques, using conventional colour aerial photographs in the scale of 1:30 000. The aerial photos were processed and mounted into digital stereograms by using StereoPhotoMaker software. By the combination of polarized spectacles and a polarized computer monitor screen, the stereogram gives the impression of a 3-dimentional vertical view of the terrain. Three stereograms were sufficient to cover the investigation area, and these stereograms were used for classification and delimitation of individual vegetation areas. We used GIS software ArcMap for digitizing polygons, classification of areas and construction of maps. The mapping based on remote sensing was corrected by field surveys in September 2010.

Following standard procedures, regolith units were mapped from their estimated distribution 0.5 m below the ground surface. Regolith was divided into occurring units of post-glacial silt, glacial diamicton, glaciofluvium, silty peat, colluvium and bedrock outcrops. Colluvium units are derived from slope processes and do appear along steep slopes below frost weathered outcrops. Occurrence of colluvium in vicinity of Two Boat Lake is rarely extensive enough to become mappable units, which means colluviums are more distributed than what appears from the map. Colluvium does, however, always occur in connection with frost weathering of bedrock. Peat is found in wetlands, but because of the constant infusion of eolian silt (described in Section 3.1.3), all peat has a varying degree of intermixed silt. The class is therefore denominated silty peat to emphasize that it is made up of mixed substances.

The non-genetic term glacial diamicton is used for poorly sorted sediments primarily derived as glacial till (described in Section 3.1.1). The material appears to have been deposited under strong influence of melt-water reworking, which makes it doubtful if it could be classified as a glacial till. Silt is the dominating regolith at the ground surface of the mapped area. As described in Section 3.1.3, the majority of the silt is supposedly deposited by eolian processes. Its areal distribution, as illustrated by on the map (Figure 3-2) is defined by the secondary process deflation, which causes erosion and subsequent exposure of underlying glacial diamicton or bedrock outcrops. This result of deflation makes underlying material to primarily become exposed on the most wind-swept areas, uphill positions and especially on crests of hills and ridges.

Figure 3-1. *Panorama photo of Two Boat Lake viewed from the northwest with Russel Glacier in the background.*

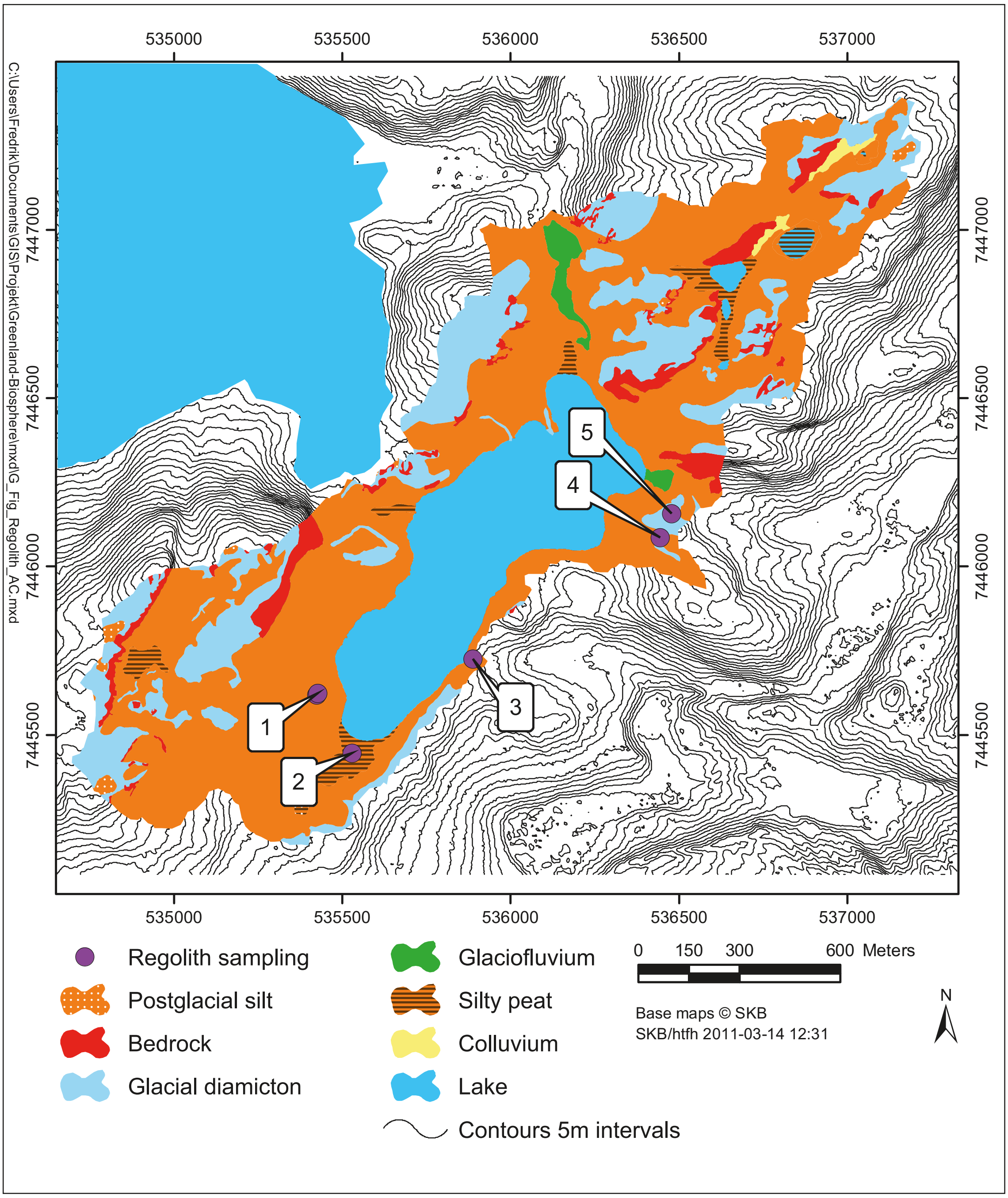

Figure 3-2. *Map of regolith distribution in the Two Boat Lake catchment. Numbers refer to locations for regolith sampling as described in Table 3-1.*

Regolith sampling was conducted at five sites (Figure 3-2) for chemical analysis to provide chemical element ratios and element-specific solid/liquid distribution coefficients (Kd). Samples were also taken for mechanical property analysis like grain size distribution and porosity. The five sites were chosen to represent, when taken together, a major part of the ground conditions found in the Two Boat Lake catchment. The sites had characteristics of 1) relatively dry and flat grassland, 2) grassland in wetter conditions on the bottom of a grass covered, dried out stream, 3) at the Two Boat Lake outlet, currently not showing any signs of surface water drainage, and 4 and 5) dry uphill position in a sandy glacial diamicton. Description of the pits and details on sample depth are given by Table 3-1.

Table 3-1. Summary of regolith sampling.

Pit ID	#1	#2	#3	#4	#5
Dominant regolith (depth from surface)	peaty silt	peaty silt	silty peat (0–0.6), fine sand (0.6–0.7), boulders and peat	sandy glacial diamicton	sandy glacial diamicton
Comment		bottom of dry stream channel, wetter than #1	layers deformed, possibly cryaturbation	bedrock surface at bottom of pit	
Thawed depth	0.49	0.52	1.0 (estim.)	unknown	unknown
Visible roots, depth		0.33		0.50	
Visible inflow of water, depth	0.49	yes (depth indefinable)	0.75	No	No
Porosity sample depth	0.10–0.15, 0.25–0.30		0.10–0.15, 0.25–0.30	0.15–0.20, 0.40–0.45	
Particle size distr., sample depth	bulk sample	bulk sample	bulk sample	bulk sample (estimated 20% stones)	bulk sample (estimated 20% stones)
Chemistry, sample depth	0.10–0.15, 0.25–0.30, 0.44–0.49	0.10–0.15, 0.25–0.30, 0.50–0.55	0.10–0.15, 0.25–0.30, 0.75–0.80	0.15–0.20, 0.40–0.45, 0.75–0.80	0.15–0.20, 0.40–0.45, 0.75–0.80
Vegetation sample (surface)	Graminae	Graminae, Salix	Graminae	Graminae, Artemisia	Graminae, Artemisia

3.1.1 Deposits associated with glacial processes

Glacial deposits are widespread in the Two Boat Lake catchment, but since deposition of eolian silt has prevailed during the period following deglaciation, glacial deposits are generally covered (further described in Section 3.1.3). The glacial deposits are only exposed where they are laid bare from silt at sites of concentrated deflation, stream-incision, or in road-cuts. This means that distribution of surficially exposed glacial sediments is not governed by glacial processes, but by subsequent sediment dynamics influenced by non-glacial processes, predominantly eolian and fluvial. Since all our knowledge on the local regolith is based on remote sensing and conventional mapping in the field, extension of deposits that underlay the silt mantle are highly uncertain. We therefore concentrated our study of the local glacial deposits to three localities for a more detailed survey. Two of the sites are located in an up-hill position where any eolian silt is supposedly deflated, and one of the sites is located at a small quarry next to the road.

The gravel pit (Figure 3-3) between the road and the Two Boat Lake reveals cross-sections through a number of units of glacial deposits. The lowermost unit consists of stratified sands, each layer a couple of centimetres thick. Stones and larger gravel occur in a low frequency throughout the beds. On top of the stratified sands is a unit of sandy-gravelly diamicton with a higher frequency of stones and large boulders. Stratification is less pronounced compared to the lower unit, which partly can be attributed to the coarser material making stratification less visible. The topmost glacial unit is a loose sandy diamicton with a high frequency of stones and occasional boulders. This unit does not show any bedding or graded horizontal differences. On top of all is the eolian deposited silt mantle that covers much of the terrain.

The two examination pits dug in an up-hill position are both very similar and reveal deposits that resemble the uppermost diamicton of the gravel-pit next to the road. A grey, sandy diamicton with a medium frequency of larger clasts forms a homogeneous profile on the hill. The diamicton is loose and has a low content of silt and clay, which makes it a material with a high porosity.

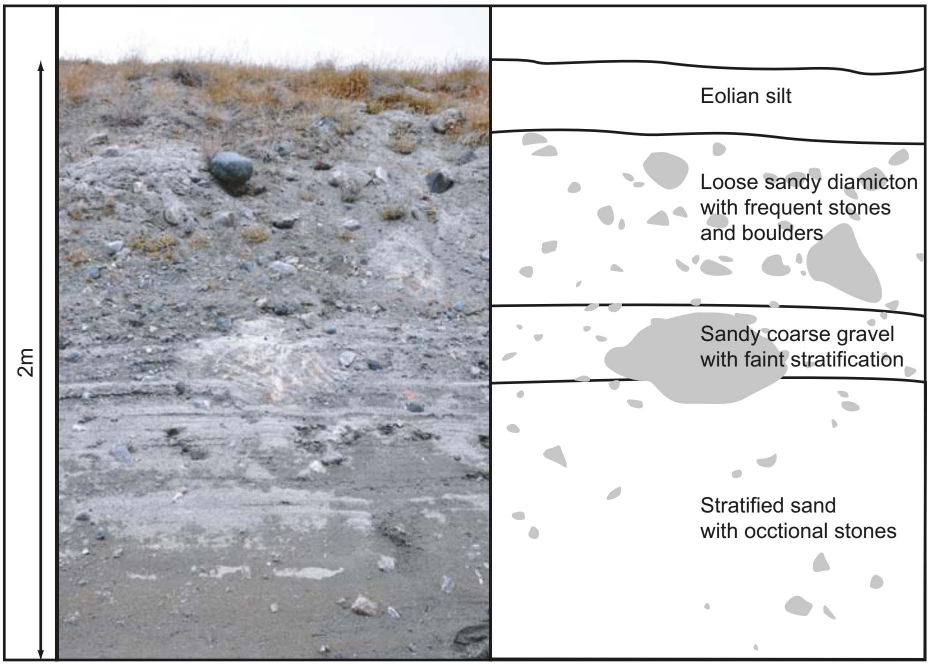

Figure 3-3. *Cross-section in a glacial diamicton and suprapositioned eolian silt mantle in a gravel pit used to provide road material for constructing the road from Kangerlussuaq to the ice margin. The sketch on the right gives properties of geological units of the left-hand photo.*

All investigated glacial diamictons of the Two Boat Lake catchment appear to be the type of sediments that are deposited at the margin of an ice sheet. They are all devoid of any fine material, are not compacted, and have no apparent glacially striated stones, which otherwise would be expected from a basal till deposited at the bottom of the ice sheet. The diamicton that surfaces at the Two Boat Lake does however resemble the deposits that are produced at the present ice margin (Figure 3-4). /Östmark 1988/ studied the glacial deposits of the Isúnguata Sermia ice margin about 3 km north of Two Boat Lake, and concluded that that major parts of the deposits are produced by supraglacial melt-out. The deposition of a melt-out till is produced by glacial debris melting out in situ at the margin, where it very well might be subjected to mixing and sorting by flowing meltwater. Such sorting by water dislocates the fine material that largely is transported out of the system by meltwater streams, thus leaving sediments of sand and larger clasts. Newly released material might be waterlogged and on unstable slopes it will flow under the influence of gravity.

Figure 3-4. *Glacial debris is released by supraglacial meltout at the margin between Isúnguata sermia and the Russel Glacier. Meltwater from glacial ice as well as from ice imbedded in the lateral moraine transport the fines and thereby leaving a sandy glacial diamicton with stones and boulders. The primary structure of the glacial till is largely reworked by ample surficial drainage and debris flows in the water-logged deposits. We assume this resembles the sedimentological environment that prevailed at Two Boat Lake at the time of deglaciation following the Last glacial maximum.*

3.1.2 Deposits associated with glaciofluvial processes

Glaciofluvial deposits in the Two Boat Lake catchment occur in the form of fossil deltas formed in a former large ice-dammed lake. The largest fossil delta is located north of the northernmost tip of the current Tow Boat Lake (Figure 3-2), most probably formed by glacial meltwater rich in debris entering from the north. The fossil delta corresponds to a water level that is approximately 40 m above the current water level of the Two Boat Lake. Such a lake configuration is likely to have occurred at times when the Russels's Glacier expanded into the NE-SW-trending valley Israndsdalen just south of Two Boat Lake. With the Israndsdalen valley blocked from drainage, glacial meltwater would be forced to flow through the area currently occupied by Two Boat Lake, entering from the northeast and draining further towards the northwest into the next northward lake basin. The existence of an ice-dammed lake and a drainage route as proposed above is supported by the compliance of approximate altitudes between the fossil delta and threshold of the, now dry, channel leading into the next northward lake. This issue could be further elaborated by accurate levelling of genetic features (fossil delta and raised threshold). Heights for the preliminary proposed development described above are from the DEM (Section 3.4.2), which has an error range that exceeds the purpose of using it for detailed comparison of heights.

An ice dammed lake would have left glacial lake sediments all through its extension, up to about 40 m above the current lake level, which is the approximate height of the fossil delta. Such sediments were not found during fieldwork, which could be explained by the difficulty to distinguish it from eolian silt (described in Section 3.1.3). However, it should be noted that silty lake sediments might underlay the eolian silt on lower altitudes around the Two Boat Lake. Because of its deposition in water, silty lake sediment would most probably have a lower permeability than superpositioned eolian silt.

3.1.3 Processes and deposits associated with wind action

The striking unit of the surficial geology in the Two Boat Lake catchment is the eolian silt which makes up an almost continuous mantle covering underlying deposits (Figure 3-2). This silt is part of a regional geological unit widely spread between the ice sheet margin and further coastward towards Kangerlussuaq. Thickness of the eolian silt at Two Boat Lake varies from approximately 1 m along lower footslopes, to < 0.2 m in the most upland areas. The maximum depth is unknown, but could potentially be considerable on the bottom of the lake. These loess-like deposits directly overlie bedrock or glacial sediments.

Newly cut cross-sections in the eolian silt appear unstratified, but this is probably a result of differences in grain size being subtle and hardly visible to the naked eye. However, older sections cut by deflation do show a noticeable fine lamination. This is because slight differences in grain size make varied resistances to the deflating forces. This subtle lamination is a general pattern caused by the highly varying energy of transporting winds. /Willemse et al. 2003/ conducted detailed analyses of grain sizes and found finer fractions of the alternating bands to be < 0.1 mm and coarser layers to have sizes of < 0.3 mm.

/Willemse et al. 2003/ studied rates and temporal variation of silt influx from peat profiles in Sandflugtdalen and Ørkendalen (Figure 3-10 for locations) mainly as a proxy for eolian activity and inferred wind patterns. Conditions seem to have been continuously favourable for eolian deposition at least since ca. 4,750 years BP. Influx rates have varied between 0.075 and 0.60 kg/m^2/year. /Willemse et al. 2003/ propose the variation in silt flux to reflect modulations of the meridional circulation and associated frequency of penetrating maritime air masses over the ice sheet during winter. The relationship is inverse in such a way that increased maritime influence on the ice sheet in winter would decrease the flux of eolian silt along the western margin. The exact physical causes for modulations in silt flux is not central for the understanding of the Two Boat Lake environment, but it is important to note that ocean-atmospheric conditions affect the deposition of silt, which is assumed to have been highly variable through the Holocene. The variable influx is apparent in silt sections at Two Boat Lake by the occurrence of palaeosols, i.e. former vegetated ground surfaces buried and preserved under periods of exceptionally high depositions rates. Figure 3-5 shows a palaeosol 0.20 m below the current ground surface. The palaeosol is not horizontal, but neither is the current ground surface. The bedrock or topmost surface of glacial diamicton are not visible in this section, but are likely to have the same general dip as the two ground surfaces (the palaeosol and the current ground surface).

Sources of the eolian silt are the glacial sediments that are constantly released by ablation of the glacial ice. Once airborne, silt can remain in aerial suspension for a long time and can be transported over considerable distances before it settles on the ground or in water bodies. The source areas are therefore regional and pickup can occur directly from the ice surface, from marginal moraines or from one of the extensive glaciofluvial floodplains in valleys draining glacial meltwater towards the ocean. The two major valleys Sandflugtdalen and Ørkendalen, each with 1–2 km wide proglacial valley-sandurs are occupied by braided streams. The widely fluctuating discharge and constantly changing courses of the braided streams make large amounts of newly deposited fluvial material exposed to eolian uptake. The sandurs are periodically flooded by draining water from jökulhlaups (water from catastrophic drainage of ice-dammed lakes).

Discharge during these floods may amount to 30–80 times the normal flow /Russel 1989/, whereby meltwater inundates the entire sandurs. Suspended sediments of silt and sand carried by the jökulhlaup remain on the sandur when water levels drop following inundation. /Dijkmans and Törnqvist 1991/ arrived at Sandflugtdalen just after the 1989 jökulhlaup and found a few centimetres thick layer of damp silt and fine sand covering the sandur. Higher parts of the sandur dried up quickly and enabled eolian transport of the fine-grained material. Wind speeds of only 6 m/s initiated small dust clouds, whereas wind speed of 14–18 m/s caused the silt to rise more than 100 meters and get transported out of the valley towards the uplands. /Dijkmans and Törnqvist 1991/ observations represent a typical chain of events that might cause a short period of increased eolian silt influx to an area like at Two Boat Lake. It also points to the flood plains as the dominating sources of eolian silt. The hilltops just north of Sandflugtdalen are covered by eolian silt usually just less than 40 cm, whereas at Two Boat Lake a few kilometres to the northeast, the thickness diminishes to approximately 20 cm on exposed hilltops.

Figure 3-5. *Sub-horizontal palaeosol 0.2 m below the current ground surface. Roots protruding from the palaeosol pertain to the Salix bush growing on the current ground surface, so they are not fossil. Roots take advantage of the organic layer for its capacity to hold moisture.*

The eolian silt at Two Boat Lake shows obvious signs of deflation on the most wind exposed patches. These deflation scars usually have sharp edges of vertical cuts through the entire silt mantle, thereby exposing the subpositioned glacial diamicton or bedrock. Where the underlying glacial diamicton is exposed, the topmost surface has experienced a loss of fine-grained material, leaving a pavement of stones and gravel, protecting the diamicton from further deflation (Figure 3-6, A). The sharp edges indicate that lateral erosion is the dominating process for deflation of the silt surfaces, certainly because of the protective function of vegetation on top. Figure 3-6, A illustrates the lateral erosion to undercut the edges below the grass turf. This undercutting causes turf edges to be unsupported, gradually curve downwards and eventually break off. With the turf edges breaking off, the lateral erosion can propagate further and expand the erosional scar at the expense of the silt mantle. A sign of the deflation being ongoing today is the lack of lichen vegetation on bedrock outcrops next to erosional edges (Figure 3-6, B). Despite the ability of lichens like *Ritzocarpon spp.* to quickly colonize rocky surfaces, the bedrock in immediate vicinity of the erosional silt remnant (lower right in picture) does not have any lichen cover. The sharp transition between the bedrock surface interpreted as recently uncovered (lack of lichens) and the longer exposed bedrock surface (covered by lichens) is however somewhat surprising. It is hard to explain in other ways than that once the protective grass turf is disturbed or removed, there is not much that holds deflation back, which effectively removes the entire silt mantle.

An obstacle like a big boulder (Figure 3-6, C) deflects the wind and thereby shelters the eolian silt positioned on the downwind side of the boulder. When the wind is forced to flow around the boulder, a more turbulent flow increases the deflation on the upwind side as well as on the sides in parallel position to the wind. The scars from deflation can therefore be used for estimating the dominating wind direction, in this case indicating a dominating wind from due east. Wind can also be estimated from the extension of lichens on bedrock surfaces. A monolithic quartz (Figure 3-6, D) provides a harsh substrate for lichen growth because of its smooth surface. No lichens grow on the upwind side of the rock, which in this case indicates deflation and a dominating strong wind direction from the east.

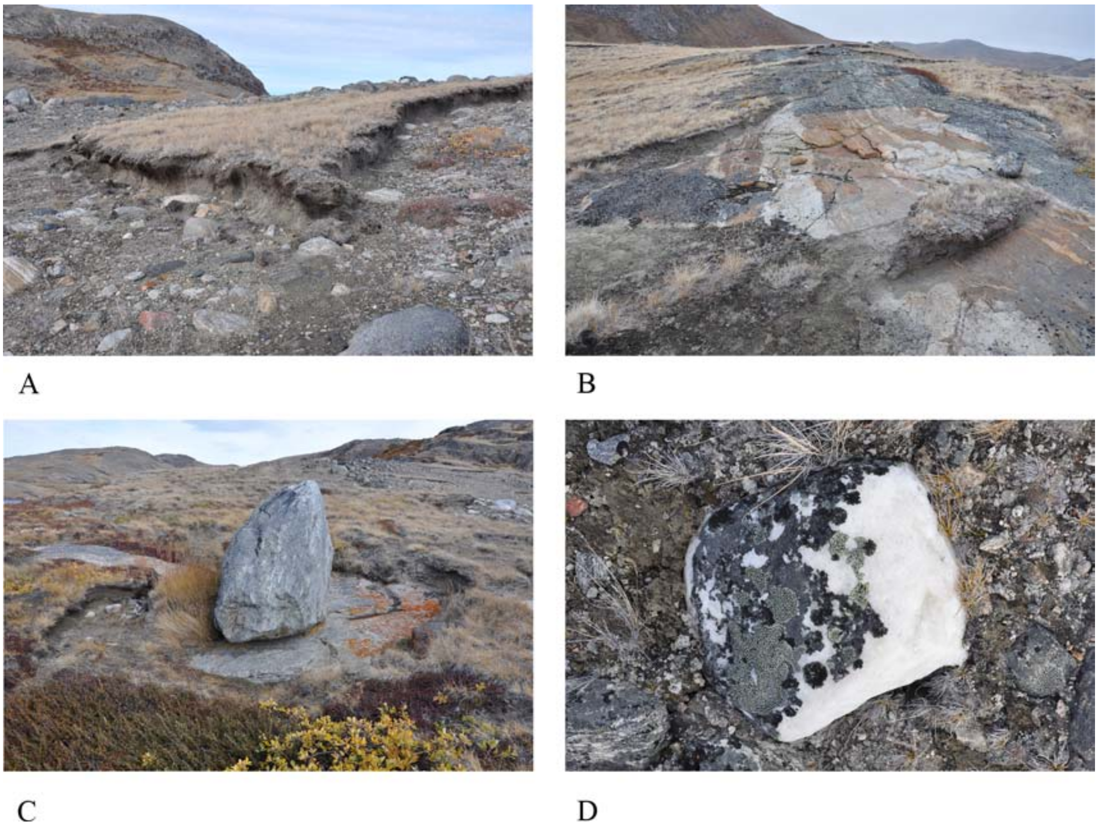

Figure 3-6. A) Vertical deflation edges enclose a remnant of the mantling eolian silt. B) Deflation has recently uncovered a bedrock surface not yet colonized by lichens. C) A boulder serving as an obstacle for wind erosion. D) Lichens are unable to grow on the upwind side of a quartz boulder.

3.1.4 Organic deposits

Because of continuous and simultaneous accumulation of both eolian silt and peat, all peat partially contains silt. The proportion of peat versus silt varies within the profile as a function of both silt influx rate and the type of vegetation during the time of deposition, i.e. the faster the peat accumulation rate, the higher the portion of peat compared to silt. Concentration of peat also varies from site to site mainly due to hydrological conditions governing conditions for local vegetation and decomposition of vegetation remains. In wetter areas, typically where topography funnels drainage along the footslopes, decomposition is slower and conditions are more favourable for peat accumulation.

Deposits where peat dominates over silt are mainly found immediately adjacent to smaller streams. Further away from the stream, land is drier and the dominance of silt gradually increases. These peaty deposits in connection to streams rarely make up mappable units and are therefore not represented on the map of regolith distribution (Figure 3-2). Only one major exception exists at the northeastern part of the lake where local discharge into the lake is by over-land flow. Peat accumulation also occurs in shallow waters along the lake shore. In positions sheltered from wave actions, the bottoms are covered by aquatic plants like *Hippuris vulgaris* and *Scorpidium* mosses, which remnants make up thin blankets of peat. This near-shore peat is regularly relocated to a dry position up on the shore by the process of making ice-push ridges (Further described in Section 3.1.5).

Two wetlands were sampled in 2008 for C-14 dating layers of peat. This was done in order to give an estimate of peat accumulation rate in representative wetlands (Table 3-2). The dating was performed on organic matter after removal of root material. Estimated accumulation rate calculated from the topmost date of a wetland in vicinity of lake #9 (Figure 3-19 for location) suggests a significantly faster accumulation compared to the lower date. This could, at least partly, be explained by the fact that influx of silt and its portion of the total accumulation is not taken into account in these estimates. The upper part of the profile does have a higher content of inorganic material that most likely contributes to the rate of total accumulation appearing to increase upwards in the profile. The C-14 dates for lake #11 (Figure 3-19 for location) have a reversed age chronology, with the lower sample having a younger age than the top sample. This disconcerting result could either be a result of contamination during sampling, or could possibly suggest that some type of displacement of organic constituents by the influence of running water. Cryoturbation is an unlikely process to give rise to the reversed ages, since there were no signs of disruption of stratigraphic horizons in the profile.

3.1.5 Landforms associated with processes at the lake shore

A considerable portion of the Two Boat Lake shore perimeter has ridges of approximately 1 m height parallel to the shore (Figure 3-7). These *ice-push ridges* are a well known phenomenon from aquatic and marine shores all over Arctic and boreal regions /Dionne 1979/. The ice-push ridges at Two Boat Lake consist of a mixture of minerogenic material in all fractions usually mixed with peat. They occur on gently sloping shores at about 1–3 m distance to the current summer shore-line (September 2010). The proximal side, the one facing the lake, is steep or almost vertical, while the distal side is more gentle and sometimes forming a depression between the ridge and the footslopes of hills surrounding the lake (Figure 3-8, A and B). Dry soil conditions on the ridge crest offer substrate for herbaceous plants and for bushes like *Salix glauca* and *Vaccinium uliginosum*. The occurrence of mature bushes illustrates that these ridges are semi-permanent features that could have developed gradually during a substantial time period.

Cross-sections of the ridges reveal a diversified mix of materials reflecting the material that is to be found in the littoral zone adjacent to the ridge. The littoral zone pictured in Figure 3-8(A) consists of a mat of the mosses *Warnstorfia tundra*, *Scorpidium scorpioides* and *Scorpidium cossonii,* as well as the aquatic plant *Hippuris vulgaris*. Therefore, the adjacent ridge consists of peat, supposedly constructed by humification of the same mix of species. The ridge has a low content of minerogenic material, apart from occasional large rocks and boulders. The ridge of Figure 3-8(B) on the other hand is mainly constructed by a coarse sandy material with a high content of larger clasts, which is the same material that is to be found in the littoral zone of that site.

Figure 3-9 shows a cross-section at the southernmost end of the lake with low humified peat (light brown), high humified peat with silt (dark brown), a boulder and a still coherent slab of silt. The boulder is positioned on and surrounded by fine sand of the type that is to be found in the shallow near-shore waters.

Table 3-2. Data on samples for C-14 dating. The active layer at the time for sampling was 0.55 m and 0.54 m, respectively. Locations are given by Figure 3-19.

Site	Depth (cm)	C-14 age (BP)	Inorganic content (% of dry weight)	Specimen
#9	25–30	135±35	83	Sedges
#9	50–54	1915±40	69	Sedges
#11	25–30	2070±70	97	Sedges, brown mosses
#11	35–40	1410±120	–	Sedges, brown mosses

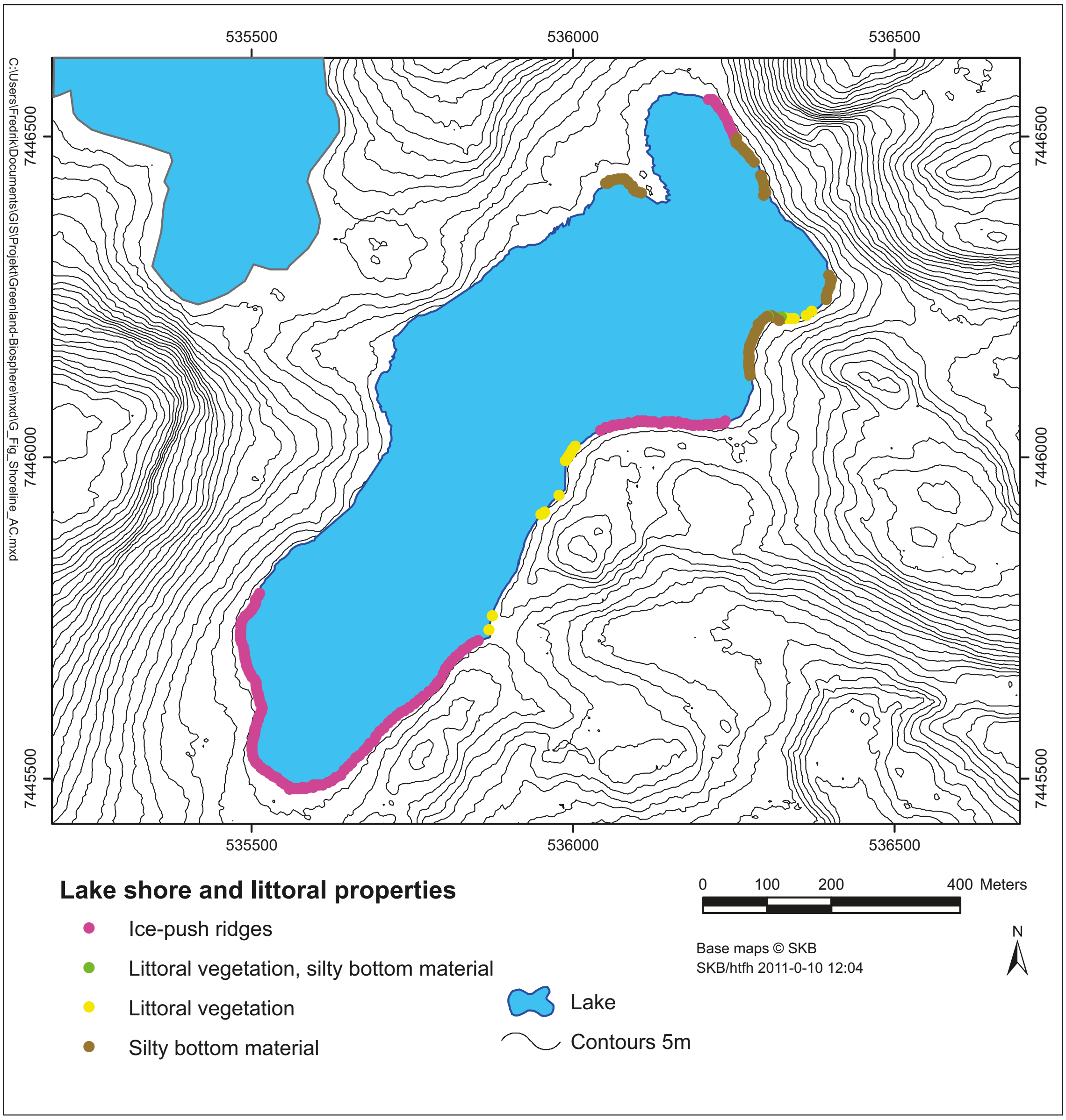

Figure 3-7. *Map of littoral properties and distribution of ice-push ridges around the shore of Two Boat Lake.*

A

B

Figure 3-8. *A) A stretch of the shore where the littoral zone is covered by Common Mare's Tail and Scorpidium mosses (Warnstorfia tundra, Scorpidium scorpioides and Scorpidium cossonii). B) A stretch of the shore characterized by stony gravel and scattered boulders. Distal to the ridge is a depression forming a small wetland of approximately 10 m*^{2}*.*

Figure 3-9. *Cross-section parallel to the shoreline showing a diversified mix of materials, such as peat, boulders and coherent slices of silt. The light gray wolly material is in fact wool! Muskoxen have used the ridge to scratch their backs and getting rid of some of the winter fur falling off in late spring.*

Much of the literature on ice-push ridges dwells on two proposed processes for their formation. The ridges could have been made by wind action forcing ice flows to stack on the shore at time of ice break-up /Norrman 1964, Peterson 1965/, or possibly by thermal expansion of the lake ice /Hamberg 1919, Sundberg-Falkenmark 1958/. It seems likely that both these mechanisms can be attributed to the formation of ice-push formations, but acting on lake shores in different geographical settings and in different climate regimes /Dionne 1979/. Wind action seems less likely at Two Boat Lake because the lake is small and does therefore has a limited fetch, and secondly the ridges do not occur in any pattern that could be attributed to a prevailing wind direction.

Ice-push ridges at the Two Boat Lake are more likely created by thermal expansion enhanced by repeated temperature fluctuations. Lake ice expands and is pushed ashore as temperature rises, especially notable when the change in temperature is large. That expansion is not enough to explain 1 m high ice-push ridges of 1–3 m from the shore like at Two Boat Lake. But a rapid lowering of ice temperature, as associated with a diurnal change in winter weather, would allow contraction cracks to form. These are quickly filled with water, which refreezes and expands the ice even further. In addition, filling of the cracks prevent them from closing. When temperature rises again, lake ice extends further compared to before the contraction. Repeated temperature variations will in this way lead to successively larger expansions of lake ice and possible push movement up on the shores. A prerequisite for the efficiency of this mechanism is that the lake ice is covered by only limited amounts of snow, which otherwise would insulate from changes in temperature propagating down through the ice /Hamberg 1919/.

Expansion of lake ice up on the shore will transport bottom material frozen to the base of the ice landward. Plastic deformation will stack the debris on top of earlier deposited material or push in forward and thereby forming ice-push ridges parallel to the shore. The stacking or pushing is facilitated by shallow depths of freezing under near-shore ice. Ice-push ridges usually occur where the shore configuration is even, having a gentle bottom slope, and where the bottom material consists of low concentration of boulders. All these criteria are fulfilled at Two Boat Lake, and thus serve as a good explanation for the pronounced and continuous ice-push ridges along the shore. It also makes a god explanation of the diversified mix if material in the ridges and the high concentration of boulders deposited in the littoral zone. The ridges have high peat content where the shallow waters are covered by *Scorpidum* mosses, and the ridges predominantly consist of clastic material where littoral vegetation is lacking.

The existence of ice-push ridges and the obvious processes that formed them might have significance for mass transport considerations in an environment like at the Two Boat Lake. This is because the ice-push mechanism serves as a process that transports material deposited in the aquatic environment up into the terrestrial environment. The amount of transport could be considerable and deposition in an essentially different regime might lead to faster decomposition of organic material and a faster turnover of chemical elements, which are to be incorporated into new pathways compared to if the material would have stayed on the bottom of the lake.

3.1.6 Permafrost

The depth of the active layer was measured with a soil probe at a number of locations (Figure 3-10) in 2008 and 2010. A general description of vegetation, soil type and other properties of interest for the evaluation was done for each measurement point. Probe surveys at Two Boat Lake (Figure 3-11) resulted in a mean depth of the active layer to be 0.69 m. The maximum and minimum depths were found to be 0.94 m and 0.55 m respectively. The standard deviation of all measurements was 0.1, in a total of 20 probed locations.

All three transects in the Two Boat Lake catchment are laid out to start from the lake shore to extend in the uphill direction. This is in order to comprise possible variation along an altitudinal gradient. However, no such altitudinal variation were found to along these transects, which partly can be a result of transects being relatively short with an altitudinal difference of approximately 40 m. Even though no quantitative measurements were done on moisture content or grain size distribution of regolith along the transects, we expect these factors to have an effect on active layer depth.

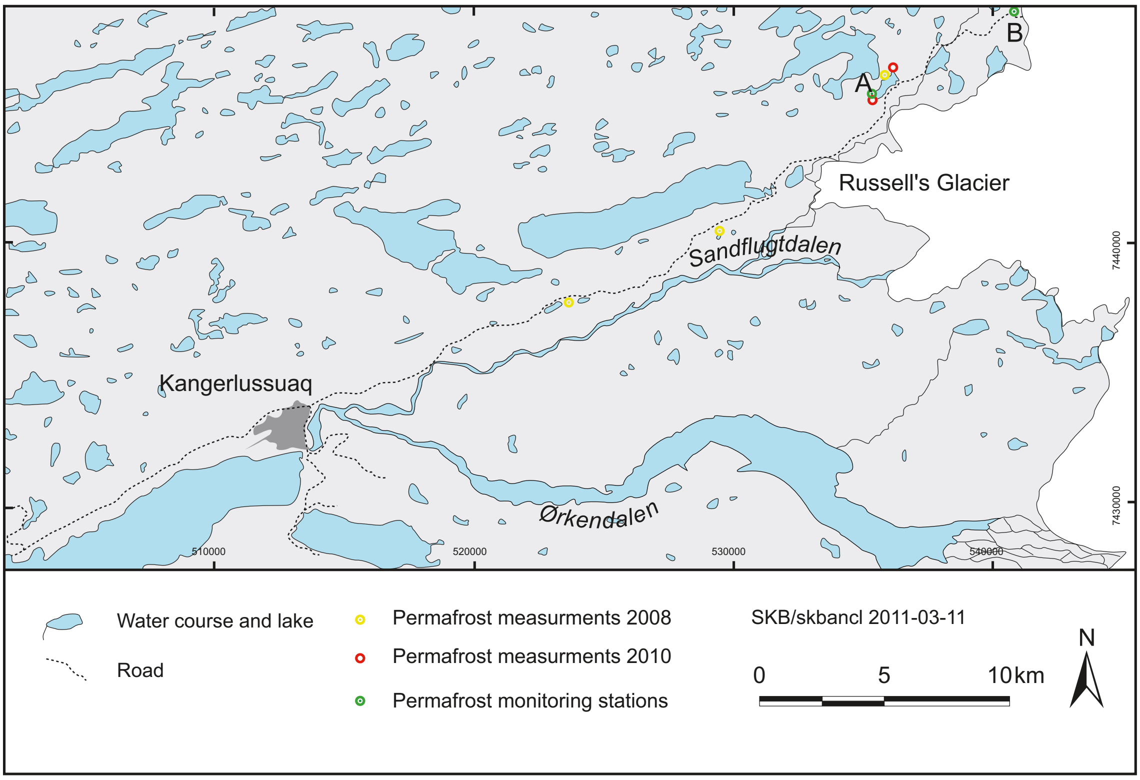

Figure 3-10. Extension of active layer measurements and transects from investigations in 2008 and 2010. Letters mark locations for ground temperature monitoring stations at A), Two Boat Lake, and B), the site for the GAP deep borehole to be drilled in the summer of 2011 /SKB 2011/.

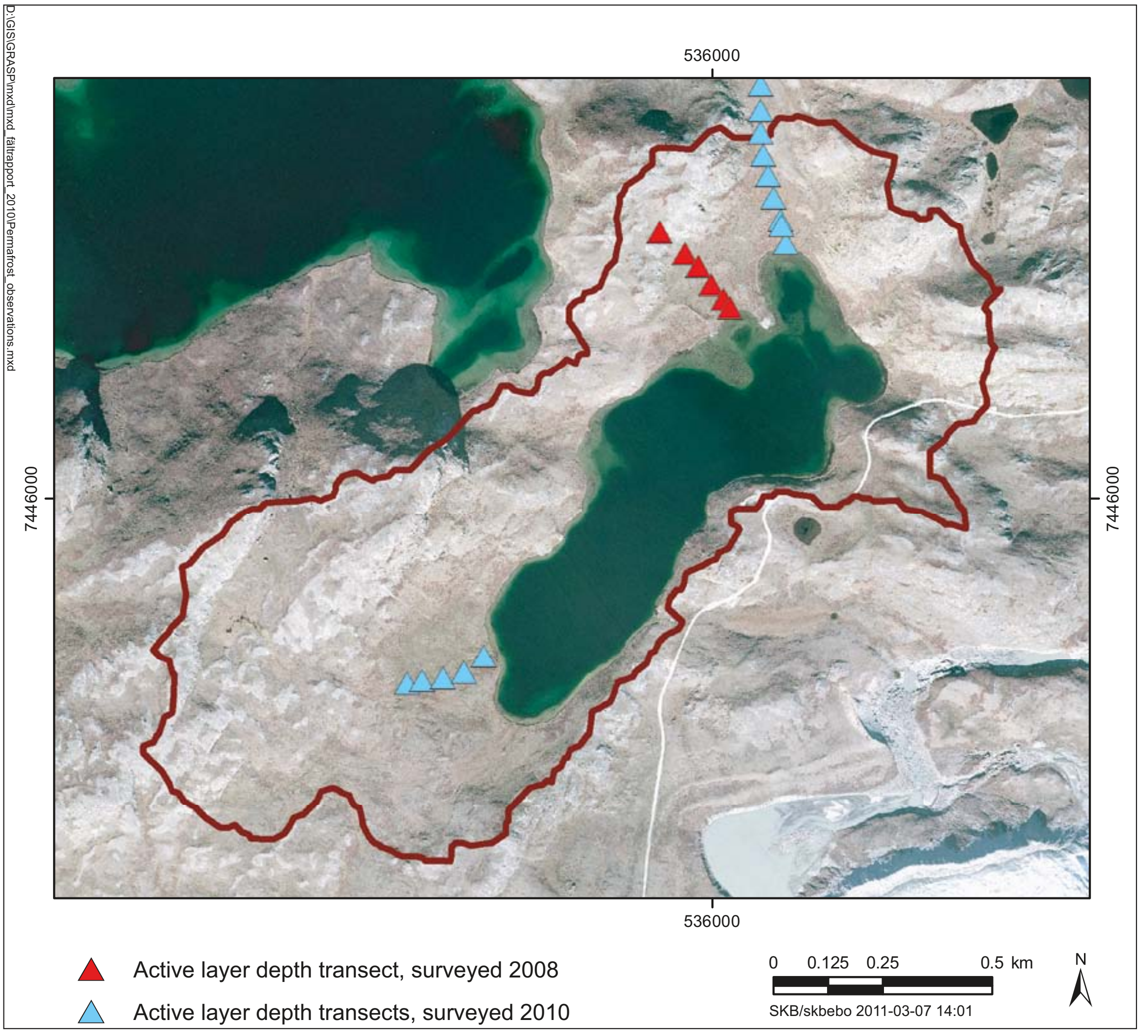

Figure 3-11. *Active layer depth transects surveyed at Two Boat Lake.*

In addition to probed transects, depth of permafrost table and ground temperature were also measured in pits dug for sampling of regolith (described in Section 3.1). Pits in silt and peaty silt all reach the permafrost table at depths that agree with the probing survey. However, two pits dug in an uphill position in coarse diamicton (reference numbers 4 and 5 of Figure 3-2 and Table 3-1) did not reach permafrost even at the depth of 0.8 m. The temperature at the bottom of one of the diamicton pits measured 5.9°C, which contrasts the probing measurements where the permafrost table was reached at a mean depth of only 0.69 m. This is probably because of the much depleted moisture content in the sandy diamicton combined with the uphill position. In such conditions, the summer warming is likely to penetrate much faster and reach deeper when the moisture content is low. This should be compared to a moist setting where a majority of the energy that heats the surface from above is consumed by melting ice in the ground.

3.1.7 Landforms associated with permafrost

Ice wedges, and their plan-view pattern as ice-wedge polygons, are created by frost cracks and cyclic expansion of the ground surface. Frost cracking begins when thermally derived stresses generated upon cooling exceed the strength of the surface material. The moment of cracking seems to occur in mid-winter when temperatures in the ground reach the annual minima and temperature fluctuations are substantial /Mackay 1974/. A thick snow cover insulates against cold winter temperatures to effectively penetrate the ground, which means that ice wedges are best developed in areas of low winter accumulation, and preferably in fine-grained sediments.

Initially, the cracks are only millimetres wide, but they may extend vertically downward to depths of several meters. When thawing starts in spring, the cracks become filled with water that is released by the onset of thawing in the active layer. Refreezing of the water below the permafrost table causes the crack to widen even further and prevents the crack from closing. The now ice-filled crack represents a zone of weakness in the permafrost and subsequent winters produce cracking along the original opening, whereby new ice is added. The gradual accumulation of ice takes the form of a downwards tapering ice wedge. In an arid environment like in West Greenland, where winter snow is limited, the cracks can be filled by windblown silt and thus forming a silt wedge. In plan-view, the wedges form a polygonal pattern as they intersect in sharp angles, and thus forming ice-wedge polygons that can range in diameter from a few meters to more than 100 m. Edges of the polygons, defined by the actual ice wedges, often form a linear depression because of summer melting and erosion by water (Figure 3-12).

Ice-wedge polygons at the Two Boat Lake are best developed in the northeastern corner of the lake and on the northern slopes of the hills forming the western catchment perimeter. These are all in relatively shaded positions to direct solar radiation, thereby having damper soil conditions. Borders of the polygons, supposedly formed by ice wedges, truncate the slopes generally either in horizontal or vertical directions. The polygons are also in positions that are utilized by concentrated surficial drainage along the footslopes. Surficial drainage is evident from the depressions along polygon edges showing clear signs of seasonal stream erosion.

One of the polygon edges at the northeastern part of Two Boat Lake were excavated during field-work in September 2010. The surface expression of the edge was a linear 0.5 m deep depression. The bottom material consisted of a moist silty peat with a depth to permafrost table at another 0.3 m. Eolian silt is clearly accumulated in the depression and the high peat content is to be expected because of the damp conditions. Some of the material at the bottom of the depression could also come from topsoil of the polygon rim which forms the lateral boundary of the depression.

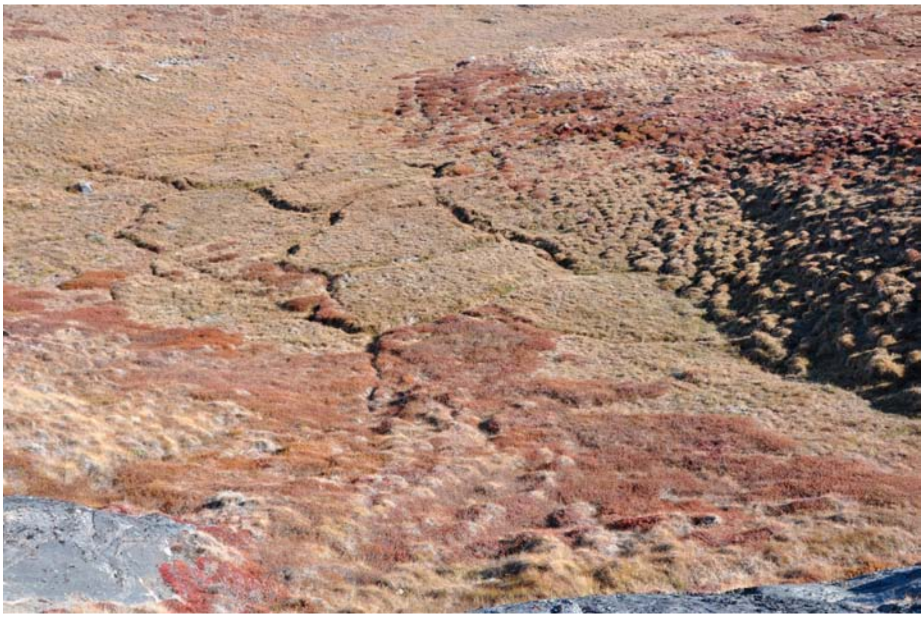

Figure 3-12. *Ice wedges are formed by thermally induced cracks that are filled with ice and eolian silt. When intersecting, they form ice-wedge polygons which are typical landforms of an arid periglacial environment. Photo from the eastern part of the Two Boat Lake catchment.*

3.2 Ecology

3.2.1 Vegetation

We performed mapping of vegetation by the same remote sensing techniques as described for mapping of regolith (Section 3.1). Areas of uniform appearance in aerial photographs were delineated as individual polygons, and these polygons were grouped in classes based on comparable qualities as appearing in the photos. The result was a polygon mosaic where the identity of the classes was largely unknown. Polygons representative for each class were examined in the field, whereby the classes were given descriptive names (Figure 3-13). We did not perform quantitive investigations of plants species densities. All field investigations were based on inventory of occurrence and visual estimates of ground coverage of each species. Some of the classes that resulted from remote sensing interpretation were merged into a common class, when examination in the field revealed it as a negligible difference in density of a certain species. However, when density differences were large enough to make up discernable boundaries in the field, classes were kept as interpreted by remote sensing.

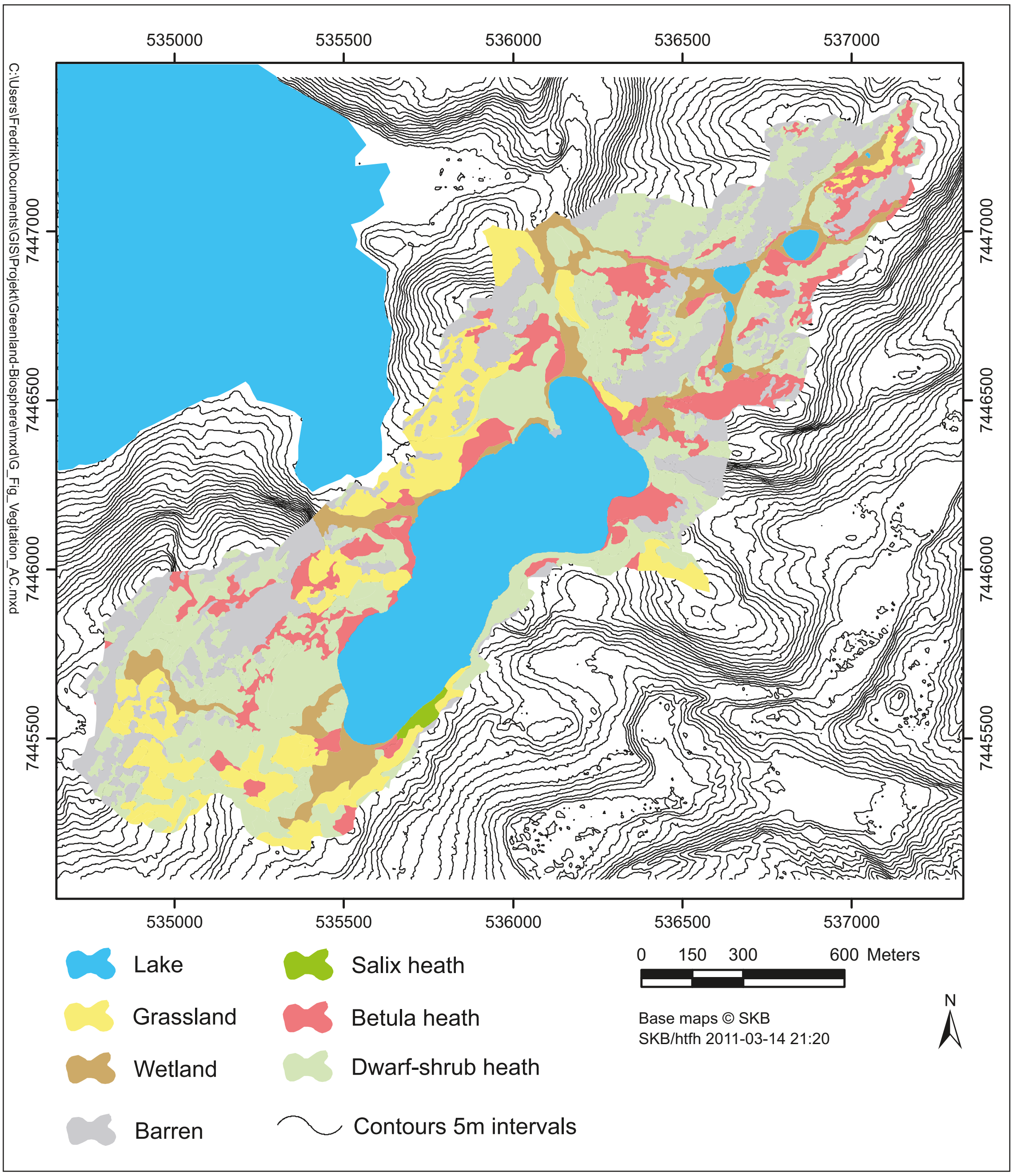

Figure 3-13. Vegetation map of the Two Boat Lake catchment.

Vegetation in general at Two Boat Lake is dominated by dwarf-shrub heath (Figure 3-13). There are no trees and bushes rarely exceed heights of 0.5 m. There is a fairly limited amount of vascular plant species, but the spatial distribution and density of individual species is highly variable in different parts of the catchment. This is mainly due to different abiotic factors such as regolith, exposure to wind and presence of patches of snow that melts late in the season /Sieg et al. 2006/.

Dwarf-shrub heath

The dwarf-shrub heath is the most extensive vegetation type at Two Boat Lake, and does also include a great variability of dominating plants. The woody plant that primarily characterizes the dwarf-shrub heaths is *Betula nana*, covering about 5–50% of the ground. The *Betula nana* generally grows in coherent stands in sizes ranging from < 1m^2, but the stands can form uninterrupted clusters of several hundred m^2. Where these clusters form mappable units, they have been assigned a specific vegetations class then called Betula heath, which should be regarded as a subcategory of the dwarf-shrub heath. The same concerns *Salix glauca*, which form dense clusters at one location. This subclass is denominated Salix heath. Other woody plants that occasionally form tussocks or more extensive clusters within the dwarf-shrub heat are primarily *Vaccinium uliginosum* (Figure 3-14, C), but also *Ledum palustre* (Figure 3-14, E) and *Rhododendron lapponicum* (Figure 3-14, D).

Betula heath

Betula heath is where *Betula nana* forms large, coherent stands, covering more than 50% of the ground (Figure 3-14, A and F). Other woody plants on the Betula heath are mainly *Vaccinium uliginosum*.

Salix heath

Salix glauca is a common plant around Two Boat Lake, occurring on all elevations from the lake shore up to crests of the surrounding hills. On one of the southeast facing slopes, *Salix* has a higher dominance than on all other grounds, which caused the introduction of Salix heath as a specific vegetation class, mainly to highlight this specific area. Within the Salix heath, *Salix* forms dense stands of copses, as compared to other areas where it mostly occur as single specimens. Copses of *Salix* on the Salix heath cover about 50% of the ground with a slight increase in density towards the lower footslope along the lake shore (Figure 3-15, A). In more elevated positions, *Salix glauca* dominance is gradually replaced by higher density of *Betula nana*. Other woody plants are *Ledum palustre* and *Vaccinium uliginosum*, each covering about 5% of the ground. Herbaceous plants are scarce, with a few occurring *Cerastium alpinum*.

Fell-fields and wind-swept barrens

In the most wind-swept areas, deflation has removed the otherwise continuous silt mantle, exposing the glacial diamicton or bedrock. Here, the vegetation is scarce, both because of the substrate, and because of the exposure to drying winds. *Rhododendron lapponicum* and *Vaccinium uliginosum* form small stands, but otherwise vegetation consists of lichens, mats of *Dryas integrefolia*, and tussocks of grasses like e.g. *Kobresia mysuorides.* Herbaceous plants *Potentilla nivalis, Saxifraga paniculata* and *Artemisia borealis* grow on the dry gravelly slopes (Figure 3-15, B).

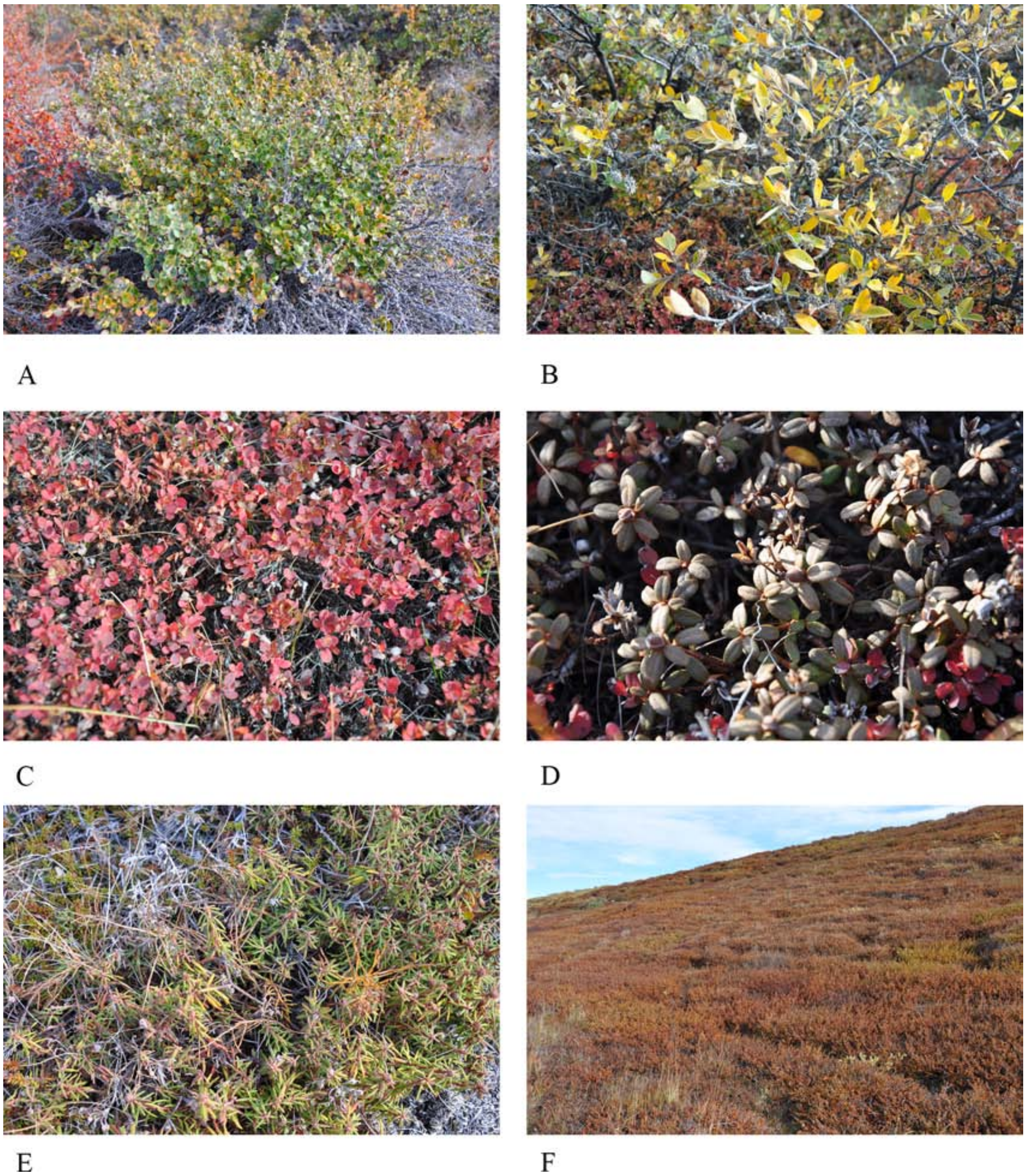

Figure 3-14. *Dominating woody plants of the dwarf-shrub heath. A) Betula nana, B) Salix glauca, C) Vaccinium uliginosum, D) Rhododendron lapponicum, E) Ledum palustre, and F) a slope of Betula heath, where Betula nana (in autumn colour) totally dominates ground coverage.*

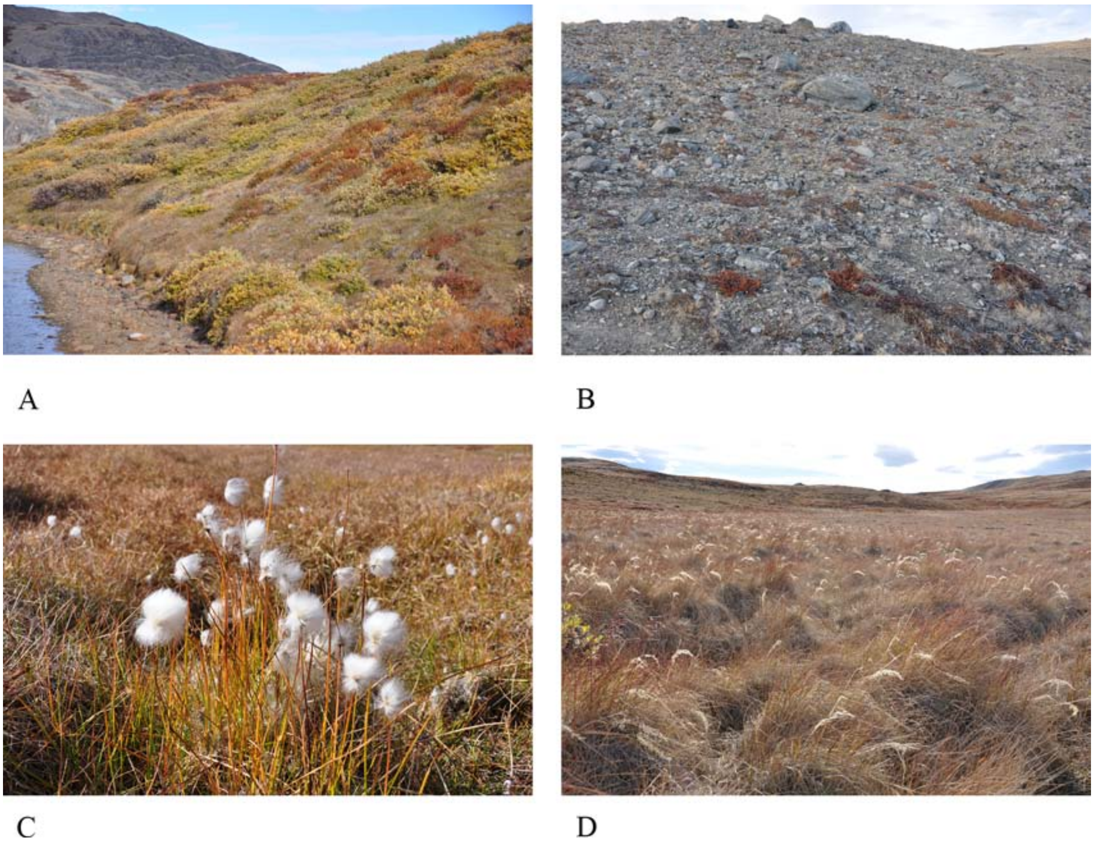

Figure 3-15. Salix heath where Salix glauca (light green-yellow) has approximately 50% of ground coverage, B) sparse vegetation on a wind-swept barren, C) Eriophorum scheuchzeri and, D) Calamagrostis langsdorfii on ground classified as wetland.

Wetlands

Because of the very limited precipitation, there are no raised bogs in the Kangerlussuaq area, which is also true for the major part of Greenland /Feilberg et al. 1984/. Instead, wetlands occur along lake shores and streams, especially where drainage is in the form of over-land flow. Water is not stagnant, but running and oozing especially in spring, thereby bringing nutrients to the plants. The wetlands are dominated by grasses like *Calamagrostis langsdorfii* (Figure 3-15, D) and grass-like plants like *Eriphorum scheuchzeri* (Figure 3-15, C) and *Carex spp* growing in a dense mat of mosses. Parts of the wetlands are hummocky, and thus partly providing dryer conditions with dwarf-shrubs growing on top of the hummocks.

Grasslands

Grasslands occur frequently around Two Boat Lake, mainly on lower ground where slopes are gentle and often concave in planar form. The topographic distribution indicates that grasslands are more common where soil conditions are more moist than average. Even within an individual area of grassland, local soil conditions govern the type of grasses that dominate. *Kobresia myosuroides*, meadow-grasses (*Poa alpina* and *Poa pratensis*) and *Deschampsia flexuosa* occur in varying frequencies throughout the grasslands.

/Thing 1984/ and /Fredskild and Holt 1993/ proposed dynamics of the grasslands around Kangerlussuaq to be highly dependent on caribou grazing. Thing studied the feeding ecology of caribou and found that although *Poa pratensis*-dominated grasslands only covered 1.6% of ground, they were used as feeding sites 25% of the time from May to early October, with a maximum of 78% in June-July. High browsing pressure and trampling on *Salix glauca* and *Betula nana* destroy the woody shrubs, and in combination with fertilization by caribou, high browsing/grazing pressure would facilitate the expansion of grasslands on the expense of heath vegetation.

3.2.2 Wetland biomass and NPP

Wetland biomass and net primary production (NPP) were investigated in 2008 at a site close to lake #9 (Figure 3-16, Figure 3-19 for location). The investigation included description of dominating species, estimation of above-ground biomass by cutting vegetation from five sample plots (0.25 m × 0.25 m) and separating sampled vegetation into different fractions of bryophytes, herbs and woody and green parts belonging to dwarf shrubs. Bryophytes dominated and dwarf shrubs contributed less than 5% of the total biomass. Below-ground biomass was estimated from above ground biomass using the mean shoot/root ratio of 0.24 from four tundra wetlands dominated by sedge-bryophyte vegetation /Wielgolaski et al. 1981/. NPP was estimated (Table 3-3) by assuming that all above-ground green tissue was produced during the growing season for herbs, grasses and dwarf shrubs. The bryophytes are perennial and the NPP was assumed to approximate the fraction of biomass increase per unit biomass of the green tissue /Wielgolaski et al. 1981/. Carbon content was assumed to be 50% of the dry weight.

Table 3-3. Estimated biomass and NPP in five plots of a wetland close to lake #9. AG refers to above ground, BG to below ground, and NPP refer to net primary production.

Plot	AG biomass (gC m^{-2})	BG biomass (gC m^{-2})	NPP (gC m^{-2} y^{-1})
1	451	588	234
2	338	389	167
3	435	581	220
4	397	500	207
5	505	460	197
Mean±SD	380±105	503±84	205±25

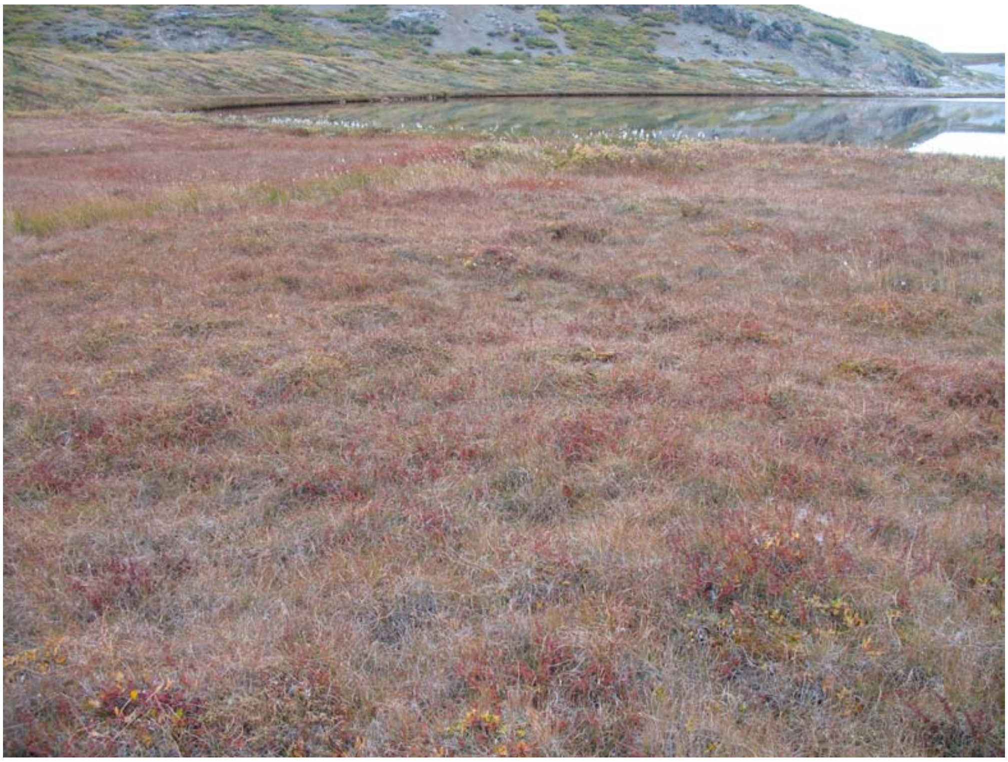

Figure 3-16. The wetland west of lake #9 that was investigated in regard to biomass, NPP and chemistry of regolith and different vegetation functional groups.

3.2.3 Fauna

Two Boat Lake and its surroundings accommodate a diversified fauna adapted to the arctic environment. The following sections are delimited to the two large herbivores caribou *(Rangifer tarandus)* and muskoxen *(Ovibos moschatus)*, because of their influence on vegetation and associated landscape development. In addition, caribou and muskoxen are the preferred game for hunting and do therefore represent potential paths for human exposure to contaminants such as radionuclides.

Caribou

The Kangerlussuaq-Sisimiut area houses Greenland's largest population of caribou (Figure 3-17), estimated at approximately 50,000 individuals in March 2000 /Cuyler et al. 2002/. The abundance is known to have been highly variable at least since the 1700s, including periods when caribou disappear almost entirely. Caribou of the Kangerlussuaq region are mainly found in small groups of one to five individuals in most seasons. There is however, an annual cycle in mean group size, with an increase from a mid winter minimum of 1.4 individuals per group towards a maximum when groups reach the size of 25 individuals in the summer post-calving season /Thing 1982/. One reason for the Kangerlussuaq caribou to gather in exceptionally small groups could be the absence of predators, which otherwise tend to make the caribou seek the protective strategy of gathering in large herds. The absence of predators might also be one of the reasons for cyclic caribou abundance known from historical records /Meldgaard 1986/. In the absence of predators, the caribou are likely to grow in numbers during several centuries followed by a sharp decline, which most likely is owing to a density-dependant forage limitation /Cuyler 2007/.

The Arctic is a highly seasonal environment, which is something all Arctic organisms have adapted to. The caribou maximize their utilisation of the seasonally available resources by migration. In West Greenland, the caribou have their winter ranges in the coastal regions and they migrate eastwards in spring to their calving and summer ranges in the vicinity of the ice sheet margin /Thing 1984/. This migration is timed to make calving coincide with the onset of the inland plant-growing season. Caribou move over large areas in search for plants of high nutritive value during summer, but they stay in the inland areas where grasslands are more widespread compared to the coastal ranges. The inland migration generally means that caribou follow the early phenologic stages of plants and

Figure 3-17. *A caribou calf at Two Boat Lake September 2010.*

utilize the variability of microclimate and local environmental conditions within the terrain /Post and Forchhammer 2008/. The hilly landscape of interior West Greenland makes the environment diversified in such a way that the onset of plant-growing starts earlier on sheltered positions on south-facing slopes. The onset of plant growth is delayed in less favourable positions like on north-facing slopes, which thereby prolongs the season for high nutritive forage for herbivores like the caribou. A more homogeneous landscape with less diversified ecosystems would be less suitable for caribou grazing.

There is a recent concern that both timing and duration of the plant-growing season are responding to climate change in a less favourable way for caribou. /Post and Forchhammer 2008/ studied caribou migration and seasonal vegetation development in the summer ranges of West Greenland caribou. Since migration of caribou to their summer ranges is cued by the change in day length, while onset of the plant growing-season on the same ranges is cued by local temperatures, there is a risk for a trophic mismatch if the two would not coincide. Spring temperatures have risen by approximately 4°C and the Kangerlussuaq population of caribou have not kept pace with the advancement of the plant-growing season in on their calving range. As a consequence, offspring mortality has risen and offspring productions has dropped fourfold /Post and Forchhammer 2008/. This mismatch could potentially be devastating for the West Greenland caribou, at least if they are unable to adapt to these new conditions.

Muskoxen

In 1962 and 1963 a total of 27 muskoxen were introduced to Angujaartorfiup Nunaa, the area just south of Kangerlussuaq in West Greenland. The group of muskoxen was translocated from Northeast Greenland in order to establish a new stable meat source for West Greenland Inuit hunters. A second objective was to secure the future for Greenland muskoxen by establishing another population separate from the Northeast and North Greenland populations. Muskoxen appeared highly adaptive to the West Greenland landscape and the herd expanded to a population of about 2,600 in 1990 /Olesen 1993/ and have since then stabilized on a constant level of about 3,000 individuals during the 1990s despite a yearly hunt of about 700 animals since 1988 /Pedersen and Aastrup 2000/. Density of muskoxen in Angujaartorfiup Nunaa has settled in a range of 0.2–0.5 individuals per km^2 /Pedersen and Aastrup 2000/, which is comparable to the range in Jameson Land in Northeast Greenland /Aastrup and Mosbech 1993/. The similarities of densities between the two areas indicate that there could be room for higher densities in Angujaartorfiup Nunaa because vegetation and growth conditions are there more favourable /Olesen et al. 1994/.

Muskoxen are primarily grazers adapted to a diet of sedges, grasses and forbs, but they also browse bushes like willow and dwarf birch. With a large body size and gut capacity, they are capable of processing large amounts of less nutritive forage. The generally thin snow cover in West Greenland makes the winters endurable for muskoxen. They stick to a diet dominated by sedges and willow throughout the year. The quality of the forage is obviously lower during winter, but the muskoxen do only to a limited degree compensate the poor nutrient content with higher amounts of forage. Instead the muskoxen conform to an energy-saving strategy during mid-winter of allocating a larger portion of the time resting /Forchhammer 1995/. Winter in West Greenland does not seem to trouble the muskoxen, which is illustrated by the negligible winter mortality among calves and yearlings. /Olesen 1993/ reports that calf or yearling carcasses have never been found in Angujaartorfiup Nunaa during winter despite extensive searching from snowmobiles in late winter seasons.

Data from systematic aerial surveys of caribou during the 1990s indicated that muskoxen had not expanded its range beyond Angujaartorfiup Nunaa /Pedersen and Aastrup 2000/. At least when considering northward migration into the area Isunngua where Two Boat Lake is located, any migration is hindered by the broad streams draining glacial meltwater in Ørkendalen and Sandflugtdalen. However, during field season 2010, the group from SKB observed numerous traces of muskox wool and droppings (Figure 3-9) as well as muskox individuals or small herds (Figure 3-18). Communication with local hunting guides revealed the footslopes around Two Boat Lake to be frequently used for grazing and as a migratory path to the extensive pastures northward.

Figure 3-18. A group of muskoxen resting in the sun in front of Russel's Glacier in September 2010.

Grazing competition

Compared to the muskox, the caribou has a more selective feeding strategy. Their smaller size and smaller gut capacity, combined with a higher metabolic rate than muskoxen require them to be both more selective and to utilize a more diverse range of forage /Klein 1990/. Lichens, which is the winter staple diet of North American mainland caribou and Scandinavian reindeer, has a low availability in the high Arctic, and is therefore less important forage for the West Greenland caribou. /Larter and Nagy 1995/ studied dietary overlap and potential for food competition between muskoxen and caribou on Banks Island, Canada, which is an area with similar environmental conditions as West Greenland. Banks Island has experienced a rapidly increasing muskox population. They found competition to be something that might occur, especially where density of muskoxen is high. The overlapping winter diets may adversely affect caribou numbers /Larter and Nagy 1995/.

3.3 Chemistry

3.3.1 Water chemistry of lakes and ponds

The field party of 2008 performed measurements of water temperature, pH, electric conductivity, dissolved O_2 and O_2-saturation in 15 lakes and small ponds. These lakes and small ponds were distributed from the coastal setting of Lake Helen just north of the Kangerlussuaq fiord, all the way to shallow proglacial lakes and thermokarst ponds in front of the ice margin (Figure 3-19, Table 3-4). Measurements were performed with a multiparameter sonde Quick sample YSI 600QS; results are shown in Table 3-5. Out of the 15 lakes and small ponds, seven were sampled for chemical analyses. These samples were filtered and acidified outdoors on the sampling occasion, and were later analysed by using Inductively Coupled Plasma/Mass Spectrometry (ICP/MS) to determine elemental composition. In addition, filter samples from three of the lakes were analysed for particulate nitrogen, phosphorous, carbon and for chlorophyll. All samples were filtered immediately after sampling into acid washed sampling bottles and frozen pending analyses.

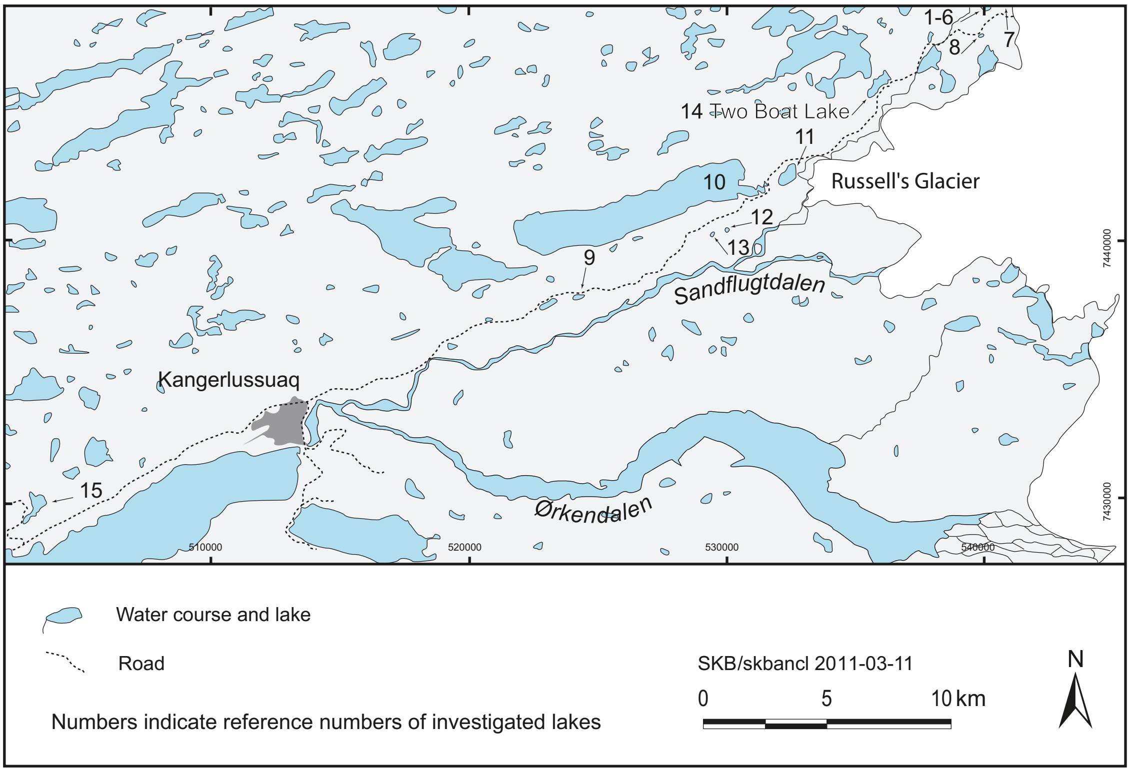

Figure 3-19. *Location of investigated lakes #1–15.*

Table 3-4. Summary of sampling at lakes sampled for chemistry analysis.

Lake identity	Comment	Sampling position
#7	Small, shallow lake. Brownish water.	central part of the lake
#8	Relatively small lake with clear water.	from the shore
#9	Small lake of about 4 m water depth. Samples for chlorophyll and total C, P and N were prepared in the field.	central part of the lake
#10 Aajuitsup Taisa	Large and deep lake (ca 40 m) with two basins.	central part of the lake
#11	Proglacial, small lake with suspended particles from inflow of glacial meltwater. Samples for chlorophyll and total C, P and N was prepared in the field.	central part of the lake
#14 Two Boat Lake	Deep and relatively large lake. Samples for chlorophyll and total C, P and N were prepared in the field.	central part of the lake
#15 Lake Helen	Relatively large lake.	from the shore

Table 3-5. Values of measured parameters in lakes. Individual lake locations are indicated in Figure 3-19 by lake reference numbers (#).

Lake #	pH	Temp (°C)	EC (uS/m)	O_2 sat (%)	Dissolved O_2
1	6.10	1.5	1	92.70	12.99
2	6.40	14.6	1	93.80	9.55
3	7.20	13.1	1	110.70	11.60
4	7.50	13.4	1	107.30	11.20
5	7.30	13.6	40	111.60	11.60
6	6.70	12.8	212	120.00	12.80
7	7.80	17.7	62	144.50	13.80
8	8.70	14.9	210	120.40	12.20
9	10.09	11.9	387	109.90	11.80
10	8.15	10.20	108	96.60	10.86
11	8.13	9.0	54	113.3	13.08
12	7.73	10.6	121	91.40	10.05
13	9.48	10.8	323	116.8	12.91
14 (TBL)	8.60	10.5	184	119.7	13.34
15	8.37	10.9	90	100.7	11.1

Analyses were done for major elements and trace elements using ICP-MS for the following lakes: 7, 8, 9, 10, 11, 14 and 15. Major anions were analysed using ion chromatography. Lakes in the vicinity of the ice margin #1–5, 7 and 11 are very diluted, with very low or no conductivity (Table 3-5). Oxygen saturation profiles were done for two of the lakes #10 and #14 (Figure 3-20).

Analyses of the major cations show that lake #9 has a different chemical profile compared to the other investigated lakes. Both Mg and Na are comparatively high and so are the pH values. Figure 3-21 reports concentrations of major cations in sampled lakes and two additional lakes analysed by GAP Project C. Measurements of the two lakes encircled by ovals have exceptionally high concentrations of all four cations. They also have higher concentrations of Cl and particulate C, N and P compared to the other lakes.

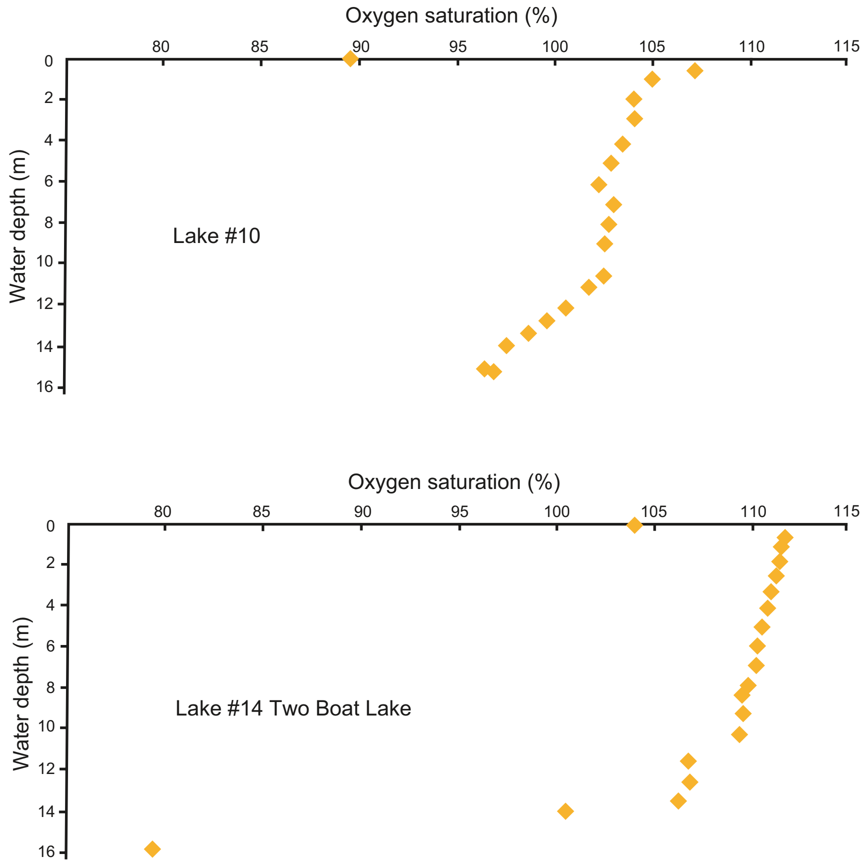

Figure 3-20. Oxygen saturation versus depth for Lake 10, which is the largest lake of the area and for Two Boat Lake (Lake #14).

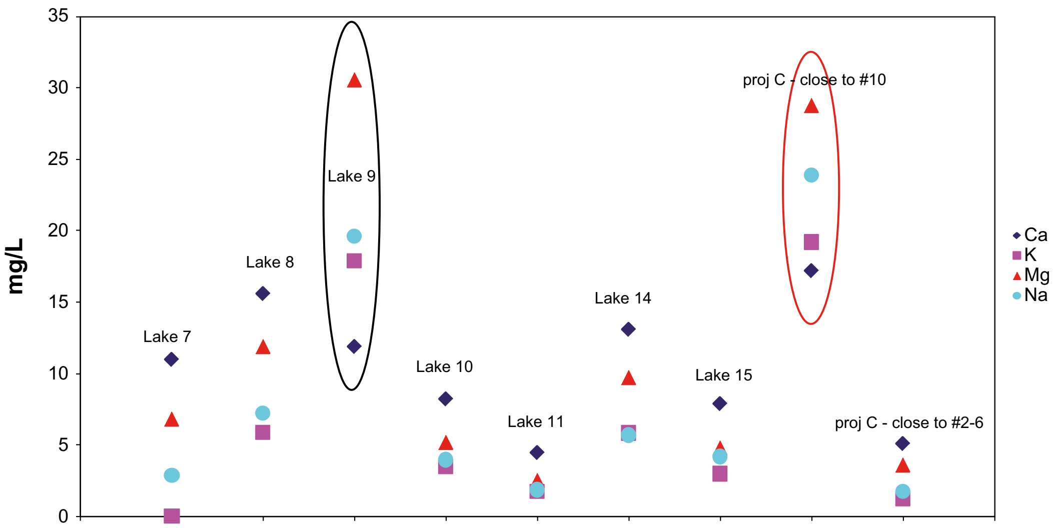

Figure 3-21. Major cations analysed in surface water samples, with the addition of two lakes sampled and analysed by GAP.

3.3.2 Chemistry of wetlands and terrestrial ecosystems

Elemental concentrations were analysed for both vegetation and regolith in a wetland adjacent to lake #9 and in a sheltered position of a north-facing slope just south of the lake. Analysed samples included herbs, bryophytes, lichens, leaves and woody parts of dwarf shrubs, and regolith. Additional samples of regolith were taken from a wetland adjacent to lake #11 and from a wetland adjacent to lake #14 (Two Boat Lake), see Table 3-6.

Table 3-6. Summary of sampling for wetlands chemistry. Identity numbers (#) refer to locations of Figure 3-19.

ID	Lake #11	Lake #14	Lake #9	Lake #9
Coordinates (X,Y)	0532586 7442739	0536128 7445717	0524014 7437723	0524373 7437487
Dominant regolith	Organic soil	Organic soil	Organic soil	?
Comment	Wetland, sedge-bryophyte	Wetland, sedge-bryophyte	Wetland, sedge-bryophyte	Depression, north facing herb rich slope
Thawed depth	0.85	> 0.55	0.54	0.30
Visible roots, depth	Difficult to assess	Difficult to assess	Difficult to assess	0.30
Visible inflow of water, depth (m)	~0.40	~0.40	~0.40–0.50	–
Chemistry, sample depth (m)	0.25–0.30	0.30–0.35	0–0.05 0.10–0.15 0.25–0.30 0.50–0.54	0–0.05 0.10–0.15 0.25–0.30
Vegetation sample (surface)	–	–	*Carex*/ *Toefeldia* and bryophyte	*Salix* leaf and wood, roots, bryophyte and lichen.

3.4 Geometries

3.4.1 Lake bathymetry

Survey of the Two Boat Lake bathymetry was conducted in September 2010. The equipment used consisted of the following items, a Zodiak rubber boat with a 4 hp outboard engine, a combined echo sounder and GPS (Garmin GPSMAP 400), a laptop (IBM Thinkpad x32) and GIS software (ESRI ArcPad 8).

The echo sounder was connected to a computer through the USB port using the NMEA 0183 data protocol. An aerial photo was used as the background layer in ArcPad and the datum was set to WGS_1984_UTM_Zone_22N. Using the track option in ArcPad the NMEA data was stored directly in a point layer in shape-format. The following NMEA sentences were stored:

1. Latitude in WGS84.
2. Longitude in WGS84.
3. Altitude in metres above sea level (m.a.s.l.).
4. Easting in WGS84 UTM Zone 22N.
5. Northing in WGS84 UTM Zone 22N.
6. UTCdate.
7. UTCtime.
8. Sog – speed over ground in knots.
9. Cog – course over ground.
10. Hdop – the horizontal dilution of precision.
11. Depth in meters.
12. Water temperature in °C.

The boat was driven at a mean speed of 6 knots and every 2 seconds a new measurement was stored in the ArcPad shape-file. The GIS point layer was continuously updated and thereby supporting navigation. Approximately 7,000 measurements were recorded in total. Using the Hdop value some low quality records (Hdop > 1.5) were deleted. After deletion 6,600 records remain (see Figure 3-22). The mean measured value is 13.1 m and the maximum depth is 29.9 m (large green dot in Figure 3-22). The echo sounder measurements were added with shoreline points by walking the shore and storing GPS coordinates (red points in Figure 3-22).

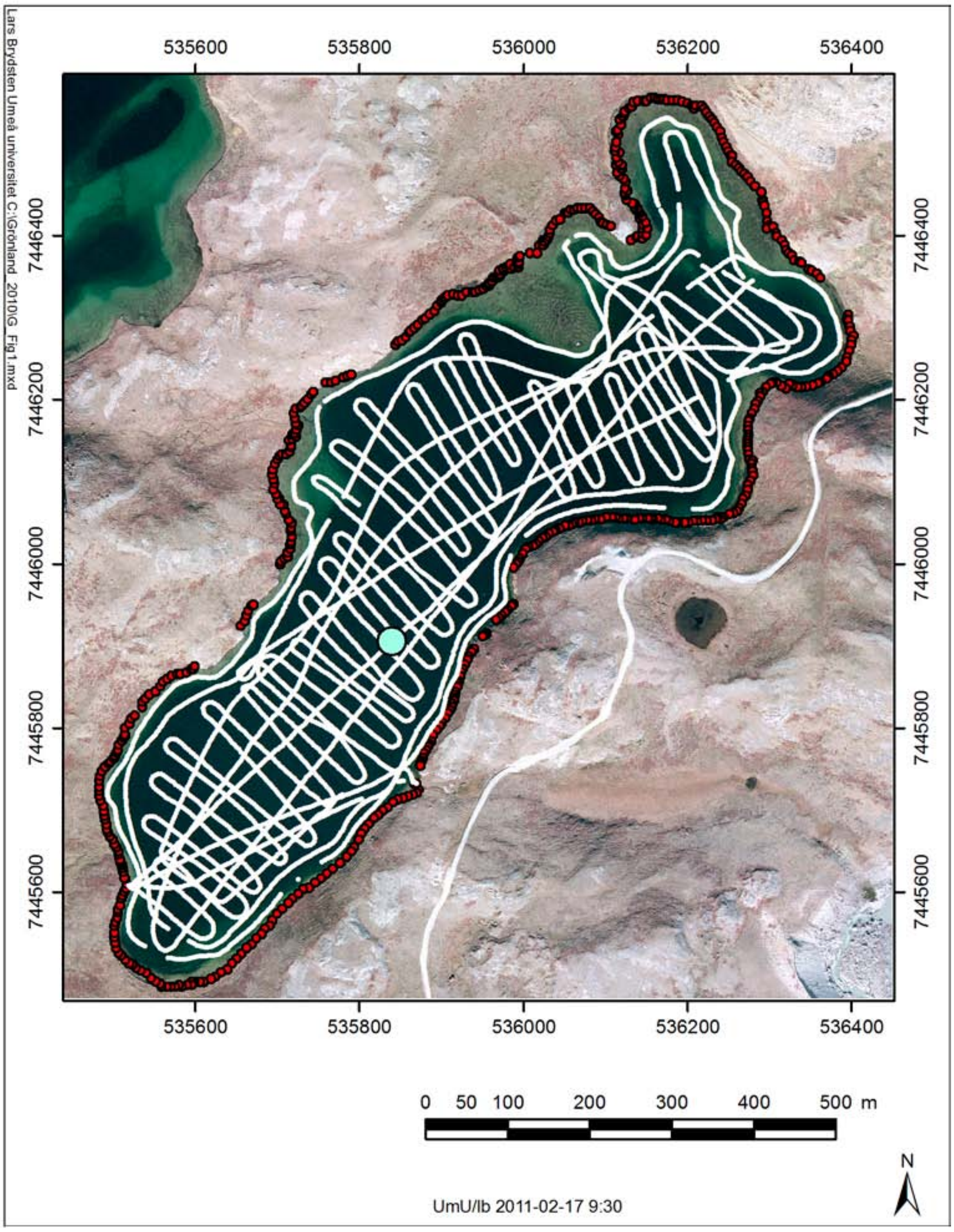

***Figure 3-22.** The echo sounder measurements (white dots) and shoreline mapping (red dots) in Two Boat Lake. The light blue dot marks the deepest measured point of the lake. The point also marks the position for conducted measurements of water chemistry depth profile.*

3.4.2 Digital elevation model (DEM)

Effort in the field was put on local updating and refining an existing digital elevation model (DEM) that includes the area from the ice sheet margin down to Kangerlussuaq air port. The pre-existing DEM is made by the air photo providing company Scancort, automatically generated by applying INPHO Match-T software version 4.0 on digital orthophotos. Height points are interpolated into a 5 meter grid.

Refinement of the Scankort DEM was conducted for the Two Boat Lake watershed only, using field data collected during September 2010, The Scankort DEM was used to model the watershed extension imported by applying ArcView software. The area illustrated in Figure 3-23 marks the area of the updated DEM.

The Scankort DEM was converted to points and points outside the square were deleted. In the original DEM, the lakes are represented by the lakes surface altitudes but the updated local DEM shows Two Boat Lake bottom altitudes. Note that all other lakes within the square will still be represented by the lake surfaces.

The points from the Scankort DEM that are situated within the Two Boat Lake polygon were deleted from the dataset. The mean value of these deleted points is 375.08 m above sea level and with lack of a levelled lake altitude this value has been used as the Two Boat Lake altitude. The shoreline points were set to 375 m.a.s.l. and the echo sounded points were adjusted so that zero water depth is 375 m.a.s.l. All three point data sets were merged into one and this data set is the input to the DEM interpolation.

The interpolation was performed in the Geostatistical function in ArcMap with the same resolution (5 meters) as the Scankort DEM. This implies that the Scankort DEM values outside Two Boat Lake will be preserved. The Two Boat Lake watershed DEM is shown in Figure 3-23. In addition to the watershed DEM with a sea level reference altitude, a smaller DEM over Two Boat Lake was constructed (Figure 3-24). Here the reference altitude is the lake surface altitude (375 m) and all values outside the lake are set to “No data”. The hypsographic curve and the morphometric parameters for Two Boat Lake are shown in Figure 3-25 and Table 3-7, respectively.

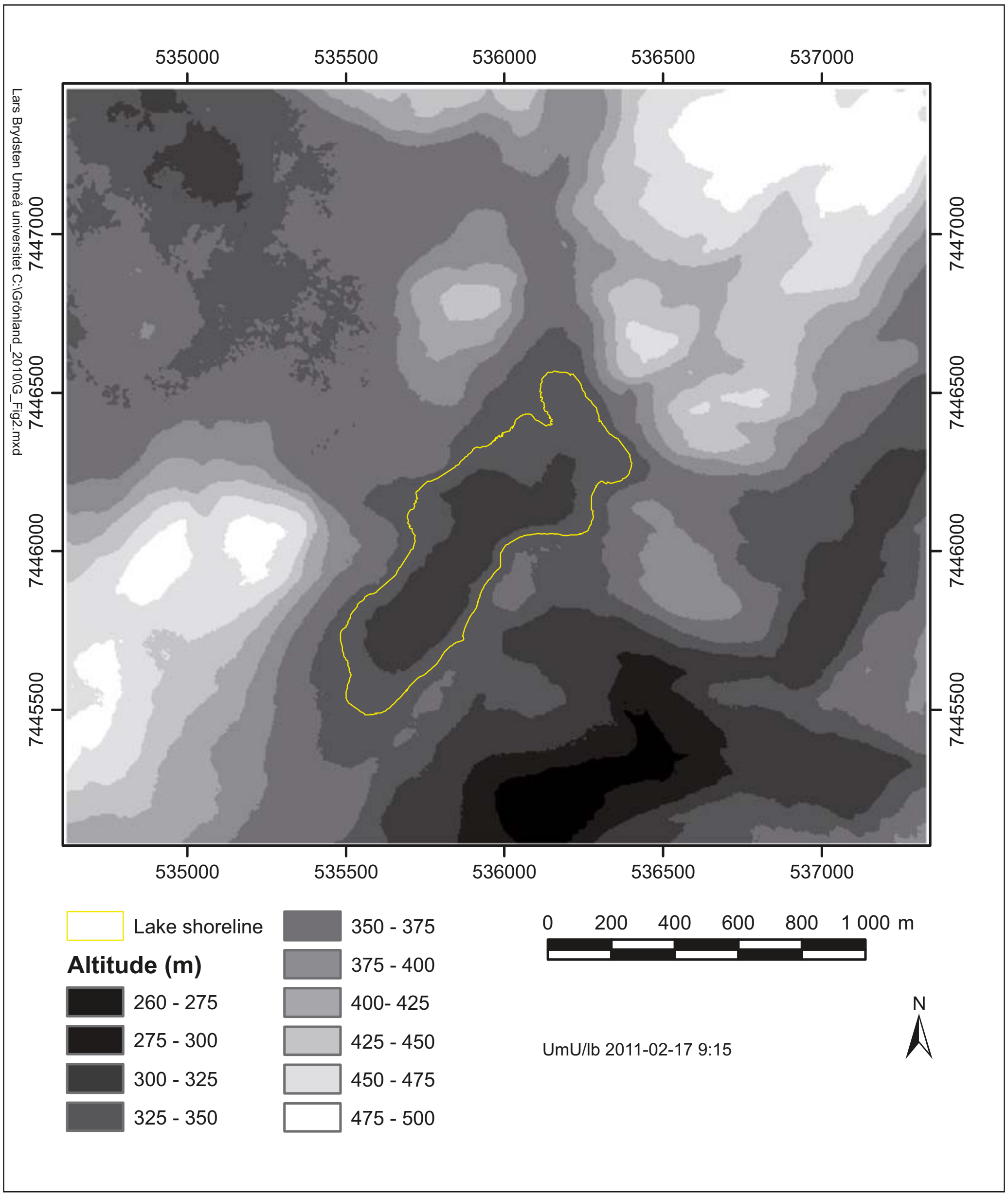

Figure 3-23. The DEM for the Two Boat Lake catchment.

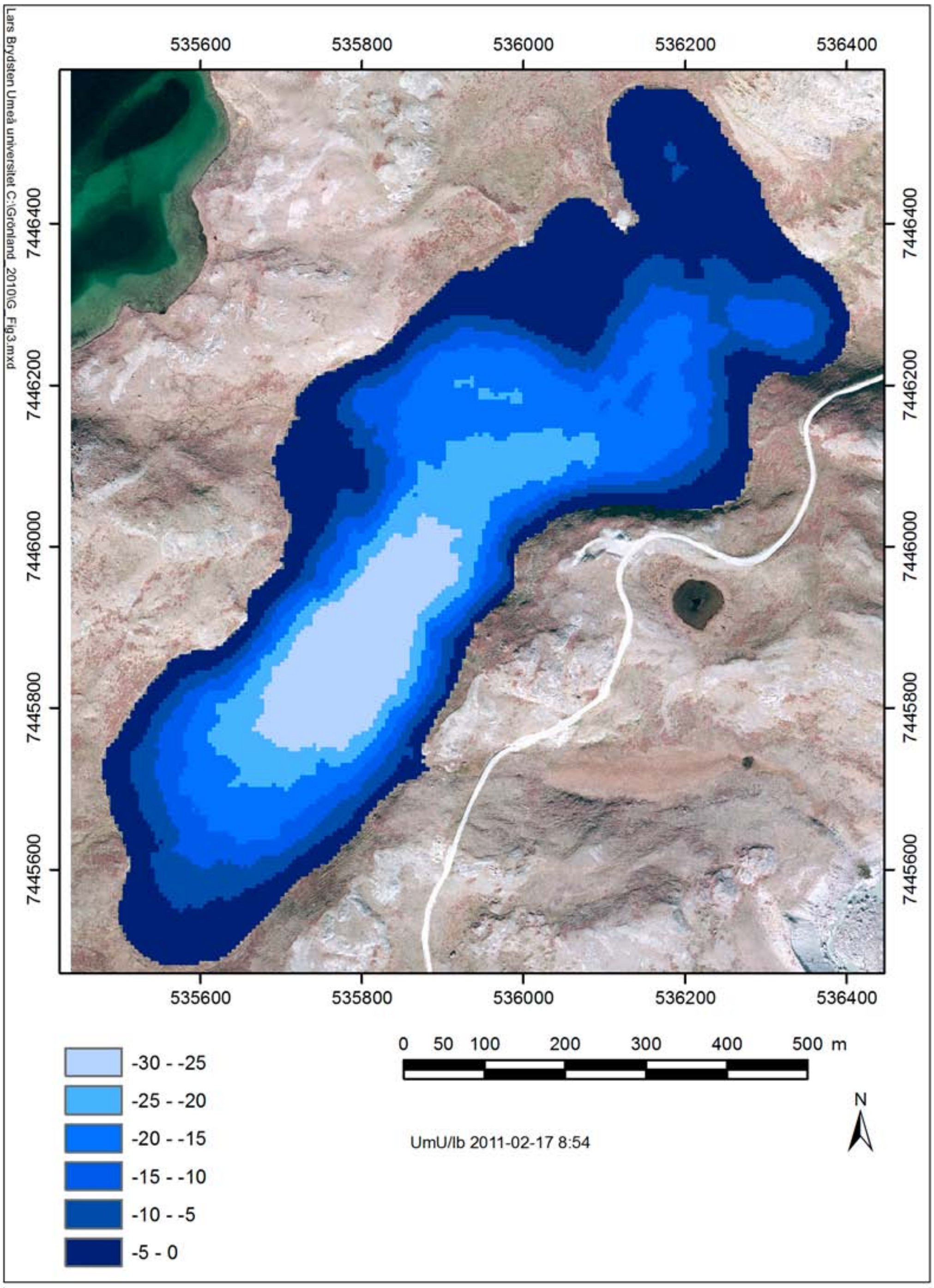

Figure 3-24. *The DEM (relative to the lake surface) for Two Boat Lake.*

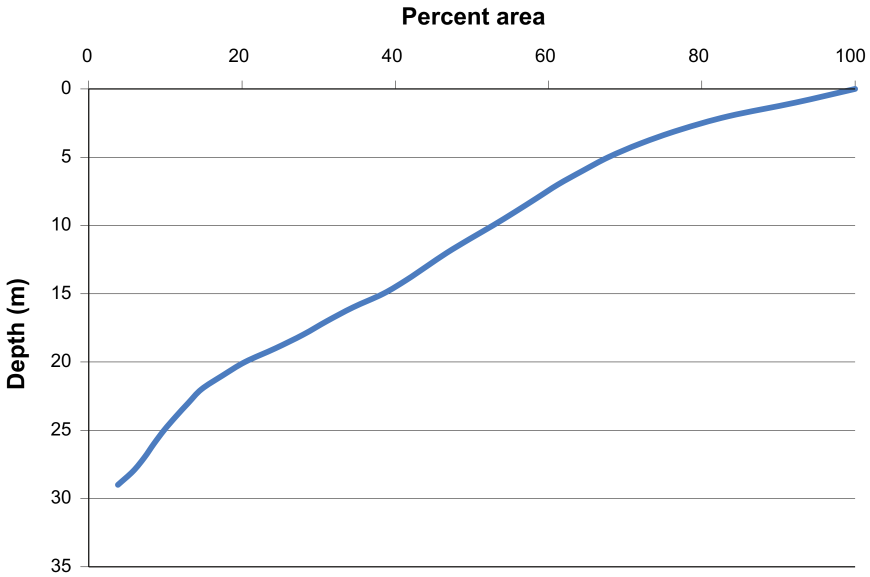

Figure 3-25. Hypsographic curve for Two Boat Lake.

Table 3-7. Morphometric parameters for the Two Boat Lake (see /Wetzel 1983/ for definitions).

Area	377,900	m^2
Maximum depth	29.88	m
Mean depth	11.84	m
Relative depth	4.3	%
Volume	4,474,300	m^3
Maximum length	1,250	m
Maximum width	410	m
Mean width	300	m
Shore line length	3,487	m

3.4.3 Catchment area extension

The GIS-modelled catchment area of Two Boat Lake according to the DEM is shown in Figure 3-26. However, the accuracy of the Scankort DEM is not good enough to produce a reliable delineation of the catchment area. A field check of the water divides was made to achieve a more reliable extension, but some uncertainty still remains. The largest uncertainties are found in the northeastern part of the catchment area. The topographical differences are very small in this part of the catchment and very small height differences have large impact on the extent of the catchment area. A walk in the northeastern part of the catchment area was made and photos and observations as slope, local heights and wetness of the ground surface were noticed. The walking route is shown as red dots in Figure 3-26.

The green dots in Figure 3-26 indicate the field controlled water divide. Using these points as input, a refined catchment area was modelled in ArcGIS. The updated catchment area of the lake is also shown in Figure 3-26. After the field check, it was concluded that the water in a relatively large part of the original catchment area in northeast flows towards the big lake in the northwestern part of the map shown in Figure 3-26. However, the topographical differences are very small and complementary measurements of the heights in the area are needed. The updated catchment area is only a result of estimates made by observations in field. The catchment area will be updated after complementary measurements have been carried out during coming field seasons. All observation points and a description of each point as well as linked photos are stored in the GRASP GIS-database.

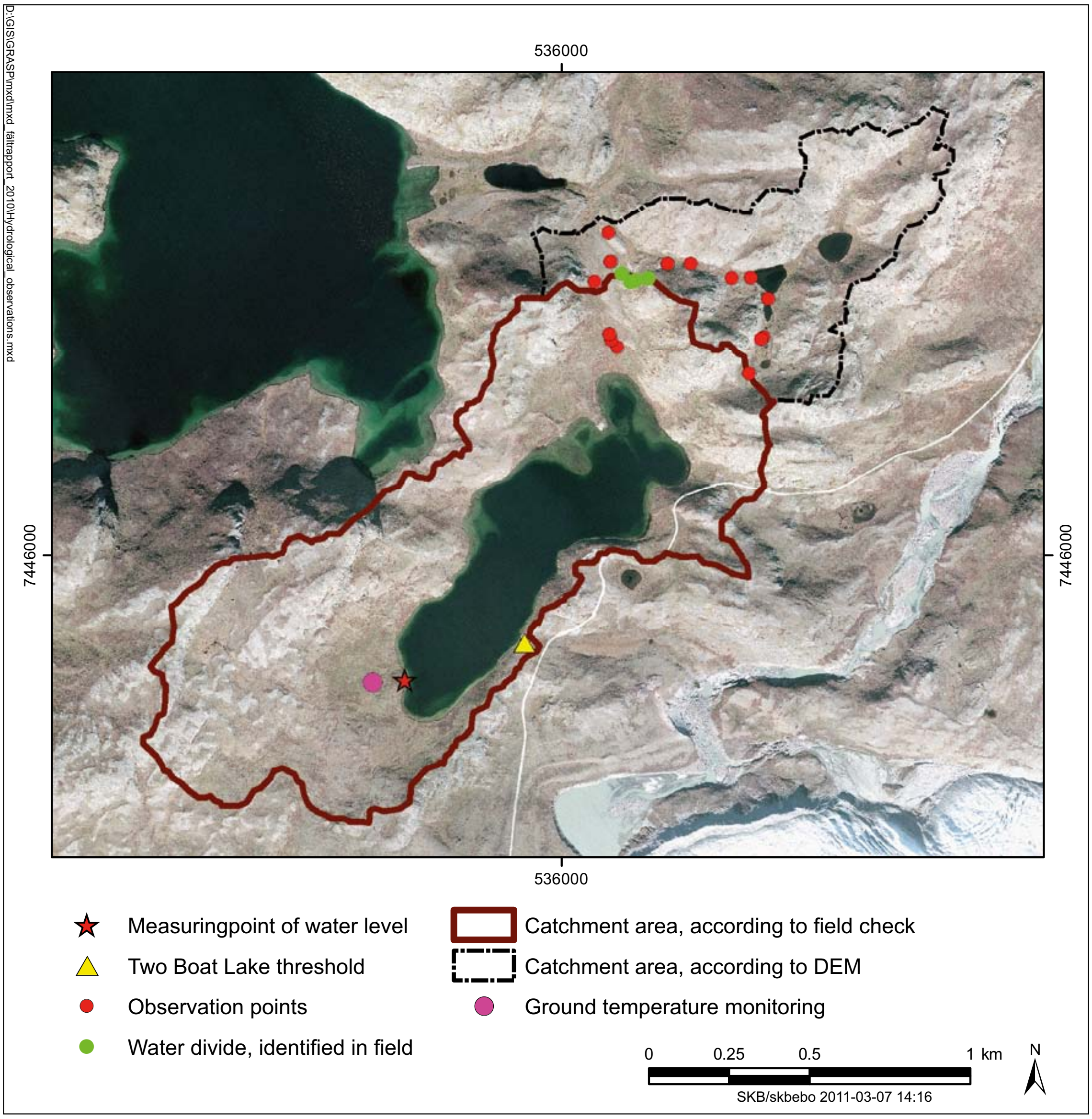

Figure 3-26. *Map showing water divide according to the Scankort DEM, the updated catchment area after field check and the location for monitoring the lake level.*

3.4.4 Establishment of lake threshold

The lake threshold and mean lake level were measured with a levelling instrument. The absolute height above sea level is not known for the catchment area. Therefore, the mean lake water level was measured relative a core drilled bore hole. The top of casing, TOC, of the bore hole is regarded as stable and the height above sea level of TOC of the bore hole will be measured in coming field seasons. The height difference between TOC and the mean lake surface September 2nd 2010 was 5.39 m. The level of the mean lake water surface was marked in the bedrock and is shown in Figure 3-33 A. The lake threshold was measured to 18.3 cm above the mean lake level, measured at the location of the threshold as marked by a yellow triangle in Figure 3-26.

3.4.5 Water chemistry depth profile

A water chemistry depth profiling was performed in the deepest part of the lake (close to the large green dot in Figure 3-22). A marked thermocline was present at approximately 16 meters depth (see Figure 3-27). Higher specific conductivity (Figure 3-28), lower dissolved oxygen (Figure 3-29) and pH (Figure 3-30) can be observed beneath the thermocline.

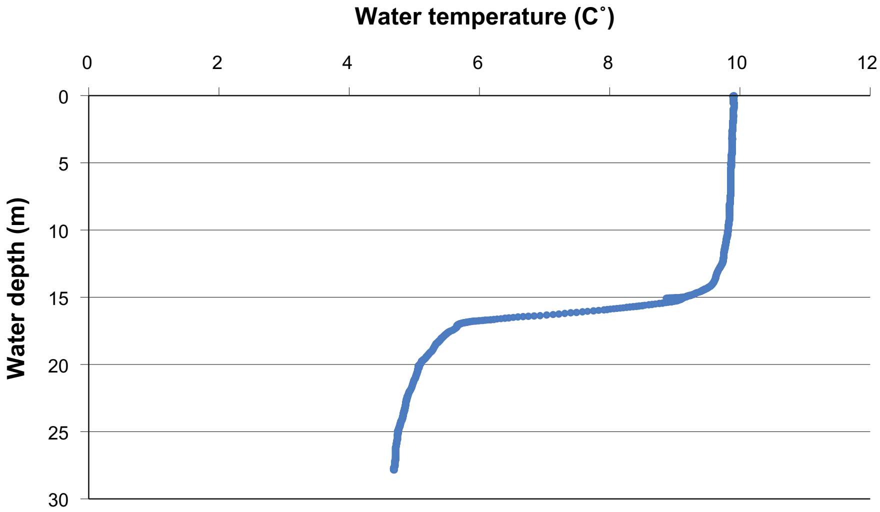

Figure 3-27. *Depth profile of temperature (C˚) in Two Boat Lake.*

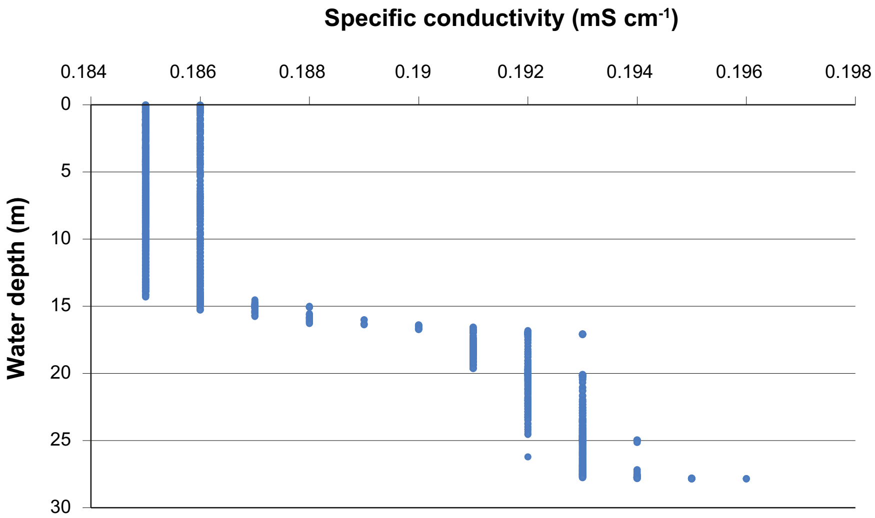

Figure 3-28. *Depth profile of specific conductivity (mS cm^{-1}) in Two Boat Lake.*

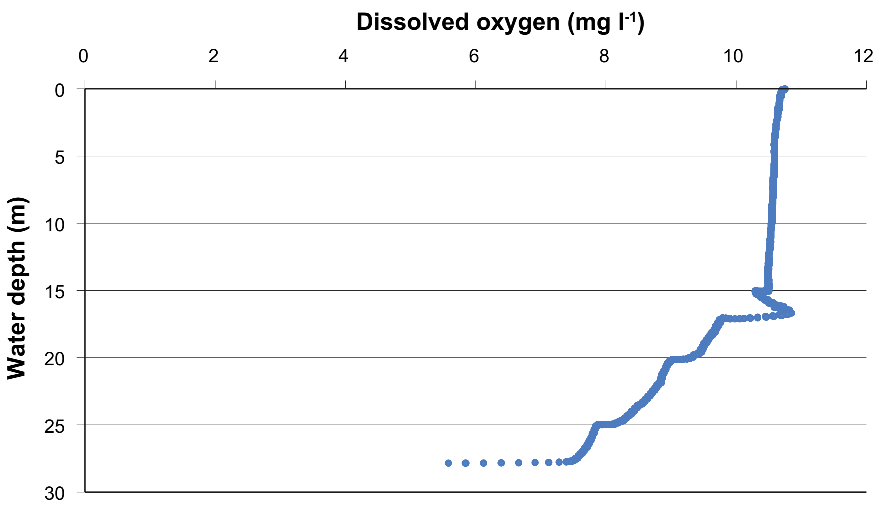

Figure 3-29. *Depth profile of dissolved oxygen (mg l^{-1}) in Two Boat Lake.*

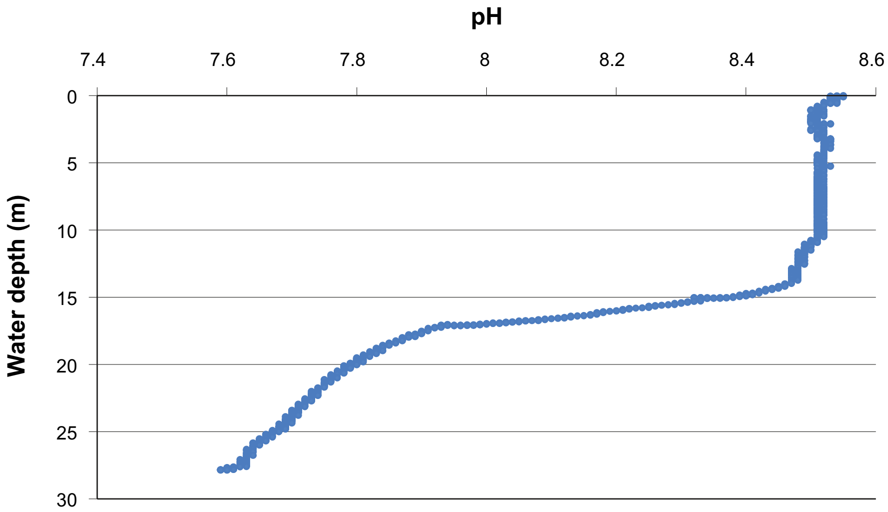

Figure 3-30. *Depth profile of pH in Two Boat Lake.*

3.5 Monitoring

3.5.1 Monitoring of ground temperature

Two ground temperature monitoring stations were installed in September 2010. One of the stations is located close to the lake shore within the catchment area of Two Boat Lake, and one is situated close to the ice margin at the site where GAP will perform deep drilling during the summer of 2011 (marked by symbols A and B in Figure 3-10). Both monitoring station consists of eight temperature sensors, of which seven sensors are placed along a vertical profile in the ground and one performs measurement of air temperature. The air temperature sensor is placed at c. 1.6 m height above ground. Depth distribution of the sensors in the ground near Two Boat Lake is shown in Figure 3-31. The deepest sensor is placed at 2 m depth. Drilling for the monitoring station close to the ice margin did not penetrate as far as two meters, but has its deepest sensor at 1.2 m depth due to technical problems during installation.

Before installation, all sensors were calibrated in an ice-water mix. The temperature of the ice-water mix was measured to –0.1˚C. The temperature of each sensor during calibration is listed in Table 3-8. Each box consists of four sensors and two boxes are placed at each soil temperature monitoring station. A photo of the temperature station close to the Two Boat Lake is shown in Figure 3-32.

Table 3-8. Temperature for each sensor during calibration.

Box 1	Temp ˚C	Box 2	Temp ˚C	Box 3	Temp ˚C	Box 4	Temp ˚C
Sensor 1	0.107	Sensor 1	–0.004	Sensor 1	0.051	Sensor 1	0.107
Sensor 2	0.107	Sensor 2	0.024	Sensor 2	0.051	Sensor 2	0.024
Sensor 3	0.079	Sensor 3	0.051	Sensor 3	0.024	Sensor 3	0.135
Sensor 4	0.107	Sensor 4	0.135	Sensor 4	0.107	Sensor 4	0.024

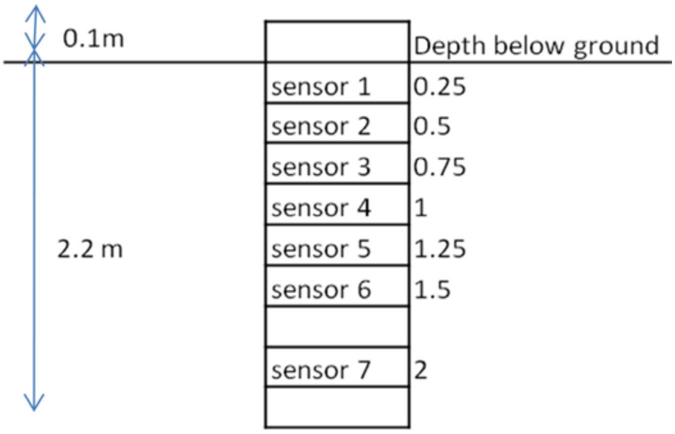

Figure 3-31. *Depth distribution of temperature sensors at the Two Boat Lake ground temperature monitoring station.*

A B

Figure 3-32. *A) Drilling a 2 m deep hole for ground temperature sensors at Two Boat Lake. B) Installed air temperature monitoring station on top of the borehole.*

3.5.2 Monitoring of lake water levels

Two Aqua Troll instruments were installed at the lake bottom to measure the variation of the lake surface water levels (Figure 3-33 A). The two gauges were installed at approximately 20 m distance from each other at 10 m water depth. A metallic wire was attached to each gauge and the wires were fastened around boulders in vicinity of the lake shore. The depths above the gauges are logged every third hour. The exact position of the monitoring stations is stored in the GRASP GIS-database.

A B

Figure 3-33. *A) Location of the reference point for the water level at Two Boat Lake as measured on 2 September 2010. The reference water level in the lake was marked in the bedrock so the exact height above sea level can be measured during coming field seasons. B) Installation of Aqua Troll measuring devices for monitoring of water level fluctuations.*

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