Cover Page

SEVENTH FRAMEWORK PROGRAMME

"Ideas" Specific programme

European Research Council

Grant agreement for: Advanced Grant

<u>Annex I – "Description of Work"</u>

Project acronym: **WATERundertheICE**

Project full title: **"Where is the water under the Greenland ice sheet?"**

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Host Institution: **University of Copenhagen**

Other beneficiaries: **none**

Table of Content

Part A

A1 Proposal summary

Proposal summary

Recent analysis of radar-depth sounder data has shown that many areas of the Greenland ice sheet have melt water under the base. The extent of the wet base and distribution of melt water are poorly known. Also lakes under the ice have not been discovered in contrast with those in Antarctica. The effect of the water beneath the ice, however, is well documented: it lubricates the bed and removes the friction between the basal ice and underlying bedrock. The ice with a wet bed flows faster, reacts rapidly to changes in climate and the basal-melt water contributes to the fresh-water supply to the ocean from the Greenland ice sheet.

The primary objectives of the project are to map melt water extent of the Greenland ice sheet and its impact by tracing internal layers and analyzing bedrock returns from airborne radio-echo sounding data, and use mapping results in conjunction with ice-sheet and hydrostatic models for the movement of the basal water to predict the ice-sheet's response to climate change. The information derived from deep ice-cores that reach the bed will be used to constrain models. We will also study the basal material (dust, DNA and microbiological material) and bedrock properties from the deep-ice core sites. This will add a further dimension to the study and provide opportunities to look for life under the ice and constrain the age of the Greenland ice sheet. The proposed research is a high risk project because of the difficulty in accessing basal conditions under 3-km of ice with a potential for high payoff science. The team will consist of scientists and engineers with expertise in the palaeoclimate, radar sounding and signal processing, and ice-sheet models.

Part B

B1 WATERundertheICE

The magnitude of the mass loss from the Greenland ice sheet is an extremely important issue in the ongoing climate debate. The Intergovernmental Panel on Climate Change reported that the predicted upper level sea level rise during the next century is badly constrained because of the unknown processes related to ice sheet dynamics[9]. This is partly related to insufficient knowledge of basal conditions at the ice-bed interface. Melt water at the interface lubricates the ice bed and cause basal ice to slide over its bed. This in turn can result in substantially increase in the ice velocities over the area in which basal melt occurs. The amount of water to be found under the ice and the basal melt rates has not been systematically determined for the Greenland ice sheet. Also it is a mystery why no subglacial lakes have been found under the Greenland ice as many have been found under the Antarctic ice sheet. The expertise available through my research on ice cores, ice sheet modelling and radio echo sounding of ice provides a strong platform for doing investigations of the melt extent and water distribution under the ice in Greenland to be complemented with interdisciplinary research and collaboration with national and international partners.

Key objectives

Understanding the role of water under the Greenland ice sheet implies answering key questions from the list below:

Where is water found under the ice?

Basal Ice melts when the temperature at the base reaches the melting point with sufficient energy to melt ice[1-3]. Regions under the ice with high values of the geothermal heat flux are likely melt zones, as are areas with high ice cap thickness and low accumulation rate. Regions with basal melt can be mapped from measured ice thicknesses, accumulation rates, internal radio echo layers, and properties of the bedrock radio echo sounding reflectors[2,4,5]. Near the margin of the ice sheet deformation-induced heat, surface melt water draining to the bed in the summer months, and ocean water under the floating ice streams add to the water production[6-8].

How does water influence the flow of the ice?

A film of melt water as thin as 0.5 mm can cause deformation-type to streaming-type flow of ice[8,11]. Ice sheet and ice stream flow models, combined with observations of the internal radio echo layers and knowledge from borehole sites, where it is possible to peep under the ice, will be used to constrain the flow and sliding at the base.

Why are there no lakes under the ice?

At present no lakes have been found under the Greenland ice sheet while more than 150 lakes[10] have been detected under the ice in Antarctica. Models for water flow based on basal pressures and channel theories, combined with possible sedimentary basins at the base will be developed to model the water movement. In addition we will look meticulously for small basal lakes and rivers in the radio echo sounding profiles and Synthetic Aperture Radar Images (SAR) of ice-bed interface.

What can the base tell about the age??

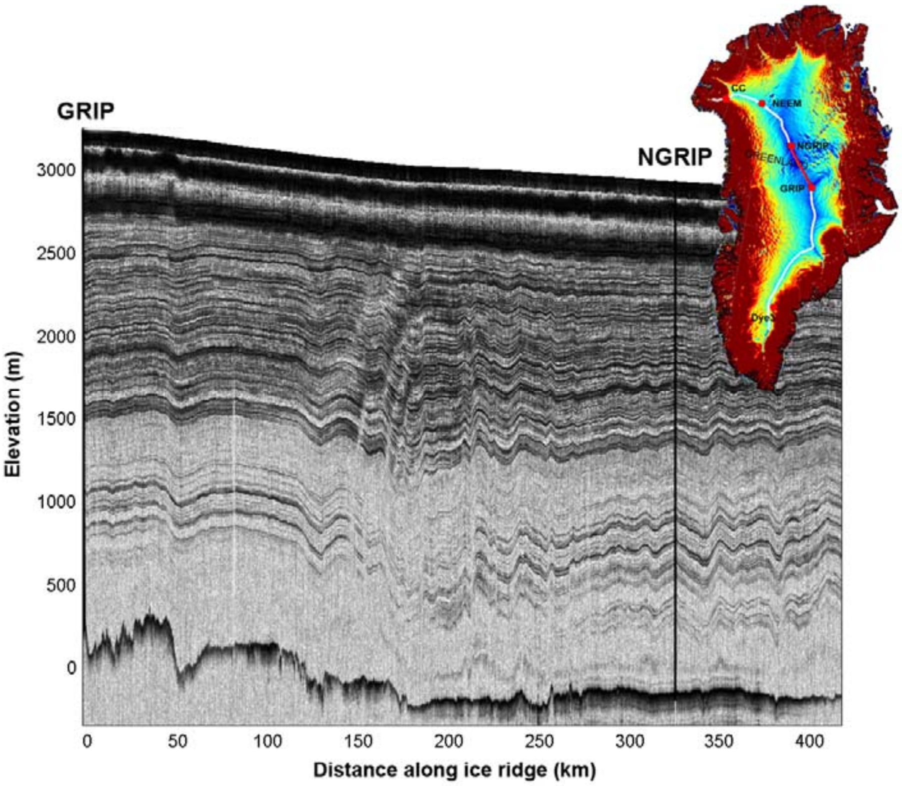
Basal material, organic and non-organic, is recovered at the base when deep ice cores are drilled[8,12-14]. The first pioneering attempts to look at the basal DNA to determine the composition and age of the vegetation have been very promising[15,16]. New dating methods have been suggested[15]. In addition to refining these methods I propose to recover material from the ongoing deep drilling project, NEEM, in north Greenland, where our ice flow models predict basal melt.

The primary objectives of the project are thus to study the role of water under the Greenland Ice Sheet and develop ice sheet and hydrological models to study the ice sheet stability in a warming climate.

B2 State-of-the-art

B2.1 Radio Echo Sounding profiles inform on basal melt

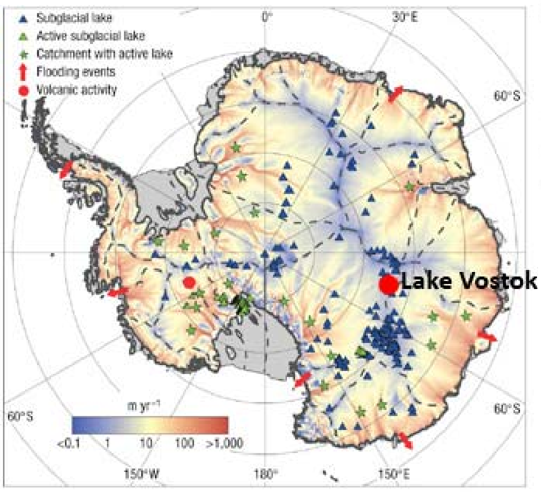
I have a very fruitful collaboration with the US NSF Centre for Remote Sensing of Ice Sheet (CReSIS; https://www.cresis.ku.edu/) at the University of Kansas and the WATERundertheICE project will strengthen this collaboration.

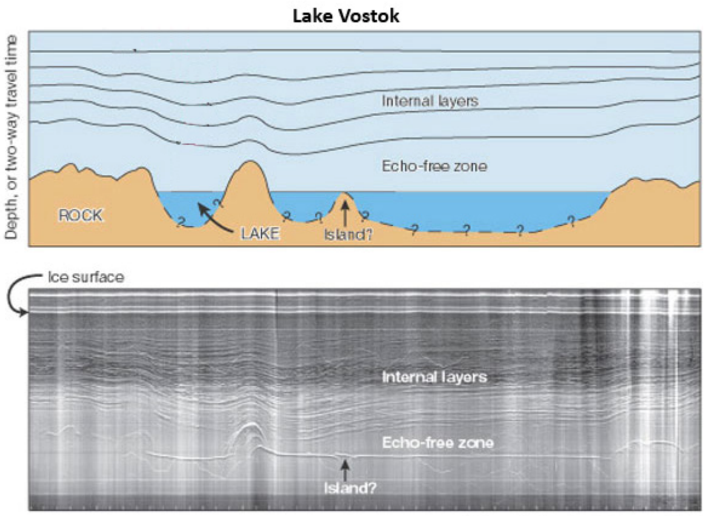


The left figure above shows a CReSIS airborne radio echo sounding image between the GRIP and the NGRIP drill sites (red line on Greenland map), comprising part of the central ice ridge (white line)[4,18]. The bedrock reflector and internal layers are mapped along the line. The GRIP drill site is on the summit of the Greenland Ice Sheet and the bedrock temperature has been measured in the borehole to be -8°C[1]. The undulations of the internal layers are seen to increase gradually with depth reflecting the shape of the bedrock as expected for ice frozen to the bed. At the NGRIP drill site the basal temperature is at the pressure melting point and the internal layers are observed to undulate even with a very flat bed. The undulations are caused by varying extent of basal melt causing the layers to move downwards. Between 170 and 220 km along the ice ridge line, the layers are seen to be significantly lowered and model reconstructions show basal melt rates of 6-10 cm pr year. An ice stream with fast flowing ice reaching from the centre of the ice sheet to the NE margin originates at this extreme melt region[3].

The map on the right above shows the CReSIS radio echo sounding data coverage during the years 1993-2003. Additional records have been obtained since 2003, especially focused on high-detail records around drill sites and the ice streams (personal communication; Gogineni; CReSIS).

The CReSIS radio echo sounding profiles contain unique information on the bedrock, basal melt and ice deformation that has been only very sparsely explored. One of the goals of my program is to integrate the radio echo sounding information with ice core data and ice sheet models to map the basal melt rates.





Siegert et al., Nature, 2001

B2.2 Lakes under the ice?

In Antarctica many lakes have been found under the ice especially in the regions close to the ice divides of the ice sheet (left figure above maps the known lakes). It is known that there are several factors that define the regions where melt and lakes are found.

- If the geothermal heat flow from the interior of the Earth and from radioactive decay within the rocks in the crust is high, melt will occur.
- Surface accumulation and the resulting downward advection by flow of the cold surface snow counterbalances the heat flow from the bedrock. Low accumulation rates and thick ice will increase the likelihood of basal melting. In general these conditions are present close to the ice divides of the ice sheets.
- A rock 'basin' must be present for a lake to form. Water is believed to flow along the base either in channels along the bed or in the near basal ice. The water moves and melts according to the pressure of the water and the ice.

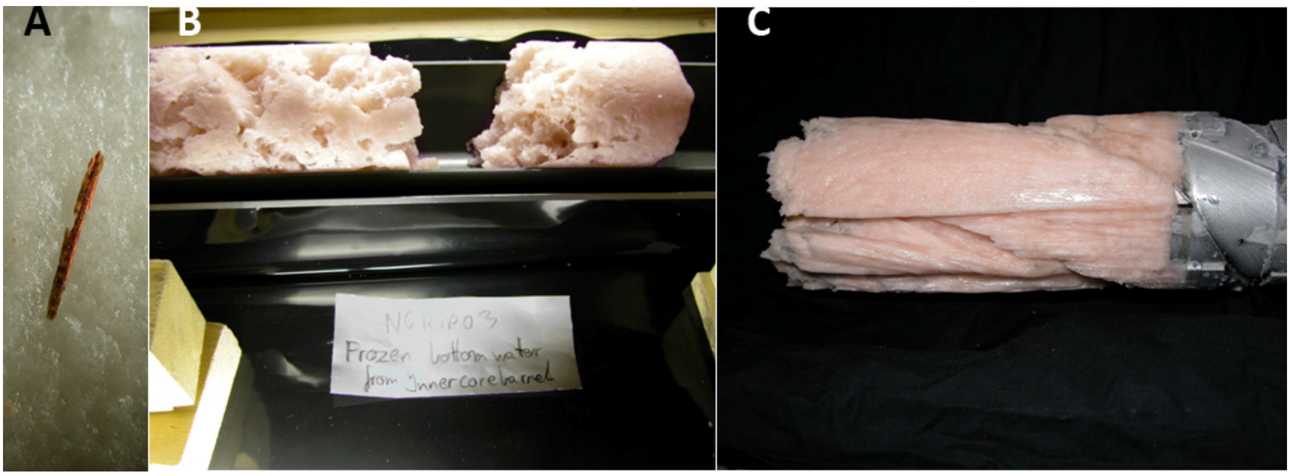
Studies of the subglacial lakes in Antarctica have been ongoing for many years and especially the Lake Vostok where Russian glaciologists are drilling an ice core[19-21]. This has initiated intense research on the subglacial lakes. The Lake Vostok (right figure above) is believed to be the largest lake under the ice in Antarctica covering an area of 240km x 50km[21]. The lake is up to 800m deep[19] and is covered by a

3700-4300m thick ice sheet[19] and due to the water pressure system and the circulation in the lake ice, accretes under the ice at the drill site[20]. At present the deep drilling has reached the depth 3623m, 120m above the lake water and the basal 60 m of the drilled ice is accreted lake ice[21]. The lake has been isolated from the atmosphere for several million years but there has been a transport of impurities deposited on the surface and slowly transported to the lake by the downward flow of the glacial ice. It is speculated if there are life forms in the lake, but the studies of the enclosures in the accreted ice have not been conclusive[13,14]. There is a strong debate on the risk of polluting the lake by penetrating the ice at the Vostok site. At the EPICA DML drill site in Antarctica and at the NGRIP drill site on the Greenland ice sheet the ice core drilling projects have penetrated the ice to the base where basal melt is occurring but no lakes are present[12]. In both cases basal material has been recovered but studies have not been completed.

It is a mystery why no lakes have been found under the Greenland ice sheet. One of the objectives of my program will be to look more carefully even for small lakes under the Greenland ice sheet based on surface topography, basal topography and the internal radio echo sounding profiles.

B2.3 Life under the ice

During the last years, biological studies of material in ice and in subglacial material has had several break throughs showing that ancient DNA can be preserved in the basal silty ice, thereby making it possible to reconstruct the fauna that covered Greenland before the present ice sheet covered the region[15,16]. Methods are also being developed to use florescence methods to detect regions in the ice containing biological material[22] and pollen especially from the smaller ice caps[23,24], located closer to pollen. Besides from recovering old material reflecting palaeoclimatic conditions, there is speculation on the possibility of bacterial life in the water system under the ice. The samples of refrozen basal water that have been recovered by the deep drills at EPICA DML and NGRIP have revealed a very high content of gas, very likely to be methane, under high pressure in the basal water system, and the downward flow of ice transports surface impurities and gases to the bed that can be used to support a basal bacterial culture.

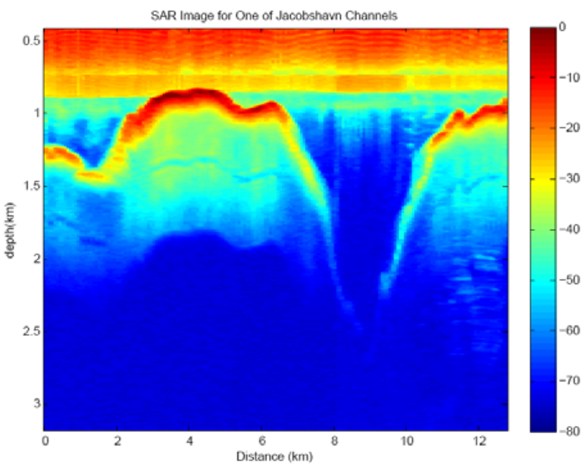


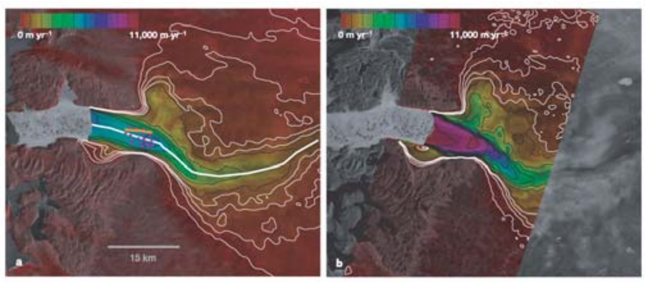
The pictures above are from the NGRIP deep drilling project. From the left (A) shows a 2 cm long piece of old willow bark recovered from the bedrock that must be a remnant from the vegetation before ice covered the site. (B) shows the refrozen basal water from inside the deep drill. The density is only 30% of the normal density of ice because the gas has escaped as the pressure was released while the drill was pulled to the surface. (C) shows the reddish refrozen basal water hanging under the ice drill. First investigations of the material show that the majority of the material has the same composition and size distribution as the surface wind blown insoluble dust deposited on the surface of the ice. It is not understood why material melted directly from ice cores is less red than that found in the basal deposits. At the Dye3 drill site in south Greenland the basal ice has been investigated for DNA[15]. Due to low basal temperatures here (-13 °C) the DNA was well preserved and it was possible to reconstruct diverse boreal forest fauna older than 450,000 years[15].

The material from NGRIP needs further investigations that will be included in my program. A vision is to expand the NEEM ice core being drilling in the years 2008-2011 with a basal program where we develop a drill that reach into the bedrock and sample water and basal material for biological investigations.

B2.4 Ice streams and ice sheet modelling

The increased loss of mass from the Greenland ice sheet observed since year 2000 is mainly due to the acceleration of the flow of the ice streams[7,25]. The ice streams have been estimated to have doubled the discharge of ice to fjords and the ocean. While it is known that the movement of ice mainly is block sliding, little is known about the amount of melt at the base of the fast moving ice either under the ice or under the floating glacier front. Where estimates have been made, they are in the order of several meters per year. The melt is believed to be caused by a combination of the internal deformation heat of the fast flowing ice (dissipation heat) and warm ocean water at the ice-bedrock interface. It is quite clear that our ability to predict the future behaviour of the Greenland ice sheet in a warming world is very dependent on improving our understanding of the flow and deformation of the ice streams[9].



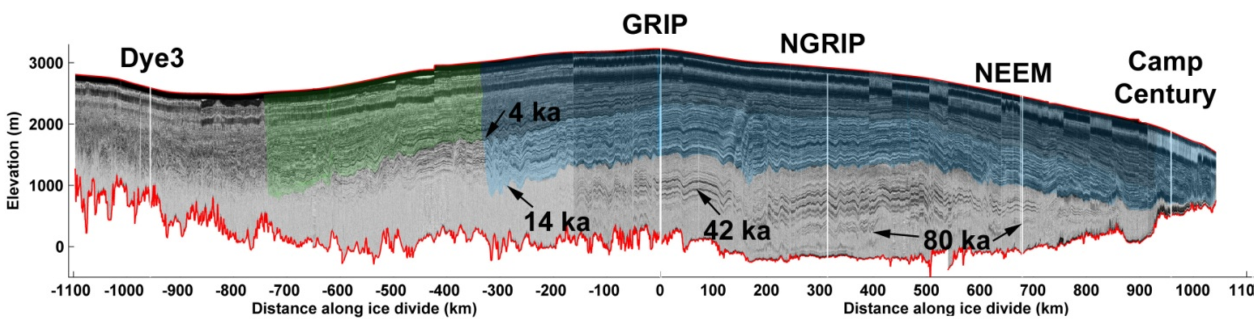


Joughin et al., Nature, 2004

The left figure is a very recent image from the CReSIS research centre (Gogineni, unpublished) showing a radio echo sounding image across the Jakobshavn Isbræ channel. It is the first time the bed has been mapped with a radar under the channel because the very wet basal ice reduces the radio echo sounding signal significantly. It can be seen that the channel is a few km wide but has a depth of 2.5km. The ice stream has increased its velocity from 5.7km/yr in 1992[26] (left panel of Joughin, 2004, figure 1) to 9.4km/yr in 2000 (right panel of Joughin, 2004). In 2002 the ice stream further increased its velocity to 12.6km/yr and this velocity has been maintained ever since. In addition to the increased velocity, the floating ice front has retreated 15 km further from the position shown on the InSAR images on the right figure[7]. Careful investigations of the radio echo sounding profiles reveal several hundred meters of ice at its melting point near the base in the Jakobshavn Isbræ channel. New results point to the impact of the ocean warming as the process increasing the ice discharge from the ice streams[27] as well as the role of the break off mechanism of ice bergs at the front of the ice stream[28]. The mapping of the channel bed reveals that beyond the present grounding line of the ice stream the surface drops to more than 1 km below sea level. Would a further retreat of the ice stream result in penetration of water under the ice here?

Ice flow models for the Greenland Ice Sheet will be developed that include the dynamics of the fast flowing ice streams. Based on the models and the bedrock mapped by the radio echo sounding, basal melt and basal sliding laws will be investigated.

B3 Objectives and methodology



B3.1 Mapping the radio echo layers in the Greenland ice sheet

The radio echo sounding images contain information on the elevation of the bedrock under the ice as well as internal layers in the ice. Examples of the internal layers in the Greenland Ice Sheet mapped by CReSIS have been shown on page 2 and also on the above figure, where I have traced layers along the whole ice ridge from the south to the north of Greenland. The ice ridge is of special interest because the deep ice core sites are placed on this ridge, allowing the age of the internal layers to be determined from the dated ice cores. The internal layers are thus layers of equal age, i.e. isochrones, and can be detected as far as 80.000 years back in time in the north of the Greenland ice sheet. The internal layers are a valuable and unused set of boundary conditions that can be used to constrain ice sheet flow models when reconstructing the past evolution of the ice sheet through the glacial and interglacial climate periods. While modelling the evolution of the ice sheet, the layers can be traced as they gradually flow down into the ice sheet. Reconstructing the past evolution of the ice sheet has relevance

– also for understanding the future – because there has been climate periods in the past, e.g. the previous interglacial period, the Eemian, 130,000 to 115,000 years before present, where temperatures over Greenland where 5^{o}C warmer than the present[29]. The evolution of the Greenland Ice Sheet in the Eemian will provide important analogies on the behaviour of the ice sheet in the coming warmer climate.

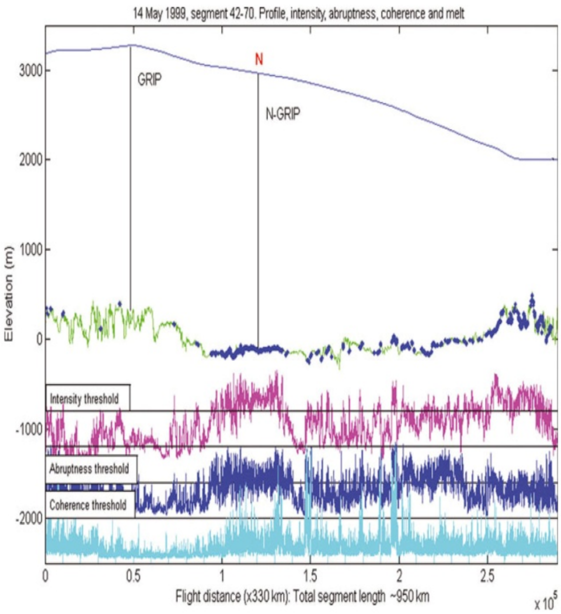
The full data set of CreSIS radio echo sounding images are available as MATLAB files. The bedrock has been traced[30] but the internal layers have only been traced on a few images. In order to trace the internal layers the datasets need to be processed so the layers become traceable. Software to trace the layers will have to be developed. The data have been obtained through airborne campaigns during 15 years (1993-2009) with different generations of radar equipment, and the data quality thus varies through the data set.

The layer tracing will be done in collaboration with the CReSIS research centre and a PhD position for a student with a strong background in programming and image manipulation will be allocated to the task. I imagine that the traced layers will be made available on the CReSIS homepage when the task is completed.

The impact of the mapping the internal layers will be to provide the society with a unique set of boundary conditions that can be used to constrain the past evolution of the Greenland ice sheet.

B3.2 Detecting regions with melt from the radio echo sounding images

(Osward and Gogineni)[18] have demonstrated that the presence of basal water can be derived from the shape of the bedrock reflector in the radio echo sounding images. The figure to the left demonstrates that melting is detected under the NGRIP drill site and marks the melt regions with blue along the profile that includes the

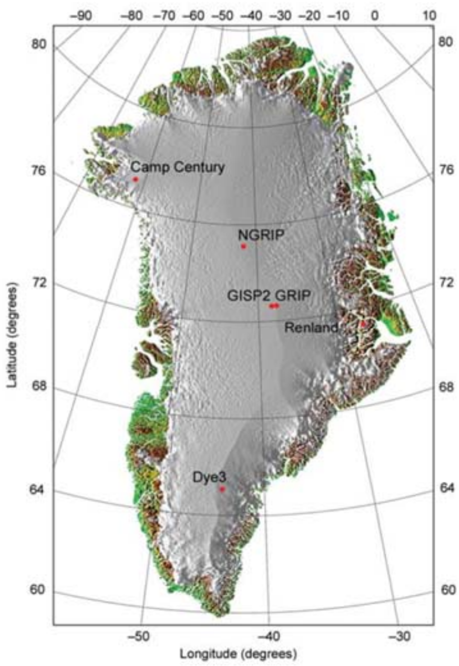


Oswald and Gogineni, J. of Glaciology, 2008

GRIP and NGRIP drill sites. The region with basal water can be recognized by the intensity and abruptness of the bedrock reflector. An alternative method of detecting basal melt is to identify the regions where the internal layers have undulations that are amplified or not correlated with the bedrock. A first attempt to trace the region with basal melt using inverse Monte Carlo methods reveals an area of 0.4 · 10^6km^2 with melt of the order of 4 km^3 per year in the northern part of the Greenland Ice Sheet. Both methods of detecting basal melt will be applied in connection with the tracing of the internal layers as mentioned in the section above. As part of these investigations we will also look for lakes under the ice. Lakes can be detected by a very flat reflector under the ice, a change in surface slope and air gravity anomalies. Again this research will be done in a strong collaboration with CReSIS. A 2 year Post Doc position has been dedicated to this task and is expected to form a team with the PhD who will trace the layers.

The impact of mapping the melt under the ice is to be able to include the melt water at the base in the mass balance estimates of the Greenland Ice Sheet. In addition it is a must to know the regions with melt and sliding ice in order to advance ice sheet models to improve future predictions.

B3.3 Using the deep ice cores and the boreholes to understand the base



The opportunities to look directly at the base are limited to the locations of the deep boreholes. In the summit region of the Greenland Ice Sheet the ice is frozen to the bedrock. After the US GISP2 drilling was completed in 1993, a 1.55 m rock core was drilled into the bedrock as a joint European/US program. The rock core consisted of grey gneissic granite, consistent with the geothermal heat flow of 51 mW/m^2 reconstructed from the borehole temperatures both at GISP2 and the European GRIP site 30 km away. At the NGRIP drill site, bedrock was reached in 2003 where a 30 m basal water column entered the borehole. The refrozen basal water was sampled by the drill but attempts to drill into the bedrock failed. From seismic recordings at the NGRIP site it is concluded that

When bedrock (hopefully) is reached at the international NEEM deep ice core site in 2011, we will be able to detect from annual layer thicknesses in the ice core and by temperature measurements if the ice is melting at the site. Inverse modelling suggests that there is slight basal melt at the site[4]. Through this program I propose to log the borehole with the temperature, pressure logger and also develop a camera that can be lowered down into the borehole to directly observe the basal conditions.

Conditions at the base and information on where the water is found in relation to the ice-bedrock interface will give us valuable information on the water system at the base. Is the water moving in a basin filled with sediments or in channels close to the bed? How thick is the layer of very fine grained impurities originally deposited on the surface, advected to the bed by ice flow and melted out of the ice-bed interface? In addition, it is of the outmost interest to be able to date the ice at the base to address for how long the ice has covered the Greenland ice sheet.

B3.4 Drilling into the bedrock at the NEEM site

In order to be fully able to make the investigations listed above there is a need to drill into the bedrock. In the proposed project, the rock drilling tool, to be attached under the NEEM deep ice core drill and operate using the cable system and computer controlling system for the drilling procedure, will be developed. To be able to lower a camera to the base and to drill into the bedrock I have allocated 2.3 year salary for mechanic support. I also propose to dedicate part of the budget as a contribution to the logistical costs of an additional field season at NEEM in 2012 to allow the basal studies and rock drilling to take place. It was proposed at the NEEM Steering Committee meeting November 2008, that all the participating nations should seek national funds to extend the NEEM project into 2012 to attempt a replicate drilling of the deep ice containing the Eemian ice and to investigate basal conditions.

The impact of investigating the base when the opportunity of a deep borehole is available is obvious. It gives insight in the melt system and water subglacial pressure system and allows us to gain basal material.

B3.5 Life under the ice ?

Is there life under the ice? Life has been found under extreme conditions when we have looked for it – under boiling conditions, freezing conditions, under no pressure in space, and under high pressure in the deep underground. Under the ice in regions with basal melt, the temperature is at the pressure melting point, the pressure is around 300 bars, and the ice transports nutrients from the surface to the base. Basal material was recovered from the NGRIP site, but it was contaminated with drill fluid that also contains organic components, and it has not been possible to deduce if there is any form of bacterial life at the base. A very high content of gas - probably methane, does however suggest the existence of life. Besides from the possibility of an isolated present ecosystem at the base, it is also possible to look for ancient organic life – from before ice covered the drill sites. We have had a strong collaboration with professor Eske Willerslev and his research group during the last years, where we have reconstructed the fauna at the DYE-3 drill site before the ice covered the region more than 450,000 years ago. The reconstruction is based on regeneration of ancient DNA found in the near basal ice.

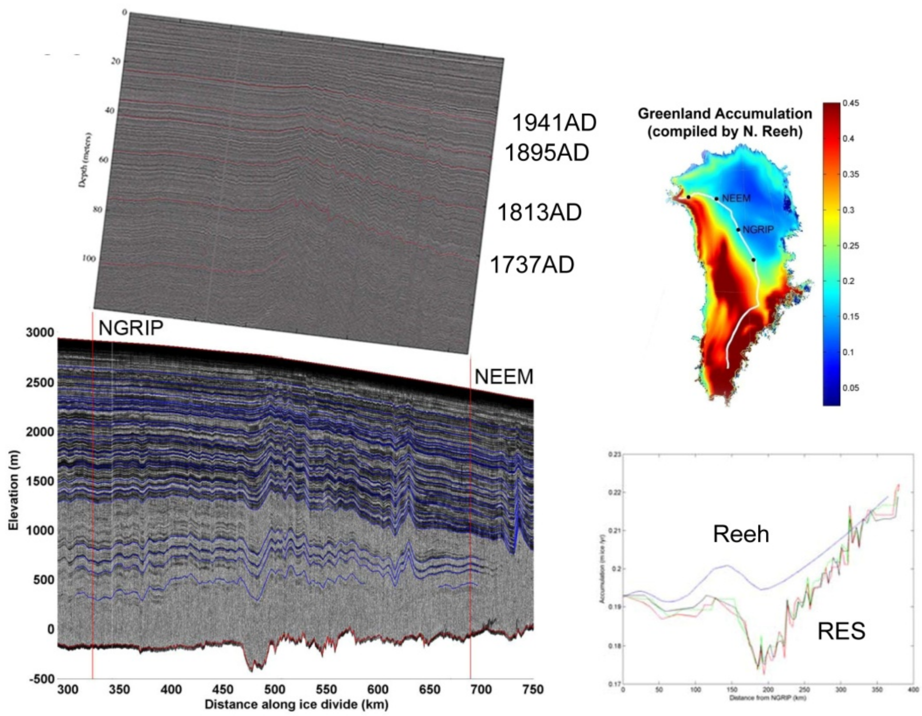
It is proposed to expand the biological investigations to the coming NEEM deep drilling site both by recovering DNA-rich material from the basal ice when bedrock is reached (expected in 2011) and also to work on methods that allow us to recover uncontaminated material from the base and from the material under the ice during a 2012 season. This is a highly experimental objective as entirely new methods are needed to make it possible to recover uncontaminated basal material. The Ice and Climate group in Copenhagen has a long-standing tradition for developing deep ice core drills and I am member of the steering groups of the IPICS (International Program for Ice Core Science) and EuroPICS (European Program for Ice Core Science) as well as the US Scientific Advisory Board for the IDPO (Ice core Drilling Project Office). Much of the expertise and initiatives needed for the development of new tools and methods are present in these groups.

In the program a 2 year Post Doc has been allocated to the DNA studies and a 2 year Post Doc will work on the basal material we find at the base to investigate if there is bacterial life at the ice-bed interface. The Post Docs will collaborate with scientists from the NEEM nations through the Consortia for Biological Material under the NEEM Steering Committee.

> The impacts of investigating basal material for DNA and for bacterial life are strong. Reconstructing DNA and dating the old ice constrains the age of the ice sheet and informs on the fauna present before the ice sheet covered the region. Bacterial life – if such a system exists and has been isolated from the atmosphere for several 100.000 years – it is highly interesting.

B3.6 Using the internal radio echo layers to determine past surface accumulation rates

Mapping of the internal radio echo sounding data can provide us with an additional and very important data set: the snow accumulation rates over the interior high regions of the ice sheet[31].



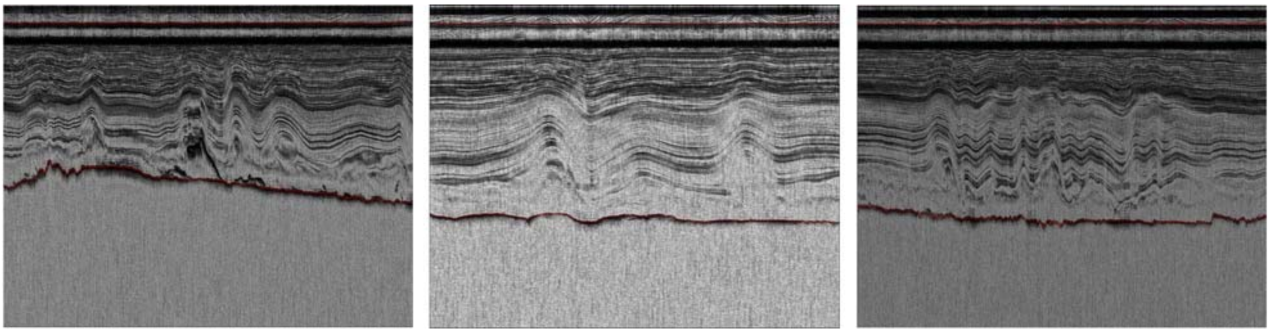
An example of the potential is shown on the above figures. The upper left figure show a surface-radar mapping of the internal layers in the top 100m along the ice ridge between NGRIP and NEEM performed in 2007 by CReSIS. It is possible to trace layers the 325 km between the ice core drilling sites, and based on the dating of these layers in the ice cores, the layer depths can be translated to surface accumulation rates along the line. When these detailed accumulation rates are compared with those produced from compiling data from snow pit and shallow ice cores studies as those published by Reeh[32]. (Greenland map; top right figure), a large difference is observed along the ice ridge line (bottom right figure).

In this program it is proposed to map the shallowest traceable internal layers to produce a detailed accumulation map of the present accumulation over the entire Greenland Ice Sheet. In addition the deeper traceable internal layers will be combined with inverse methods to reconstruct past accumulation rates.

B3.7 Combining ice sheet models with radio echo sounding knowledge

The evolution of the Greenland ice sheet is modelled by both ice ridge/flow line 2-D models and also by 3-D models (e.g. the SICOPOLIS model[33,34]; the PISM model[35]). We intend to use the traced internal radio echo sounding layers as constrains for the models. Simulations with the modelling of the evolution and flow of the ice, layers of equal age will be traced with the model and compared with the observed radio sounding layers. In addition to modelling the flow, the ice temperatures will be modelled and the knowledge on the extent of basal melting from radio echo soundings will be used to constrain the modelled temperatures. The information on basal melt will be used to include basal sliding where there is melt.

This will be the first attempt to model the dynamics of the Greenland ice sheet using empirically derived accumulation rates, melt rates, sliding information, and verifiable temperature profiles.



B3.8 Developing basal sliding conditions

Attempts will also be made to constrain the basal sliding under the ice by observations based on the internal layers in the ice. As the ice flows over areas with melt, ice is drawn towards the bedrock. The figure above shows three examples of radio echo sounding images from North Greenland areas with very changeable melt rates. It can be seen that the undulations of the internal layers are enhanced with depth but it can also be seen that there is a spatial difference of the placement of the undulations with depth reflecting the flow of the ice. Flow models including basal flow laws can be tested in these regions to determine the basal sliding.

In the very fast ice streams of the margin regions, basal ice is at the melting point and internal reflectors are not present on the images. Here the surface velocities mapped by satellite InSAR imagery need to be included together with assumptions on close-to-block-flow of the ice to further investigate basal sliding laws[28,36-39]

A 2 year position for a senior researcher, Aslak Grindsted, has been allocated to the ice sheet modelling. Aslak has strong experience in ice sheet modelling and it is my hope that a permanent position at the Niels Bohr Institute will become available for Aslak Grindsted to apply at the end of the funding period suggested here. In addition a PhD position to model ice stream flow is proposed. We expect the ice stream modelling to be coordinated with international attempts through the EU FP7 Ice2Sea program, the US Community model initiative and the modelling group lead by Kees van der Veen at CReSIS.

The impact of mapping accumulation rates, developing ice sheet and ice stream models is to improve ice models so we can predict the evolution of the big ice sheets in a warming world. This is one of the gaps identified by the IPCC 2007 report[9]

B3.9 Modelling the basal water movement and melt production

Based on the bedrock map, the extent of basal melt, and the knowledge from the boreholes, we will estimate the movement of water under the ice using models based on the ice and water pressures and theories for water flow channels either along the bed or in the ice.

The first papers on estimates of melt under the ice in North Greenland[1,3,4] find melt rates of up to 10 cm/yr, which corresponds to geothermal heat flow values of more than 1000 mW/m^2, and a spatial scale of basal melt variations of the order of 10 km along the base. These results indicate that there is a need of rethinking what causes the high and spatially highly variable melt rates under the ice. Clearly heat is needed, but the traditional method of envisaging the heat to be provided by the geothermal heat flow produced by the inner parts of the Earth and the underlying rocks in the lithosphere is not consistent with the estimated melt characteristics, as the composition of the rocks cannot vary sufficiently to produce the observed pattern.

I imagine that the movement of basal water needs to be included as a source of local heat production. If water flows to the areas of high melt either along the bed or surfaces from faults in the underlying rocks, it is possible to increase the heat available at specific spots of the bedrock without assuming unrealistically high heat production rates in the near-surface rocks.

Attempts to construct water and ice flow models that can model/explain the observed pattern of melt along the base is a part of the proposed program. These calculations will also either lead to identification of areas where lakes are likely to form or to explanations of why there are no or only very small lakes under the Greenland ice cap.

A 2 year Post Doc is allocated to the task of modelling the subglacial hydrological system. We will build a new network around this research field with researchers like R. Bell and M. Studinger with whom we already have collaboration on use and interpretation of radio echo sounding layers.

The impact of gaining understanding of the subglacial hydrological system will support the goal of locating lakes under the ice. As the water influences the flow of ice so strongly it is important to know where it is and how it moves!

B3.10 Impact of the water on the future evolution of the Greenland Ice Sheet

Combining the knowledge gained on where water is present, how the water moves, how it influences the mass balance of the ice sheet, and finally the impact on the ice flow both in the central parts of the ice sheet in North Greenland and under the fast flowing ice streams near the margins, will prepare us for the ice sheet modelling. The ice sheet modelling will attempt to determine the influence on basal water on the evolution of the ice sheet both at present and in future warmer conditions. The amount of melt water produced will also be estimated, and the effect of release of the melt water to the surrounding relevant to the ocean circulation system, will be evaluated.

In the WATERundertheICE project the SICOPOLIS and the PISM models will extend with water moduls developed for the basal water impacts. In addition we will use models like ELMER that include the full stress field and there by are suited for addressing the local and quite complicate ice steam systems. In order to improve the models to predict the future evaluation of the Greenland ice sheet the knowledge on the present surface mass balance obtained in B3.6 will be extended to a changing climate using state-of-the-art energy-balance models. In addition we will collaborate with other modelling initiatives like the just-launched FP7 Ice2Sea program and the US Community model initiative and the ice stream modelling lead by Kees v.d.Veen (CReSIS) and Martin Truffer (University of Fairbanks).

We will strive towards having the first results ready for the next report from The Intergovernmental Panel on Climate Change in 2012.

A very central part of the WATERundertheICE project will be the next generation of researchers. The project proposes to include 4 Post Doctoral and 2 PhD positions. These positions will be internationally announced to recruit the best-qualified candidates. The international reputation of the team and the importance of the planned activities will provide the basis to attract the world's best candidates. A significant part of the proposed budget is for young researchers, and we also expect to attract additional funds to support their work. The global alliance IARU (International Alliance of Research Universities) has selected global change, including climate and greenhouse gas research, as one of five subjects of collaboration. This will give the WATERundertheICE project exceptional opportunities for exchange of Post Docs and PhD students from 10 of the top universities in the world.

Polar research involving ice cores and climate is very exciting, and has a great appeal for primary and high school students. We expect that all scientists at the WATERundertheICE project will participate in the education of students at the bachelor, master and PhD levels. The project will also attract international students because of its unique expertise.

B4 Why this program fits perfect with me

The combination of experience with both ice-flow-related interpretation of the vast amount of information recorded in the radio echo sounding images and the knowledge available from the deep ice cores and boreholes is a rather rare interdisciplinary research combination. For several years I have hoped to get an opportunity to investigate the enormous potential that is present here. I have done pilot studies within the WATERundertheICE research themes during the last few years but never had an opportunity to fully define a program. I find that the background that I have with the very close connection to the ice core programs, the expertise in developing ice flow models related to understanding ice core properties, and the strong collaboration with CReSIS is a unique background and just what is needed to define a new and very interesting program that is also highly relevant to our struggle to understand the future mass loss from the Greenland ice sheet.

The proposed WATERundetheICE project is a realization of a dream I have had for some years and I am confident that with my strong network of national and international collaborators it will be possible – for the first time – to explore the full potential of the knowledge available on water under the Greenland ice sheet.

I will place all my research (50% of my time) within the WATERundertheICE project. The links to the Centre for Ice and Climate and the NEEM project are so strong and the WATERundertheICE is shaped just for me!

B5 National and International collaboration

In order to succeed, it is of paramount importance to have a strong network of national and international research collaborations. The Centre for Ice and Climate, that I lead, has the goal of using ice core data to gain knowledge on the past warm interglacial climate, and we have a broad network of collaborators including most of the ice core groups in the World, a broad net of palaeoclimate researchers that also includes work on marine and lake palaeo-records and ^{14}C dating. The centre has a strong component of atmosphere modelling including collaboration with the research groups at the Bjerkness Centre, Hadley, NCAR and University of Alaska and Hamburg. For the ice sheet modelling we collaborate with the European modelling network included in the EU FP7 Ice2sea program and the US modellers from University of Washington, CReSIS at University of Kansas and The University of Fairbanks. As the leading group of the international deep drilling program NEEM with 13 international partners we have strong collaboration with most ice core programs and ice drilling programs and great expertise in development of ice drills and logging tools. Finally I have a very strong collaboration with the CReSIS- an NSF Science and Technology Center at the University of Kansas. They have collected the radio echo sounding images that are the very base of this program. I have presented the WATERundertheICE program to CReSIS and we have agreed on the collaboration which will involve exchange of researchers, joint workshops and an extensive guest program. (contact: Director Prasad Gogineni; gogineni@cresis.ku.edu).

B6 Resources

The WATERundertheICE research group will be embedded in the Centre of Ice and Climate. The Centre of Ice and Climate has ice sheet modelling activities that are highly related to the ice core research. Through the WATERundertheICE program we will be a team of 2 senior researchers (Dorthe Dahl-Jensen and Aslak Grindsted), 3 Post Docs and 2 PhD's. I will be involved in all the ten activities described in Tabel B6.3. Aslak Grindsted is a strong modeller and will be involved in the activities B3.7, B3.8 and B3.10. The two 2-year Post Doc for tracing melt (B3.2) and modelling the melt (B3.9) will be announced internationally and the strongest candidates hired after evaluation. The 2-year post doc for DNA studies (B3.5) will be for Astrid Grene when she finishes her PhD. She has the needed expertise and forms the link to the Centre of Excellence for GeoGenetics at the University of Copenhagen. The 2 PhD positions for tracing RES (B3.1 and B3.10) and ice stream modelling (B3.8 and B3.10) will also be announced internationally and the strongest candidate hired after evaluation.

The WATERundertheICE project is expected to enhance the collaboration and exchange of researchers especially between the CReSIS radar research group from University of Kansas. A salary budget has been dedicated for exchange and we have already arranged for Professor Prasad Gogineni, centre leader from CReSIS to have a 9 month sabbatical with us in 2011. Professor Jean Jouzel will spend a month with us in 2010. A budget has been reserved for the salary of a mechanic engineer and equipment to develop the drill equipment needed to drill into the bedrock at NEEM. In order to be able to drill into the bedrock we need to add a field season to the NEEM project. A budget has been dedicated to the logistics of this and the partners of the NEEM project have been encouraged to apply for additional logistic expense for the NEEM program. A travel budget is reserved for the travel of the WATERundertheICE team to meetings and symposiums related to the program. In addition a budget is reserved for inviting guests and experts to Copenhagen to share new research results and do research. I have budgeted with three workshops to be held in Copenhagen during the duration of the project. The workshops will be held in relevant research subjects as 'Modelling of ice streams', 'Movement of water under the ice' and 'Tracing RES and basal melt under the Greenland ice sheet' and will enable us to invite a group of experts to Copenhagen to share methods and results. Near the end of year 4, I plan to host a bigger meeting, a symposium in Copenhagen to have an opportunity to present the research from the WATERundertheICE project and discuss it with other experts before the final phase of publishing will happen in the last year of the project.

The support for mechanic engineering, secretary and student projects will be done in collaboration with the Niels Bohr Institute, where the needed resources and expertise is present.

The access to the borehole and the logistic component in the WATERundertheICE project will be done in collaboration with the NEEM project including the 13 international partners in the project.

The audit will be done after each financial reporting period and the funds for this is placed as subcontracting cost.

The other projects the group are involved in like the EU FP7 programs Ice2Sea and Past4Future, the Danish Centre for Regional change in the Earth System and the Greenland Climate Research Centre all have components that will support and compliment the WATERundertheICE project but no significant overlap. In the EU FP7 program Ice2Sea we have resources for a 2 year Post doc to obtain ice cores from the Greenland ice sheet at the sites we earlier have drilled ice cores to update the mass balance at these sites. The increase knowledge on the mass balance from the ice cores will support the research proposed in the WATERundertheICE program where the Radio Echo layers will be used to produce masse balance maps. In the Past4Future we will as an in kind service use the PRISM ice sheet model to model the evolution of the Greenland ice sheet 115.000 years ago and during the last 11.000 years. In the WATERundertheICE project we will develop modules regarding the water under the ice for the PRISM model and investigate the effect of the water under the ice.

With the very strong international network we have, I believe we are very well suited to perform the research described in the WATERundertheICE project.

	Cost Category	Year 1	Year 2	Year 3	Year 4	Year 5	Total (Y1-5)
	Personnel:						
	PI	0	0	0	0	0	**0**
	Senior Staff						**194.181**
	Aslak Grindsted	25.532	76.597	78.613	13.438	0	
	Post docs						**450.804**
	Tracing melt	35.611	71.222	36.955	0	0	
	Modelling melt	0	0	35.611	75.253	36.955	
	DNA studies	0	75.657	77.941	0	0	
	PhDs						**445.205**
	Tracing RES	0	55.096	75.253	77.941	20.157	
	Ice Stream Modelling	34.939	73.193	75.253	38.971	0	
	Students	10.079	10.079	10.079	10.079	10.079	**50.393**
	Exchange Program	13.438	80.629	13.438	13.438	13.438	**134.381**
	Secretary assistance	13.438	13.438	13.438	13.438	13.438	**67.191**
	Mechanic (Rock drill)	47.033	47.033	0	0	0	**94.067**
Direct Costs:	**Total Personnel:**						**1.436.221**
	Other Direct Costs:						
	Equipment						**73.910**
	Rock drill, PC's	26.876	13.438	26.876	6.719	0	
	Consumables						**49.752**
	Office	12.497	12.497	12.497	6.212	6.047	
	Travel	13.438	13.438	13.438	13.438	13.438	**67.191**
	Travel invited Experts	13.438	13.438	13.438	13.438	13.438	**67.191**
	Publications, etc	6.719	6.719	6.719	6.719	6.719	**33.595**
	Logistic field support	0	28.959	268.762	0	0	**297.721**
	Symposium	0	0	0	23.516	0	**23.516**
	Workshops	10.079	0	10.079	0	10.079	**30.236**
	Total Other Direct Costs:						**643.112**
	Total Direct Costs:						**2.079.333**
Indirect Costs (overheads):	Max 20% of Direct Costs						**415.866**
Subcontracting Costs (Audit):	(No overheads)	960	960	960	960	960	**4.800**
Total Costs of project:	(by year and total)	316.702	710.680	923.030	376.082	173.505	**2.499.999**
Requested Grant:	(by year and total)	316.702	710.680	923.030	376.082	173.505	**2.499.999**

Tabel 6.1 Resource break down in relation to project years and researchers related to the project

Cost Category	month 1 to 18	month 19-36	month 37 to 54	month 55-60	TOTAL
Personnel	431,543.00	668,053.00	289,591.00	47,033.00	1,436,221.00
Subcontracting, Audit	1,200.00	1,200.00	1,200.00	1,200.00	4,800.00
Equipment	33,595.00	33,595.00	6,719.00	0.00	73,910.00
Consumables	18,746.00	18,746.00	9,236.00	3,024.00	49,752.00
Logistic field support	14,480.00	283,242.00	0.00	0.00	297,721.00
Travel of team members	20,157.00	20,157.00	20,157.00	6,719.00	67,191.00
Travel cost of invited experts	20,157.00	20,157.00	20,157.00	6,719.00	67,191.00
Workshops and Symposium	10,079.00	10,079.00	28,556.00	5,039.00	53,752.00
Publications	10,079.00	10,079.00	10,079.00	3,360.00	33,595.00
Sub-total Other Costs	127,293.00	396,055.00	94,904.00	24,861.00	643,112.00
Overheads	111,767.00	212,822.00	76,899.00	14,378.00	415,866.00
TOTAL	**671,803.00**	**1,278,130.00**	**462,594.00**	**87,472.00**	**2,499,999.00**

Tabel 6.2 Resources breakdown in activities and reporting periods

Number	Key intermediate goal	Estimated % of total requested grant	Expected to be completed on month :	Comment
B3.1	Mapping the radio echo layers in the Greenland ice sheet	10%	44	The layer tracing will be done in collaboration with the CReSIS research centre and a PhD position for a student with a strong background in programming and image manipulation will be allocated to the task.
B3.2	Detecting regions with melt from the radio echo sounding images	10%	44	This research will be done in a strong collaboration with CReSIS. A 2 year Post Doc position has been dedicated to this task and is expected to form a team with the PhD who will trace the layers.
B3.3	Using the deep ice cores and the boreholes to understand the base	13%	36	Through this program I propose to log the borehole with the temperature, pressure logger and also develop a camera that can be lowered down into the borehole to directly observe the basal conditions. The data will be used in the tasks B3.5, B3.8, B3.9.
B3.4	Drilling into the bedrock at the NEEM site	10%	36	Together wil the NEEM partners we propose to extend the NEEM project with an additional field season toe drill into the bedrock. The tools needed to achieve this goal will be developed through WATERundertheICE. The results will be used in the tasks B3.5, B3.8, B3.9.
B3.5	Life under the ice ?	15%	36	In the program a 2 year Post Doc has been allocated to the DNA studies and a 2 year Post Doc will work on the basal material we find at the base to investigate if there is bacterial life at the ice-bed interface. The Post Docs will collaborate with scientists from the NEEM nations through the Consortia for Biological Material under the NEEM Steering Committee.
B3.6	Using the internal radio echo layers to determine past surface accumulation rates	3%	54	In this program it is proposed to map the shallowest traceable internal layers to produce a detailed accumulation map of the present accumulation over the entire Greenland Ice Sheet. A strong collaboration with Ice2Sea is expected. The results will be used in B3.7 and B3.10.
B3.7	Combining ice sheet models with radio echo sounding knowledge	6%	54	The information on basal melt will be used to include basal sliding where there is melt. Ice Sheet models will be developed by Aslak Grindsted and team members of WATERundertheICE and from the Center of Ice and Climate.
B3.8	Developing basal sliding conditions	17%	60	Aslak Grindsted and a PhD position to model ice stream flow will lead these activities.
B3.9	Modelling the basal water movement and melt production	6%	60	A 2 year Post Doc is allocated to the task of modelling the subglacial hydrological system. We will build a new network around this research field with researchers like R. Bell and M. Studinger with whom we already have collaboration on use and interpretation of radio echo sounding layers.
B3.10	Impact of the water on the future evolution of the Greenland Ice Sheet	10%	60	The full WATERundertheICE team will participate in this activity. . In addition we will collaborate with other modelling initiatives like the just-launched FP7 Ice2Sea program and the US Community model initiative and the ice stream modelling lead by Kees v.d.Veen (CReSIS) and Martin Truffer (University of Fairbanks).
	TOTAL	**100%**		

Tabel 6.3 Breakdown of cost in subtasks

B7 Ethical Issues

	Research on Human Embryo/ Foetus	YES	NO
	Does the proposed research involve human Embryos?		X
	Does the proposed research involve human Foetal Tissues/ Cells?		X
	Does the proposed research involve human Embryonic Stem Cells (hESCs)?		X
	Does the proposed research on human Embryonic Stem Cells involve cells in culture?		X
	Does the proposed research on Human Embryonic Stem Cells involve the derivation of cells from Embryos?		X
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X

	Research on Humans	YES	NO
	Does the proposed research involve children?		X
	Does the proposed research involve patients?		X
	Does the proposed research involve persons not able to give consent?		X
	Does the proposed research involve adult healthy volunteers?		X
	Does the proposed research involve Human genetic material?		X
	Does the proposed research involve Human biological samples?		X
	Does the proposed research involve Human data collection?		X
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X

	Privacy	YES	NO
	Does the proposed research involve processing of genetic information or personal data (e.g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?		X
	Does the proposed research involve tracking the location or observation of people?		X
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X

	Research on Animals	YES	NO
	Does the proposed research involve research on animals?		X
	Are those animals transgenic small laboratory animals?		X
	Are those animals transgenic farm animals?		X
	Are those animals non-human primates?		X
	Are those animals cloned farm animals?		X
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X

	Research Involving Developing Countries	YES	NO
	Does the proposed research involve the use of local resources (genetic, animal, plant)?		X
	Is the proposed research of benefit to local communities (e.g. capacity building, access to healthcare, education, etc)?		X
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X

	Dual Use	YES	NO

	Research having direct military use		X
	Research having the potential for terrorist abuse		X
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X

Other Ethical Issues	YES	NO
Are there **OTHER** activities that may raise **Ethical Issues**?		X

B8 Research Environment

B8.1 My host institution

The WATERundertheICE project is proposed to be placed at my current institution, Niels Bohr Institute at the University of Copenhagen.

The University of Copenhagen is one of the top universities in the World (2008 ranking: 48) and is one of the 10 universities in the International Alliance of Research Universities (IARU). The IARU Universities have just hosted an international Climate Congress in Copenhagen 10-12 March 2009. University of Copenhagen has the clear aim of supporting research of highest quality and has a very supportive international office including a strong expertise in EU programs. Denmark and Greenland have very strong ties and there is a strong tradition at the University of Copenhagen for Greenland related research in a broad span of research areas including geophysics, geology, geography, astronomy, archaeology and human society. One of the priority research themes is Arctic Research and at present the University is building a graduate climate program that we are involved in. As the WATERundertheICE project is a Greenland project there is no better place to be placed than the University of Copenhagen where the Greenland related interdisciplinary environment is so strong.

The Niels Bohr Institute is the Institute for Physics at the University of Copenhagen. At present five Centres of Excellence are embedded at the Niels Bohr institute. It is vital for our program to have access to bright students well versed in physics and mathematics which favours the Niels Bohr Institute as the hosting institute. The institute is strongly involved in the super computing facilities in Denmark and has a strong PhD program. The institute has workshops that have developed drill parts and other instruments for our research activities and the WATERundertheICE program also includes use of these workshop facilities.

The Centre of Ice and Climate is a Centre of Excellence at with a staff of 46 (senior researchers, post docs, Phd's administrative and technical staff). The research relates to ice cores and climate and the Centre hosts the logistic office and the lead of the international NEEM deep ice core project. The NEEM drill is developed by the research group. While the focus of the Centre research differs from the WATERundertheICE project there is strong expertise in the research group that supports the proposed research especially by providing ice sheet and ice flow models and a big data base of ice core measurements.

B8.2 Collaborating Research Institutes and Projects

The collaboration with international institutions is vital for the success of the WATERundertheICE project and the most important collaborations are listed below:

B8.2.1 CReSIS (Centre for Remote Sensing of the Ice Sheets)

The Centre of Excellence for Science and Technology is placed at the University of Kansas, Laurence, USA and is directed by the centre leader Prasad Gogineni. The centre has developed the radars used to map the bedrock and internal layers in the Greenland ice sheet. Although several other research groups have obtained images from the Greenland ice sheet the images from CReSIS are by far the most extensive and in my opinion by far the best images. The collaboration with CReSIS will include exchange of senior and junior researchers and students between the groups. The mapped internal layers obtained through the WATERundertheICE program will be offered to the CReSIS so it can be placed on the net together with the radar images. We imagine that the proposed research will result in many joint publications between the groups. The CReSIS research group include modellers of the fast flowing ice streams which we hope to collaborate with.

B8.2.2 NEEM

The North Greenland deep drilling program is a very important site for gaining knowledge of water properties at the base and study site for finding biological material under the ice. The NEEM deep drilling project is an International Polar year program with 14 international partners. The WATERundertheICE research will be proposed to the Steering Committee of the NEEM project and it is our hope that several of the other partners in the project will be able to co-fund the 2012 NEEM field season and participate in the development in the rock drill. The research of NEEM will lead to and dated ice core and a known climate history covering the 150.000 years we hope is present in the NEEM ice core. The institutions participating in the NEEM project are the leading international research groups in ice and climate research and they also include researchers developing ice flow models that can be involved in the WATERundertheICE project.

B8.2.3 EU FP7 Ice2Sea project

The aim of this program is to model the future evolution of the ice sheets, the predicted loss of mass and the resulting sea level rise. As a partner in this program the state-of-art ice sheet and ice flow models will develop. The WATERundertheICE project will be able to contribute knowledge on the water into the Ice2Sea program. An important aim of the Ice2Sea program is to have predictions and publications ready for the UN fifth IPCC report to be published in 2012. This will also be an important target for the WATERundertheICE project.

B8.2.4 Centre for GeoGenetics

The WATERundertheICE program will enhance the collaboration with the research group of Eske Willerslev. Eske Willerslev has just been granted a Centre of Excellence to start 2010. In connection to the DNA research done on the south Greenland Dye3 ice core clean labs have been build in connection with our freezers at the Niels Bohr Insitute. In addition to the DNA group there are several of the NEEM nations interested in participating in the studies of biological material in and under the ice. I see this as a very promising collaboration including US researchers as Buford Price and John Priscu.

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