White paper

Ice coring for ice dynamics

Introduction

There is considerable concern about the stability of parts of the Greenland and Antarctic ice sheets, particularly in the face of anthropogenic climate warming. The velocity of some fast-flowing ice streams in Greenland has greatly increased in the last decade. It has also been suggested that West Antarctic glaciers may already be exhibiting signs of instability. There have been great advances in modelling ice dynamics across ice sheets, streams and shelves in recent years. The ice streams with their origin and the coupling to the ocean are however badly understood as observations especially at the base where melt occurs are challenging. One further barrier to progress is a lack of knowledge about how the rheological properties of the ice develop with depth and across flow regimes, and about the properties of the basal part of the ice column and its interaction with the bed. Furthermore, unexpected structures have been observed in radar profiles that probably are patterns or of a rather intricate behavior of anisotropic ice under the local deformation regimes. Complex 3D flow patterns, extensive basal freezing or alternating slip and stick basal conditions have also been suggested as reasons for formation of the structures. All these issues can be most directly addressed by making targeted drillings aimed predominantly at understanding ice dynamics, rather than documenting climate.

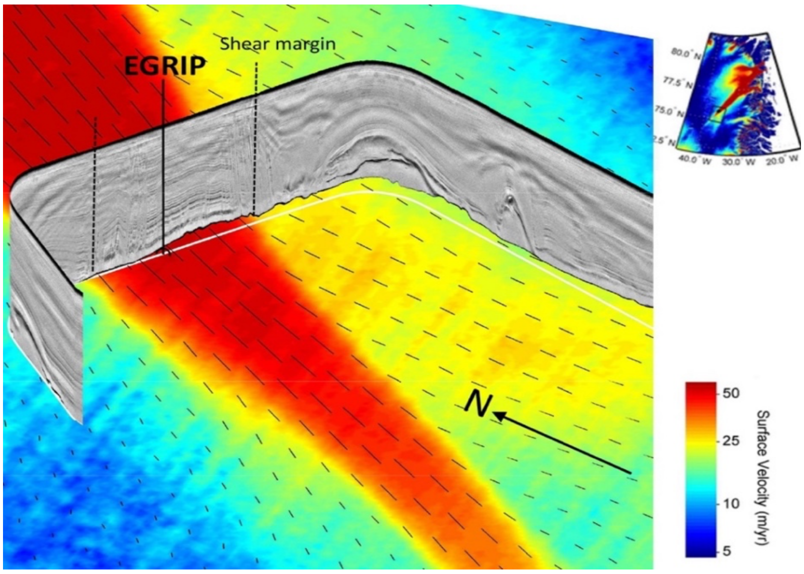

Figure 1 Surface velocities in the vicinity of the EGRIP camp on the North East Greenland Ice Stream (NEGIS). A Radio Echogram with the Depth Penetrating Radar (Operation IceBridge 2014) reveals well defined layering over the drill site, shear margins and large basal structures on the outside of the ice stream.

The scientific issues

From existing deep ice cores, we observe the development of anisotropy in polycrystalline ice orientation structure with depth and the development of large and interlocking ice crystals in succession with fine crystals near the bed. These features influence the flow-rate-controlling deformation mechanisms and thus in-situ-rheological response of the material during the deformation of ice which can lead to stratigraphically influenced/disturbed ice in a significant amount of the existing cores especially close to the bed. The large crystals are partly described by warm basal temperatures but are also related to ice that is not deforming. The consequences of the anisotropic polycrystalline ice are seen in several of the deep ice cores where the stratigraphic layering is altered and e.g. folds and buckling ice occurs. Further complicating the picture is that the ice crystal size and degree of anisotropy also relates to the (soluble and insoluble) impurities in the ice so the glacial and interglacial layers with different impurity concentrations show different ice rheology.

Studies of the still not well described deformation of anisotropic ice and the mechanisms that cause ice to form deformation structures are important for the overall flow of the ice sheets. Besides the influence of anisotropy, the role of refreezing basal water, the role of slip and stick zones at the bed, the change from shear-dominated flow to ice flow dominated by membrane stresses, and the importance of converging/diverging flow have also been invoked in explaining the basal structures in the ice. If we are to improve estimates of sea level rise, we need to be able to predict future flow changes especially of localized dynamic regions within the ice sheet such as the ice streams and their margins. Ice dynamic studies should address the development and flow of water under the ice as well as the role of grounding lines and ice-ocean interaction. Furthermore, the combination of ice structure and radar stratigraphy aids in the validation of ice-flow models in highly anisotropic zones, such as ice rises where the Raymond effect operates.

To gain knowledge of these features there is a need to drill ice cores, make rapid access holes and observe the deformation of the boreholes. The interesting regimes for ice dynamic sites are often sites where the surface velocity and its gradients are significant and thus target different sites than the paleo-climate sites where surface velocity often is low to reduce upstream related complications.

The challenge

The challenge is to identify key sites in Greenland and Antarctica where ice dynamics ice coring or rapid access drilling would yield advances.

- Drill sites through ice streams to gain understanding of the flow and deformation and water movement.
- Drill sites near grounding lines would teach us about the transition zone between ice sheet and ice shelf flow.
- Drill sites near observed big structures under the ice to understand their origin at the location and their influence on deformation.
- Ice rises and similar features that have an unknown flow history and the evolution and impact of pronounced Raymond bumps on the local dynamics.
- As the formation of stratigraphic disturbances in paleo-climate motivated ice cores like ‘oldest ice projects’ is unwanted, ice dynamic studies of such cores are indispensable.

Meeting the challenge

At present a few sites have been identified where an ice dynamic core would be of great value. For all the sites discussed below – pre-studies with surface-based radio-echo sounding are crucial.

- The EGRIP site (see Figure 1) is located in the centre of the large North East Greenland Ice Stream (NEGIS) at a site where the ice thickness is 2550 m and the surface velocity is 55 m/yr. From an ice dynamic view understanding of the flow and deformation of the fast-flowing ice as well as studies of the hydrological system near the base will increase our knowledge of how ice deforms in an ice stream and the role of anisotropy here. As seen on Figure 1 the shear margins are strongly decoupled from the ice stream itself and would also be interesting to penetrate – perhaps with a rapid access drill. As a third interesting site close to EGRIP there are several basal structures, some nearly 50% of the ice thickness. A rapid access drilling though one of these structures is planned as part of the EGRIP program.

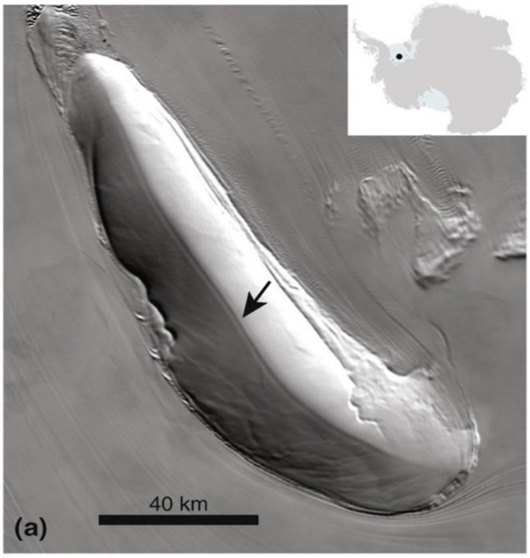

Figure 2 MODIS image of the Korff Ice Rise in the Weddell Sea Embayment. The ice thickness at the ridge is 400-450 m has a very pronounced Raymond Bump. (Figure from Matsuoka et al., Earth-Science Reviews, 2015 150, 725-745)

- The Korff Ice Rise in the Weddell Sea Embayment has been suggested as a site to drill an ice core or penetrate with a rapid access drill (Rob Mulvaney, personal communication). The ice rise might only be few thousand years old and radio-echo sounding over the rise shows a pronounced Raymond bump at the ridge (arrow on Figure 2)

- The Halvfarryggen Ice Rise has been suggested as a site to drill an ice core (Drews *et al.*, 2013), reaching back >10 ka. The ice rise exhibits a split triple junction of ice divides and a Raymond double bump. It has been characterized by various geophysical means, as most prominently airborne radar and seismic profiles, and exhibits anisotropic features (e.g. Hofstede *et al.*, Annals of Glaciology, 54(64), 2013) (refer to Figure 3).

- Other sites with basal structures that have been targeted are the structures in the Petermann ice stream system on the Greenland ice sheet where anisotropic material properties under convergent flow cause layer folding. Similar basal structures in the bedrock valleys in the Gamburtsev Mountains mountain range in Antarctica has been suggested to be formed by upwelling structures, e.g. refrozen basal water.

- Finally, as many of the existing ice cores have disturbances near the bed a more detailed study of ice and the role of anisotropy here would be valuable.

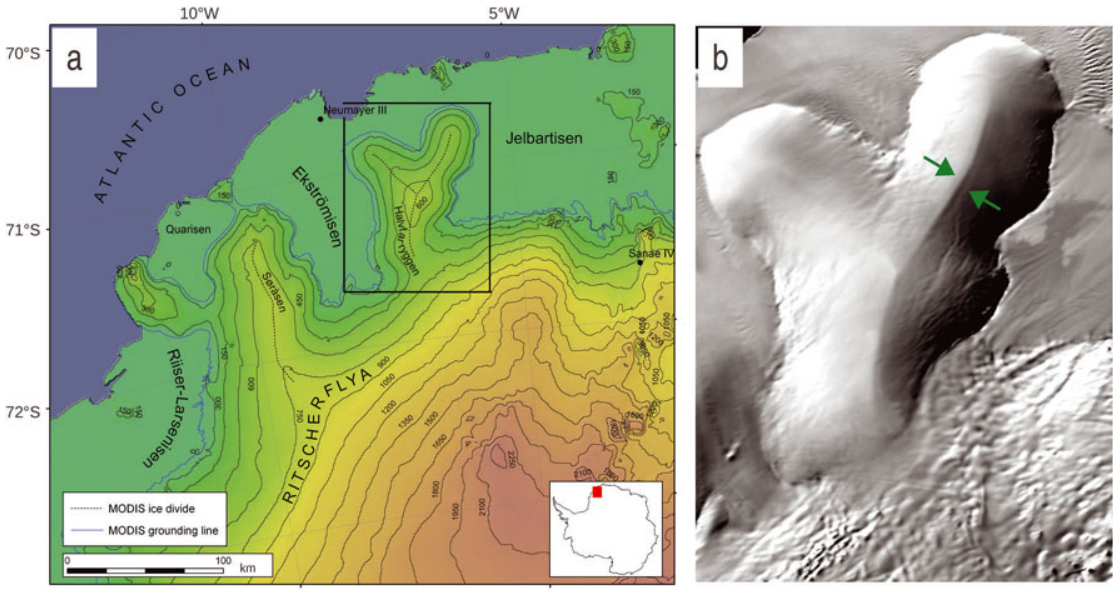

Figure 3: (a) Overview of the Halvfarryggen area (adapted from Neckel, 2010). The black box marks Halvfarryggen which is zoomed in on the right. The inset delineates the location (red box) within Antarctica. (b) MODIS image of Halvfarryggen (Scambos and others, 2002 updated 2011). The Y-shaped ice divides appear clearly and are partly accompanied by double-ridge features (green arrows). (Drews *et al.*, Journal of Glaciology, 59(213), 2013)

Methods

Ice dynamic drill sites are often located at sites, where the surface velocity if significant. This proposed a challenge in relation to placing the camp in safe areas without crevasses as well as in the applied drill technology, e.g. due to differing material properties of the ice. Both ice coring and rapid access drills are tools to consider. An ice core contains information on ice rheology and allows for development of constitutive laws for ice deformation under natural material properties and boundary conditions. Rapid access drills are developing that can inform on stable water isotopes through the study of ice chips and greenhouse gases – both climate proxies that can also inform if e.g. refrozen water exists. For both types of drills, studies of the borehole with logging tools and cameras can map the deformation of the borehole and contribute to observing the hydrological system near the bed.

The international dimension

Ice drilling projects for ice-dynamics-motivated ice cores need major logistics and are very suited as international projects. The expertise in relation to crystal orientation fabric analysis, geophysical characterization of the drill site vicinity and ice dynamics modelling would be strongly enhanced by international collaboration, enabling the complementary expertise from different groups.

The next steps and schedule

EGRIP is an ongoing project (2015-2022). With the development of rapid access drills, projects aiming towards improving the understanding of ice dynamics will ‘rapidly’ form.

International Partnerships in Ice Core Sciences (IPICS) is a group of scientists, engineers and logistics experts from the leading laboratories and national operators carrying out ice core science. At the first IPICS meeting, in Washington, DC in 2004, participants identified several high priority international scientific projects to be undertaken over the next decade or more. At the second IPICS meeting, in Brussels, Belgium, in October 2005, IPICS was placed on a more formal footing. Subsequent meetings have refined and formalised the white papers and established a quadrennial open science conference. IPICS now has an international steering committee including representatives of 23 nations, and an additional international group of drillers and engineers has been organized.

The current document is one of up to 5 describing the current IPICS science priorities; a further paper looks at some of the technical challenges and drilling needs for implementing the IPICS plans. The currently active white papers are entitled:

1. The oldest ice core: A 1.5 million year record of climate and greenhouse gases from Antarctica.

2. History and Dynamics of the Last Interglacial Period from Ice Cores.

3. Terminations and seesaws: an ice core contribution to understanding orbital and millennial scale climate change

4. The IPICS 2k Array: a network of ice core climate and climate forcing records for the last two millennia

5. Ice coring for ice dynamics

6. Ice core drilling technical challenges

For more information about IPICS or any of these projects please contact the IPICS co-chairs:

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