Assessing the History of the Greenland Ice Sheet through Ocean Drilling

Ocean Leadership & International Ocean Discovery Program, National Science Foundation, IGBP Past Global Changes Workshop Report

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Executive Summary: A workshop was convened to discuss new methodology, technologies, drilling locations and site surveying needed through which the International Ocean Discovery Program (IODP) can constrain the sensitivity of the Greenland Ice Sheet (GIS) to past climate changes, particularly during interglacial and earlier climate periods warmer than present. The impetus for this workshop directly stemmed from the IODP Science Plan for 2013-2023, where one of the major goals was to use ocean drilling to elucidate past GIS behavior. Participants included marine geologists, paleoceanographers, stratigraphers, geochemists, geophysicists, seismic surveyors, glaciologists, ice-sheet and climate modelers and those from the drilling communities that can provide information as to how best facilitate these objectives.

The participants concluded that process-oriented questions should be addressed that will inform on the GIS sensitivity to climate change. Specifically, what are the respective roles of atmospheric and oceanic forcings in controlling the extent of glaciation on Greenland? Is subsurface oceanic temperature important in predicting the behavior of the GIS? What is the role of buttressing ice shelves and sea ice? How does freshwater discharged from Greenland influence global ocean circulation? To answer these questions, three time intervals were identified. In the Miocene to Pliocene, the main goal is to document when and under what climate conditions Greenland's valley glaciers expanded and became an ice sheet. In the Pliocene, the goal is to determine the volatility of the GIS to inform on the long-term sensitivity of this ice sheet to greenhouse gas concentrations similar to or slightly higher than current levels. In the Quaternary, the goal is to examine GIS behavior relative to climate both before and after the transition from 40 to 100 kyr glacial-interglacial cycles ~1 Ma ago. This would include expansions during global glacial maxima of different magnitudes (e.g., Marine Isotope Stages, MIS, 2, 4, 6, 8, 10 and 12), and the amount of inland ice retreat during interglacial boreal summer insolation maxima of different amplitudes (e.g., MIS 1, 5e, 7, 11, 19 and 31).

Workshop discussion focused on how ocean drilling can address these questions and scientific priorities. It was concluded that an extensive effort must be put into site surveying and coring well in advance of drilling around Greenland, both to refine scientific questions via regional process studies, and to locate the best drilling targets to address specific questions. Higher resolution preglacial and subglacial topographic maps of Greenland and its margin would help inform the selection of drill sites needed to document the early phases of late Neogene glaciation and identify major catchment basins of Greenland. As a drilling strategy, records from the continental slope and rise can inform on large-scale GIS changes whereas drilling on the continental shelf and in fjords will document instability of individual glacier systems. Significant progress is being made, although continued work is needed, on proxy development to track the areal extent of the GIS and date these proxies in sediment archives. Surface and subsurface ocean temperatures should be reconstructed in concert with the GIS records because ocean warming may play an important role in triggering ice-sheet instability and driving marine ice-margin retreat, requiring near-field sea surface temperatures and more distal subsurface ocean temperature records from detailed depth transects. Sea-ice and ice-shelf records are also needed, because the GIS is sensitive to albedo/heat flux changes associated with sea-ice extent and the buttressing affect of potential ice shelves. Because of this broad spatial approach, developing drill-core chronologies that are independent of climate and correlatable between drill sites is needed for the successful reconstruction of paleo-GIS history. Ocean drilling is required around all of Greenland to document its late Neogene evolution and the sensitivity of different sectors to climate change. These activities should develop in close collaboration with the climate-ice sheet modeling community to create data-driven models, readily test hypotheses, and provide ice sheet-climate targets to the modeling community.

1. Introduction

The response of the remaining ice sheets to global warming represents the greatest uncertainty in predicting future sea-level rise, with complete deglaciation of the Greenland Ice Sheet (GIS) estimated to raise global sea level by ~7.3 m (Meehl et al., 2007). Recent glaciological studies have discovered an acceleration in GIS mass loss (e.g., Alley et al., 2005; Shepherd & Wingham, 2007; Rignot et al., 2011), and during the late 1990's and early 2000's, GIS outlet glacier velocity increased with attendant thinning (Rignot & Kanagaratnam, 2006; Howat et al., 2007; Pritchard et al., 2009; Howat & Eddy, 2011; Thomas et al., 2011). Highlighting the need to better understand the interaction between GIS margins and ocean water temperature (Schoof, 2007; Alley et al., 2008; 2010; Nick et al., 2009; Motyka et al., 2011), the outlet glacier acceleration and retreat was concurrent with the incursion of warm Irminger Current waters around southeast to central west Greenland, which penetrated up fjords to marine-terminating ice margins (Holland et al., 2008; Murray et al., 2010; Rignot et al., 2010; Straneo et al., 2010; 2011; Mortensen et al., 2011). Recently, a large piece of the outer ice shelf of the Petermann Gletscher, the largest, coldest, and presumably most stable "end member" of the remaining ice shelves, disintegrated in 2010 (Falkner et al., 2011). It is still unknown if such events are part of natural variability or can be linked to recent warming, which raises questions about the relative importance of natural and anthropogenic forcings on current GIS behavior.

Observations of GIS mass changes, outlet-glacier velocity and fjord-water temperature are, however, restricted to only the past few decades. Alternative methods for understanding ice-sheet behavior are thus required like the use of the geologic history of GIS behavior during past deglaciations and interglaciations as a direct record of ice-sheet response to a wider range of climate change (Fig. 1) than has occurred in the last decades. The extent and behavior of the GIS during the Pliocene and Miocene, when CO_2 was at present day levels and higher (Raymo et al., 2009; Tripati et al., 2009; Pagani et al., 2010), will also provide indispensible information on future GIS stability (Fig. 1). Extending the GIS record beyond the last deglaciation (~21-6 ka) requires the use of marine archives because ice cover during the last glaciation has removed most of the terrestrial record of earlier GIS behavior and extent. Thus there is a key need to develop and utilize marine proxies of GIS behavior that will discern its response to varying degrees of natural forcing.

To begin to tackle this undertaking, a workshop on assessing the history of the GIS through ocean drilling was convened Nov. 7-9, 2011 in Corvallis, OR on the Oregon State University campus. The primary goal was to develop a framework to coordinate future ocean-drilling experiments that will document and constrain the sensitivity of the GIS to climate warming. The following questions provided the overarching motivations for this workshop. ***How has the GIS varied in extent/volume prior to the last deglaciation (>21 ka)? What were the dominant forcings of past major changes in the GIS? How do we obtain this information?*** Discussion focused on potential marine archives, drilling targets, geologic proxies of GIS behavior, relevant past climate conditions, and methods for dating such records, along with approaches to integrate paleo-modeling with paleo-data. The workshop established an international community of scientists that plans to assess the past behavior of the GIS from a marine perspective. Participants reflected a range of disciplines, including climate and ice-sheet modelers, glaciologists, glacial geologists, sedimentologists, organic and inorganic geochemists, geophysicists, paleomagnetists, paleoceanographers, and paleobiologists. Participants also included members of the Antarctic research community in addition to Greenlandic researchers. Unfortunately, members of the Geological Survey of Denmark and Greenland and invited Danish scientists were unable to attend. Therefore this workshop served as a starting point for international collaborations with additional targeted workshops and scientific proposals as the next set of deliverables.

To continue the development of a Greenland IODP community, the workshop conveners initiated a website[1] with an on-line chat room[2] for further discussion of ideas and advancement of drilling plans and proposals. The conveners and steering committee will propose a new IGBP Past Global Changes (PAGES) working group called *DEGREE* (*DEglaciated GREEnland*) to facilitate future communication to further planning for coordinated implementation of field and model studies. The DEGREE working group plans to develop several proposals for IODP expeditions that will focus on Greenland paleo-history and process.

2. Principal Findings and Recommendations

The group concluded that ***process oriented topics*** could be addressed through ocean drilling, including, but not limited to the following questions.

- What are the respective roles of atmospheric and oceanic forcings in controlling the extent of glaciation on Greenland?
- Is subsurface oceanic temperature important in predicting the behavior of the GIS?
- What is the role of buttressing ice shelves and sea ice?
- How does freshwater discharged from Greenland influence global ocean circulation?

Participants noted several key time intervals spanning the history of the GIS that provide attractive targets for addressing these questions.

- It remains unclear when and how Greenland's valley glaciers expanded and became an ice sheet; documentation of the pre-glacial climate state and transition to glaciation will shed light on this issue.
- Analysis of the volatility of the GIS during the Pliocene would provide information on long-term sensitivity of this ice sheet to greenhouse gas concentrations similar to or slightly higher than current levels.
- The Quaternary Period offers several useful targets, such as GIS behavior during the transition from 40- to 100-kyr glacial-interglacial cycles ~1 Ma ago, potential variations in the relative timing and extent of an expanded GIS on the continental shelf during global glacial maxima of different amplitudes such as Marine Isotope Stages (MIS) 2, 4, 6, 8, 10 and 12, and the amount of ice retreat inland during interglacial boreal summer insolation maxima of different amplitudes (e.g., MIS 1, 5e, 7, 11, 19 and 31).

These targets fall directly in line with *Challenges 1 and 2* of the *2013-2023 International Ocean Discovery Program* theme on *Climate and Ocean Change*[3]. The evolution of the GIS through the Pliocene addresses IODP Challenge 1:

"How does Earth's climate system respond to elevated levels of atmospheric CO_2?"

Establishing the GIS response to Pliocene climate variability, and Quaternary deglaciations and interglaciations addresses IODP Challenge 2:

"*How do ice sheets and sea level respond to a warming climate?"*

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[1] http://geoscience.wisc.edu/degree
[2] http://geoscience.wisc.edu/degreetalk
[3] http://www.iodp.org/Science-Plan-for-2013-2023/

These targets also address Research Interest 3 of the *Paleo-Perspectives on Climate Change (P2C2)* program of the *U.S. National Science Foundation*[4] *(NSF)*:

> *"How sensitive was ice (i.e., sheets, caps, mountain glaciers) and sea level to rapid changes in climate especially during past warm climates?"*

In addition, the proposed targets address other NSF research initiatives to understand ocean/ice-shelf/ice-sheet interactions[5].

The following action items will begin to address the process-based questions to be answered through ocean drilling.

1) An extensive effort must be put into site surveying and coring well in advance of drilling around Greenland, both to refine scientific questions via regional process studies, and to locate the best drilling targets. Survey strategies include shallow and deep penetration seismic profiles of sufficient resolution to image sedimentary processes, multibeam bathymetric and backscatter mapping, and regional studies based on new sediment cores. Although some of the discussed drilling sites have some existing survey data, most will need a more targeted surveying effort. Cores should test the utility of proxy records in reconstructing GIS behavior and be selected for modern process studies.
2) A higher resolution preglacial topographic map of Greenland will help identify major catchment basins of Greenland, aiding in the selection of drilling sites that will record the early phases of late Neogene glaciation. Some constraint on the Greenland topographic changes during the late Neogene also would assist in assessing the ice-sheet's long-term sensitivity to climate change.
3) Large-scale GIS changes can be addressed by continental slope and rise drilling, which can better inform ice-sheet models.
4) Instability of individual glacier systems can be addressed through focused study of outlet glaciers, in troughs on the continental shelf, and in active fjord systems with marine terminating or shelf-buttressed glaciers that connect to the inland ice, which can inform higher-order but smaller-scale ice-sheet models.
5) Surface and subsurface ocean temperatures should be reconstructed in concert with the past history of the GIS because ocean warming may play an important role in triggering ice-sheet instability and driving marine ice-margin retreat. This will require reconstructing near-field sea surface temperatures and looking further afield to reconstruct subsurface ocean temperatures with detailed depth transects.
6) Improvements in sea-ice and ice-shelf proxies are needed, because the GIS is sensitive to albedo/heat flux changes associated with sea-ice extent and the buttressing effect of potential ice shelves. Opportunities exist for process studies under ice shelves, or in open water adjacent to recently retreating ice shelves, that will refine our understanding of sedimentary signatures of ice-shelf behavior in the past.
7) Ultimately, ocean drilling is required around all of Greenland to document its late Neogene evolution, the sensitivity of different sectors to climate change, and the related spatial pattern in ocean temperature change. Given the technical challenges of drilling in hostile environments, we envision a coordinated strategy that capitalizes on both traditional IODP drilling (*JOIDES Resolution*) and a variety of alternate platforms operating from icebreakers or through ice shelf or sea ice.

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[4] http://www.nsf.gov/pubs/2010/nsf10574/nsf10574.htm
[5] http://www-po.coas.oregonstate.edu/research/polar/ocean-ice-workshop/

8) Ocean-drilling projects should develop in close collaboration with the climate-ice sheet modeling community so that data driven models can be constructed, hypotheses can be readily tested, and ice sheet-climate targets provided to the modeling community.

Workshop participants highlighted the need for detailed site surveying and coring in advance of drilling. Surveying based on regional bathymetric mapping, subsurface seismic reflection profiling, and process studies on shorter cores will refine scientific questions, establish the viability of proxy approaches, and identify the most appropriate sites for drilling. Many of the geographic areas of interest have never been mapped, much of the older analog seismic reflection data is either of poor quality or was designed for low-resolution deep-penetration studies of crustal structure, not appropriate for understanding the details of sedimentary processes. New geophysical tools for high-resolution multichannel seismic reflection, and modern digital data processing will advance understanding of regional sedimentation, which will make drilling much more cost effective. Many cores available in established repositories are short, or in bad condition, or have been consumed or otherwise compromised. New coring technologies offer the potential to probe the system around Greenland with greater spatial resolution than can be done with drilling alone. ***The workshop considered a coordinated and comprehensive strategy for studying the Greenland system that uses all of these tools.***

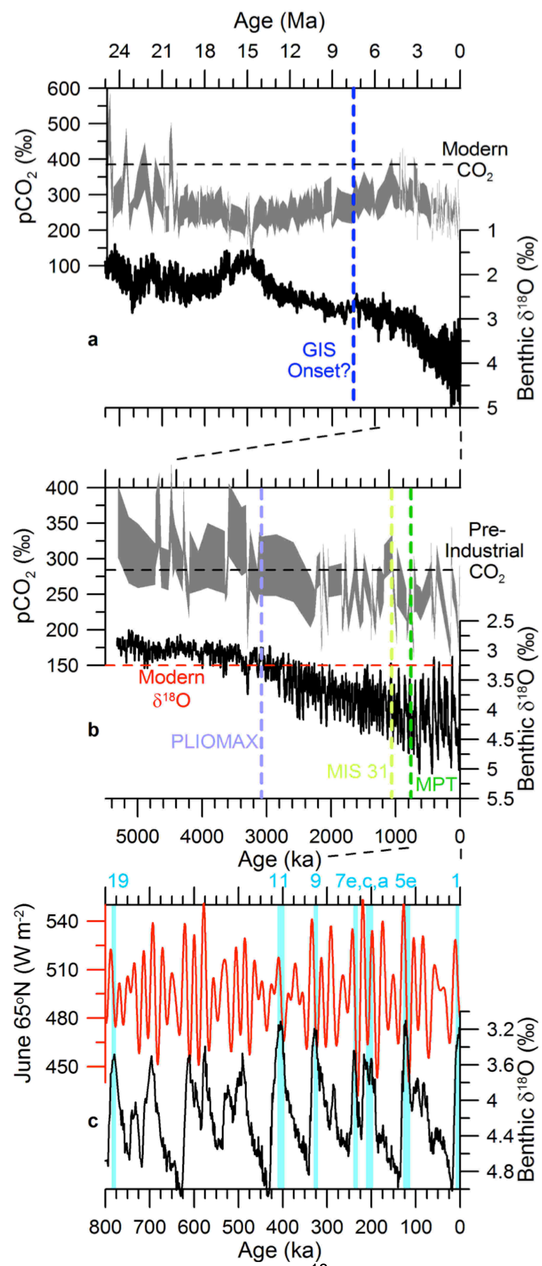

Fig. 1. CO_2 and benthic $\delta^{18}O$ for the Miocene (**a**) and Pliocene (**b**) to present and boreal summer inolation and $\delta^{18}O$ for the last 800 ka (**c**) (Pearson & Palmer 2000; Zachos et al., 2001; Laskar et al., 2004; Lisiecki & Raymo, 2005; Pagani et al., 2005; 2010; Hönisch et al., 2009; Tripati et al., 2009). Important climate intervals and MIS's labeled (see text for description).

3. Motivation

3.1. Climate Targets

The most-recent climate interval with a significantly smaller-than-present GIS was the last interglaciation (MIS 5e, ~128-116 ka; Fig. 1c; Shackleton et al., 2003) when Arctic summer temperatures were on average warmer than the Holocene and global sea level was >4 m above modern (CAPE Project Members, 2006; Overpeck et al., 2006; Kopp et al., 2009). Although ice core data suggest a smaller GIS during this interval, the same $\delta^{18}O$ data can be interpreted in contrasting manners, indicating almost compete deglaciation of south Greenland (Koerner, 1989; Koerner & Fisher, 2002; Otto-Bliesner et al., 2006) or the persistence of a significant south GIS (NGRIP, 2004; Oerlemans et al., 2006; Willerslev et al., 2007). Ice-sheet models simulate a smaller GIS but range in volume reduction from <1.6 m to >5.5 m of equivalent sea-level rise (Fig. 2), thus explaining only a fraction to almost all of the MIS 5e sea-level highstand (Cuffey & Marshall, 2000; Tarasov & Peltier, 2003; Lhomme et al., 2005; Otto-Bliesner et al., 2006; Robinson et al., 2011). Pollen and fern-spore records from ODP Site 646 and HU90-013-013 on Eirik Drift south of Greenland suggest more vegetation on south Greenland during MIS 5e but do not constrain the actual ice-margin extent (Hillaire-Marcel et al., 2001; de Vernal & Hillaire-Marcel, 2008). Eirik Drift bulk magnetic grain-size and terriginous element concentration (i.e., Ti and Fe) indicate a longer interval of elevated GIS runoff and ice retreat relative to the Holocene but likewise do not directly provide information on the actual degree of ice retreat (Stoner et al., 1995; Carlson et al., 2008). However, new Eirik Drift silt grain size Sr-Nd-Pb isotope records indicate that although the south GIS retreated a greater distance than during the Holocene, no single south Greenland terrane was completely deglaciated (Colville et al., 2011), in agreement with some ice-sheet model simulations (Fig. 2) and ice core record interpretations (NGRIP, 2004; Oerlemans et al., 2006; Willerslev et al., 2007).

The impact GIS runoff had on ocean circulation and climate during MIS 5e is also unresolved. One coupled climate model simulates that Greenland runoff had minimal impact on circulation, leading to a warmer-than-present boreal MIS 5e (Otto-Bliesner et al., 2006; McKay et al., 2011). Other climate models simulate at least regional cooling and reduced convection around south Greenland during MIS 5e (Govin et al., 2012; Sanchez-Goni et al., in press). Paleoceanographic studies based on dinoflagellate cysts and δ^{18}O records suggest surface waters warmer-than-present in the Labrador Sea, with a more stratified water column and the absence of deepwater formation during MIS 5e (Hillaire-Marcel et al., 2001; 2011). Given that this climate interval is an important target for climate models in the third Paleoclimate Modelling Intercomparison Project (PMIP)[6] and is the most recent period for assessing cryospheric responses to a warmer-than-present boreal summer, it is critical to precisely constrain the GIS extent and its regional climate, for which ocean drilling can provide an essential component. These and other types of proxies hold the potential to reconstruct GIS variability at other locations and directly extend its history back to the inception of the GIS, which will require greater spatial coverage of long marine records.

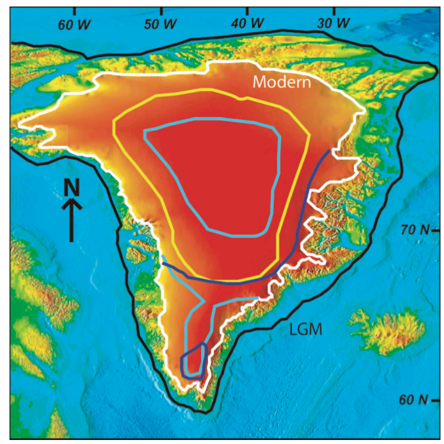

Fig. 2. MIS 5e GIS extents from the same ice-sheet model but different climate forcing schemes. Light blue are two extents of Cuffey & Marshall (2000) with only a remnant ice dome in central Greenland or significant ice persisting in south Greenland. Dark blue shows the maximum retreat modeled by Otto-Bliesner et al. (2006) with only a small ice dome persisting in south Greenland; a second simulation of theirs modeled an extent similar to the minimum retreat of Cuffey & Marshall (2000). Yellow denotes the minimum retreat predicted by Lhomme et al. (2005), with south Greenland completely deglaciated.

Older interglaciations also provide compelling targets for assessing the GIS response to various levels of radiative forcing. MIS 7 experienced the largest variations in precession of the last 450 ka due to a peak in eccentricity (Fig. 1c). However, sea level during MIS 7 may have been below present (Waelbroeck et al., 2002; Siddall et al., 2003; Bintanja et al., 2005; Thompson & Goldstein, 2005; Dutton et al., 2009), implying the persistence of other Northern Hemisphere ice sheets through this interglaciation (Ruddiman & McIntyre, 1982). MIS 7 will test if the south GIS retreated within its present extent due to a larger increase in boreal

[6] http://pmip3.lsce.ipsl.fr/

summer insolation than during MIS 5e, while other Northern Hemisphere ice sheets were too large to deglaciate before the next decrease in precession (Ruddiman & McIntyre, 1982).

In contrast, MIS 11 was during the last minimum in eccentricity (Fig. 1c). MIS 11 relative sea-level data range from 0 to +20 m (Hearty et al., 1999; Poore & Dowsett, 2001; Bowen et al., 2010; Rohling et al., 2010), recording a eustatic sea-level high stand of 6-13 m after accounting for glacio-isostatic effects (Raymo & Mitrovica, 2012). Pollen records from ODP Site 646 on Eirik Drift suggest the growth of *Picea* forests on south Greenland during MIS 11 (deVernal & Hillaire-Marcel, 2008), which agrees with DNA analyses of the basal ice in the Dye 3 ice core of the south GIS (Willerslev et al., 2007) and suggests deglaciation of south Greenland. Ice-rafted debris (IRD) also ceased to be deposited in the Labrador Sea during MIS 11, consistent with a deglaciated south Greenland (Hillaire-Marcel et al., 2011). These limited observations need to be further constrained as does the climate evolution around Greenland because this interglaciation is beyond identification in Summit Greenland ice cores (Bender et al., 2011).

Another interglaciation of interest is MIS 19, which has been touted as the closest analogue to the Holocene (Fig. 1c) (Loutre & Berger, 2000; Tzedakis et al., 2012). Because the Matuyama to Brunhes (Channell & Kleiven, 2000) polarity reversal occurs in MIS 19, the stratigraphy of this interglaciation could potentially be well dissected. Eirik Drift pollen records resemble Holocene records for this period (de Vernal & Hillaire-Marcel, 2008), in agreement with this comparison. MIS 31 is significant because of the proposed complete deglaciation of the West Antarctic Ice Sheet with warmer than present waters around Antarctica (Scherer et al., 2008; Pollard & DeConto, 2009). Whether or not the GIS disappeared during MIS 31 would provide important insight into polar interglacial connections. A polarity transition (lower Jaramillo) also occured during MIS 31, again offering expanded stratigraphic potential necessary for detailed examination. Determining the extent and volatility of the GIS during older Pleistocene glacial-interglacial cycles before the mid-Pleistocene transition (MPT) in the "40-kyr world" (Fig. 1b) would improve understanding of cryospheric evolution across the Quaternary.

The intervening glacial states are important for the paleo-histories of both the GIS and the Laurentide Ice Sheet. One key outstanding question is the extent, if any, of a large ice shelf in Baffin Bay and across the Labrador Sea. Ice shelves around Antarctica provide a powerful buttressing force and are responsible for the existence of the West Antarctic Ice Sheet. Did such an ice shelf cover Baffin Bay, allowing the build up of a large Foxe Dome of the Laurentide Ice Sheet and support an Innuitian Ice Sheet (England, 1999; England et al., 2006; Zreda et al., 1999; Dyke et al., 2002)? An ice shelf over Baffin Bay and into the Labrador Sea would also protect the west GIS from northward incursions of warm Atlantic waters (e.g., Knutz et al., 2011) and potentially delay deglaciation until the shelf had collapsed. An ice shelf that extended southwards into the Labrador Sea could potentially control the binge-purge cycle of the Laurentide Ice Sheet that gave rise to Heinrich Events (Hulbe et al., 2004; Marcott et al., 2011). Heinrich Events are notably absent from the glacial periods older than ~640 ka, implying that either Laurentide dynamics in Hudson Strait changed around the end of the MPT (Hodell et al., 2008) or maybe a large ice shelf only existed in the Labrador Sea in the late Quaternary.

In addition to the Pleistocene glacial-interglacial cycle, the extent and variability of the GIS during the preceding Pliocene (PLIOMAX) and Miocene provide important information on the volatility of this ice sheet during intervals of present and future atmospheric CO_2 concentrations[7] (Fig. 1a & b) (Lunt et al., 2010; Raymo et al., 2009; Pagani et al., 2010; Lawrence et al., 2010). Mid-Pliocene sea-level estimates range from +5 to +40 m with potential fluctuations of 10-30 m (Raymo et al., 2009; 2011). The subsequent Quaternary ice ages have heavily over-printed many of these relative sea-level records and the actual eustatic high stand remains unknown

[7] http://geology.er.usgs.gov/eespteam/prism/prism_pliomip.html

(Raymo et al., 2011). This raises questions of whether Greenland was ice-free during this period and when did Greenland valley glaciers coalesce into the GIS (Lunt et al., 2008; Dolan et al., 2011). Unfortunately, such records currently do not exist. The only firm geologic constraints are in ODP Site 918 off of southeast Greenland that documented the onset of a marine terminating ice cap on Greenland in the late Miocene at ~7 Ma (Larsen et al., 1994), and ODP Site 987 in the Scoresby Sund Fan that dates debris flows in the fan back to ~5 Ma (Channell et al., 1999). However, IRD with glacial striations are found in late-Eocene sediments from ODP Site 913, suggesting valley glaciers somewhere in the vicinity of the Greenland-Norwegian Seas (Eldrett et al., 2007). Pollen concentrations from ODP Sites 645 in Baffin Bay and 646 on Eirik Drift show significant decreases in pollen at the former Pliocene-Pleistocene boundary ~1.8 Ma, with 646 suggesting that the decline may have started in the mid Pliocene potentially reflecting the development of a larger GIS (de Vernal & Mudie, 1989a;b).

3.2. Past Ocean Drilling

Five ODP Legs and two IODP Expeditions have drilled in the vicinity of Greenland (see Fig. 3 in section 5.5). ODP Leg 105 Site 646 is located on Eirik Drift, supplying the continuous records of planktonic $\delta^{18}O$ and pollen back to ~960 ka (de Vernal & Mudie, 1989b; de Vernal & Hillaire-Marcel, 2008). Site 645 in Baffin Bay has a pollen record extending back to the early Quaternary (de Vernal & Mudie, 1989a). ODP Leg 151 collected from Site 913 on the northeast Greenland margin that extends back to the Eocene (Eldrett et al., 2007), but foraminifera preservation is poor (Spiegler, 1996), core recovery is poor for late Neogene and Quaternary sediments, and the core is far removed from Greenland. Sites 907 and 909-911 are even further removed from the Greenland margin. They archive sediment from the Iceland Plateau back to the middle Miocene and from Fram Strait back to the Pliocene, respectively (Koç & Scherer, 1996; Spiegler, 1996). ODP Leg 152 collected from Sites 914-919 off of southeast Greenland but focused on recovering crustal rocks rather than Cenozoic sediment. Sites 914-917 sampled a progradational wedge, establishing the presence of the GIS in the Miocene ~7 Ma (Larsen et al., 1994). Site 918 recovered sediment back to the early Quaternary ~2.2 Ma (Fukuma, 1998), with poor recovery back to the Oligocene, documenting the onset of IRD deposition at ~11 Ma (Helland & Holmes, 1997). Nearby Site 919 extends to ~1 Ma based on magnetic stratigraphy (Fukuma, 1998), with a high-resolution relative paleointensity record extending back 500 ka (Channell, 2006). Site 919 has a low-resolution planktonic $\delta^{18}O$ record back to ~900 ka (Flower, 1998). ODP Leg 162 Site 987 is located off east Greenland close to Scoresby Sund, extending back ~7.5 Ma (Jansen et al., 1996). Glacial debris flows were mainly recovered with magnetic stratigraphy providing a well-constrained age model (Jansen et al., 1996; Channell et al., 1999). ODP Leg 163 revisited the region of Leg 152, but focused drilling on plate rifting rather than Cenozoic sediments. IODP Expedition 302 (ACEX) in the central Arctic documented a large influx of coarse-grained sediment at ~3.2 Ma. This event could mark the expansion of the GIS (Moran et al., 2006), but the location is relatively far removed from north Greenland (Backman et al., 2006). IODP Expedition 303 drilled three sites off south Greenland on Eirik Drift; two of which extend to the late Pliocene (Channell et al., 2006).

Despite these numerous expeditions around Greenland, only two locations have records monitoring GIS behavior (ODP Leg 105 and IODP Expedition 303 from the Eirik Drift, and ODP Leg 152 from southeast Greenland), leaving large regions of Greenland unconstrained beyond the last deglaciation. Furthermore, only one core from these two regions extends beyond the late Pliocene (Site 918) (Larsen et al., 1994), leaving much of the Pliocene and Miocene as of yet un-sampled. More extensive expeditions sampling multiple locations around Greenland with the deep drilling capabilities of IODP (*JOIDES Resolution* and Mission Specific Platforms) are clearly required to determine the GIS long-term history.

3.3. Chronology

Chronological advances are improving our ability to date and correlate marine records, particularly in regions such as the seas around Greenland where foraminifera for bio- and chemo-stratigraphy are rare. Paleomagnetic methods are the most obvious tool as they often work well in ice-proximal locations; augmenting, refining and in some cases even replacing standard $\delta^{18}O$ and other stratigraphic and absolute dating method less suitable for the environment (Stoner et al., 1998; 2000; Channell et al., 1999; 2012; Evans et al., 2007). Several paleomagnetic methods now improve upon the well-known geomagnetic polarity time scale (Cande & Kent, 1995). Relative geomagnetic paleointensity is now tightly coupled to the marine $\delta^{18}O$ record back to ~1.5 Ma (Channell et al., 2009), providing suborbital chronological control under optimal conditions. Recent advances in paleomagnetic secular variation (Stoner et al., 2007) and our understanding of the magnetic acquisition process (Strano et al., 2010) could allow sub-millennial stratigraphies to be developed over limited time intervals.

The development of a new generation of downhole magnetic logging tools including the Magnetic Susceptibility Sonde and Multisensor Magnetometer Module allows for the *in situ* collection of environmental and polarity magnetic stratigraphies in glacial proximal areas where core recovery is poor. This opens a new window of opportunity through which drilling can help assess the history of the GIS by dating lithologies that are hard to recover, but still provide critical information on glacial histories (e.g., trough-mouth fans).

4. Strategies for Addressing Greenland's Paleo-History

Given its significance for future sea-level rise, our current knowledge of the history of the GIS is inadequate. Proxies, chronologic methods and drilling technology are now capable of documenting the paleo-history of the GIS and its surrounding climate from the Miocene to present; here we outline strategies for their implementation.

4.1. Reconstructing the Greenland Ice Sheet

Marine records are proving to be a promising means of reconstructing the past fluctuations of the GIS beyond the last glacial maximum. Sr-Nd-Pb isotopes of the silt-size fraction can record the provenance of silt discharged from the GIS to the ocean (Colville et al., 2011). This is possible because Greenland's terranes have distinct ages and crustal evolutions that are largely mirrored in the Sr-Nd-Pb isotope composition of suspended sediment in meltwater streams draining the ice sheet. Ocean currents transport this suspended sediment to marine drifts around Greenland, with the fraction of sediment sourced from each terrane determinable by simple mixing calculations. The absence of sediment sourced from a given terrane therefore indicates that terrane to be ice-free, allowing the tracking of ice presence/absence on portions of Greenland. In addition to *in situ* measurements, Pb isotopes of the dissolved load are also a useful tool for documenting past weathering intensity on Greenland. Up to half of the dissolved Pb flux in Greenland streams could be derived from weathering of exposed rock/sediment relative to subglacially discharged Pb. Pb concentration increases down stream from glaciers, potentially providing an additional proxy for relative GIS extent.

Another proxy is the ^{10}Be concentration in sediment discharged from Greenland that could track the area exposed by GIS retreat within its present margin or the amount of time ice remained at a smaller than present extent[8]. ^{10}Be accumulates during ice-free periods and pulses to the ocean upon ice advance, with sand-size sediment providing an integrated signal. With the use of different sites around Greenland, a more variable ^{10}Be signal in the ocean could indicate greater ice variability on land. Conundrums, however, include whether the signal shows greater

[8] http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1023191

exposure of bedrock/sediment from ice retreat or a longer ice-free period, the ability of sand to be transported to the deep ocean without the assistance of icebergs that requires a marine-terminating margin, and whether such a signal would be measurable in marine sediments.

Similar to radiogenic isotopes, Greenlandic silt has a different magnetic signature than silt derived from Icelandic basalt and thus silt records of magnetic susceptibility could identify past periods of elevated GIS discharge. Magnetic minerals show strong differences and particle size dependence between Icelandic and Greenlandic sources, which allows the reconstruction of terrestrial end-members for sediments in ocean cores (Hatfield et al., 2011). With these end-members, the GIS sediment contribution to drift sites can be reconstructed across glacial terminations and interglaciations. Preliminary application to the Eirik Drift finds elevated MIS 5e Greenlandic signatures relative to the Holocene in agreement with the Sr-Nd-Pb isotope record suggesting prolonged retreat but ice persistence on south Greenland (Hatfield et al., 2011).

The more traditional IRD ice-sheet proxy is useful for documenting the presence/absence of marine-terminating GIS margins (e.g., Bauch et al., 1999; Oppo et al., 2006; Hillaire-Marcel et al., 2011). Mineral-specific radiogenic isotopes (Sr, Nd, Pb) can potentially trace the source of IRD to a given Greenland geologic terrane, narrowing the possible locations of a given GIS marine margin (Bailey et al., 2011). Likewise, reworked palynomorphs may identify the source(s) of IRD in Baffin Bay (de Vernal & Mudie, 1989a). Biomarkers unique to oil shale could provide a new tracer of IRD, whereas ice-sheet fan-specific biomarkers could potentially allow the tracking of icebergs from individual outlet glaciers.

4.2. Reconstructing Paleoclimate around Greenland

Traditional assemblages of foraminifera and dinoflagellate cysts hold underutilized potential for tracking the migration of water masses and thus reconstruction of gyre circulation around Greenland. Benthic foraminifera have proven to be a reliable tracker of the presence of warm intermediate Atlantic waters around south Greenland, which could play an important role in governing marine GIS margins (Jennings et al., 2002; 2006; 2011; Seidenkrantz et al., 2007). Dinoflagellate cysts can also identify the presence of warm Atlantic surface waters (e.g., de Vernal & Hillaire-Marcel, 2008; Van Nieuwenhove et al., 2011). Diatom abundance may also be a useful paleoclimatic-chronologic tool at least in subpolar regions (Koç et al., 1999).

Combining foraminiferal assemblage and planktonic $\delta^{18}O$ records with pollen and spore records in the same core allows direct comparison of ocean-terrestrial climate change without the need for well-developed chronologies, especially beyond the ability of radiocarbon. Eirik Drift pollen records detail the extent/concentration/speciation of flora on Greenland for the last million years (de Vernal & Hillaire-Marcel, 2008). Applying this assemblage/$\delta^{18}O$ approach to other regions of Greenland could identify which portions of the GIS are more climatically sensitive. Pollen can also be far-transported by wind in addition to riverine-marine transport but wind transport near Greenland has yet to be shown as a major influence on marine sediment records.

Advances in Mg/Ca paleothermometry on foraminifera tests (Klinkhammer et al., 2004) hold the potential for the measurement of calcification temperatures down to -1°C, which will allow the reconstruction of subsurface and bottom water temperatures around Greenland (Nürnberg et al., 1996; Mashiotta et al., 1999; Winsor et al., 2009; Obbink et al., 2010; Marcott et al., 2011), and complement inferences of water mass conditions from cyst and foraminifera assemblages (Bauch et al., 1999; Hillaire-Marcel et al., 2001; Jennings et al., 2006; 2011; de Vernal & Hillaire-Marcel, 2008). The use of flow-through time-resolved analysis and a temperature calibration specific to the cold waters of this region can overcome potential complications from diagenesis, reduced sensitivity to temperature changes in colder waters, and the influence of salinity on Mg/Ca. The concurrent measurement of $\delta^{18}O$ on the same tests allows for the isolation of seawater $\delta^{18}O$ (Shackleton, 1974; Wu & Hillaire-Marcel, 1994; Jonkers et al., 2010), which is a proxy for salinity (LeGrande & Schmidt, 2006).

Biomarker proxies can track past climate, icebergs and sea ice around Greenland. They do not break down during early diagenesis and thus are a useful tool in harsh environments like around Greenland. Although transport from other regions to a given drill site can be a problem for reconstructing local climate, this also provides an innovative tool for tracking past ocean surface currents (Knutz et al., 2011). Alkenones can reconstruct temperature down to ~6°C. Archea and associated TEX_{86} temperature proxy could provide temperature records down to freezing. Also of import, the IP_{25} proxy tracks the location of sea-ice margins, which may help determine the presence/absence of sea ice in Baffin Bay and the Labrador Sea.

4.3. Dating Records from near Greenland

The traditional chemo-stratigraphic tool of $\delta^{18}O$ has proven useful for constructing age models around south Greenland beyond the capabilities of ^{14}C (Hillaire-Marcel et al., 2011). However, benthic foraminifera are rare in many sites near Greenland due to high sedimentation rates and planktonic foraminifera test $\delta^{18}O$ can have large overprints of temperature and meltwater, complicating correlations between cores and MIS identification. $\delta^{13}C$ is a complimentary chemo-stratigraphic tool and shows reproducible orbital-scale variations between cores from different Arctic regions (Hillaire-Marcel et al., 1994, 2011).

In addition to these chemo-stratigraphic methods, paleomagnetic relative paleointensity (RPI) now supplements magnetic polarity stratigraphy, allowing correlation of marine records within a basin at millennial resolution (Stoner et al., 1998) and globally at a suborbital scale (Channell et al., 2000; 2009; Stoner et al., 2000; 2003). The recent global PISO RPI and $\delta^{18}O$ stack now provides a template for age-model reconstruction back to 1.5 Ma. RPI allows for age-model construction where foraminifera are rare to absent or heavily influenced by other climate factors than global ice volume (Channell et al., 2009). In Arctic cores that have undergone some diagenetic transformation of their magnetic phase (Xuan & Channell, 2010), an interpretable signal may still be preserved in magnetic grain size parameters that mimic the global benthic $\delta^{18}O$ back to at least MIS 6 (Xuan et al., 2012). A combination of the chemo- and RPI-stratigraphic approaches allows the construction of more precise age models than can be achieved independently. For instance, their co-use on Eirik Drift (Stoner et al., 1998; Evans et al., 2007) and Site 919 in the Irminger Basin (Channell, 2006) has identified changes in sedimentation rates on sub-orbital time-scales.

In regions with significant detrital inputs, core recovery can be discontinuous complicating the use of these stratigraphic methods. However, new down-hole logging tools allow for collection of critical sedimentological and magnetic polarity information without the need for physical sediment recovery. Ideally, the down-hole logging tools should be applied in a dedicated logging hole that can inform further drilling in the region, though a strategy where logging supplements intervals of poor core recovery is likely to be most productive.

4.4. Modeling the Greenland Ice Sheet

Ice-sheet modeling will be an important component for studying the paleo-GIS to test atmospheric and oceanic controls on ice-sheet fluctuations, and simulate the development of instabilities in the GIS. Ice-sheet instability from the crossing of tipping points occurs when an ice sheet transitions from one stable state to another. This is not a transient response to a forcing but rather an irreversible change to a new stable state upon crossing of a bifurcation point, which may be difficult to predict due to seasonal variability in ice-sheet velocity. Ice-sheet models can now contain higher resolution nested regions that can resolve high-resolution ocean-ice interactions (Condron & Winsor, 2011), which are a key component to triggering rapid ice-sheet retreat. To properly simulate past ice-sheet behavior, surface and subsurface ocean temperatures are a critical component (Pollard & DeConto, 2009) as is knowledge of the subglacial and preglacial topography, the latter necessary for long-term modeling of the GIS. Regional climate models can capture this diverse terrain and simulate precipitation patterns driven by the Icelandic Low and the Westerlies off of Baffin Bay and the Labrador Sea, also necessary for accurate paleo-GIS modeling (Seth et al., in review). In addition, knowledge of past sea-ice and ice-shelf extents is needed to properly simulate GIS extent (Koenig et al., in review). Although developing rapidly, in their current state such models are heavily parameterized, and will benefit from regional paleo-data to constrain their behavior.

5. Implementation Strategies

The following regions are necessary drilling targets for future IODP expeditions to assess the long-term history of the GIS. *Their selection was based on limited knowledge of the preglacial Greenland landscape and the potential for these drilling sites to provide records that would address the targeted climate intervals and process-based questions*.

5.1. Time Intervals of Interest

The following time intervals should be targeted and will help in addressing the process-oriented questions related to the history of the GIS and its (in)stability.

1. Establish the climate state during the Miocene before a GIS existed (there may have been small valley glaciers on Greenland as early as the Eocene).
2. Establish when and to what aerial extent valley glaciers coalesced to form the GIS in the late Neogene.
3. Document the volatility of the GIS (if in existence) during the Pliocene when atmospheric CO_2 concentrations were close to present concentrations.
4. Record the timing and pattern of GIS advance and retreat relative to global glacial events during the Quaternary, noting glacial periods when the GIS reached its maximum extent at the continental shelf break (e.g., MIS 2, 4, 6, 8, 10 and 12) and any potential change during the transition from the 40- to 100-kyr glacial-interglacial world.
5. Identify if ice shelves existed over Baffin Bay and possibly the Labrador Sea during glacial periods, and if so, which glacial periods.
6. Record the minimum extent of the GIS during interglaciations over a range of boreal summer insolation maxima (e.g., MIS 1, 5e, 7, 11, 19 and 31).

5.2. Strategies for Addressing Process-Oriented Questions

The following research strategies will address the proposed process-oriented questions.

- *What controls the rate of ice mass change on Greenland and the respective roles of atmospheric and oceanic forcings?* These questions will be addressed by targeting outlet glacier fjord and shelf records, and through the longer records from the continental rise where glacial-interglacial GIS fluctuations and ocean temperature records can be reconstructed. Ultimately, records surrounding Greenland will be required with transects from the continental rise to shelf/fjord settings to link proximal ice-sheet records with distal climate records. Although continuous atmospheric temperature records are lacking beyond ~130 ka from Greenland, a first order forcing can be approximated from boreal summer insolation that can be further improved by regional climate modeling.
- *Is subsurface oceanic temperature important in predicting the behavior of the GIS?* The drilling of sites more distal to Greenland will document when and to what degree the

subsurface ocean warmed before penetrating around Greenland. Depth transects combined with GIS proximal drilling on trough mouth fans will be necessary to document subsurface ocean temperatures. Through improved paleomagnetic stratigraphies, the relative timing between GIS (and ice shelves if they existed) retreat and subsurface warming might be resolvable. High-resolution ocean and ice-sheet modeling will test hypotheses arising from these records.

- *What is the role of ice shelves and sea ice?* Records from the Labrador and Greenland Seas and Baffin Bay as well as fjord outlet glaciers will potentially document the existence of ice shelves or extensive sea ice, which can be compared to the GIS records from the same cores to address their roles in modulating GIS behavior.
- *How does Greenland freshwater influence global ocean circulation?* Records from Nares and Fram Straits will track the influence of Arctic freshwater discharge to the North Atlantic, which may be modified by direct freshwater input from Greenland, and by restricting or re-directing shelf-focused geostrophic flows; both may have large far-field effects on buoyancy forcing of thermohaline circulation. Records from central to south Greenland will also include the influence of GIS runoff, which could be linked to proximal bottom water circulation records and more distal records of North Atlantic circulation.

5.3. Site Survey Plan

With the possible exception of previously surveyed DSDP/ODP/IODP sites, extensive site surveying missions are needed before any new drilling expeditions are undertaken. Such surveying missions should follow on and be informed by a compilation of all existing and/or accessible site survey data (such an exercise was beyond the scope of this workshop). Compilation of existing survey data and planning for new surveying will be conducted in collaboration with the Geological Survey of Denmark and Greenland. Extensive seismic surveying and bathymetric mapping plan will allow the collection of the best drill cores in a given location, and for the stratigraphic linkage of discontinuous continental shelf, slope and fan records to the continuous continental rise records, key for reconstructing the full behavior of the GIS. We advise, at a minimum, the use of the following methodologies.

- For high-resolution surface and shallow subsurface seismic reflection imaging (“micro”), use GI guns, digital multichannel streamers, multibeam bathymetry and backscatter mapping, and digital CHIRP.
- Detailed imaging might be conducted with either a deep-tow “Huntec”-style boomer profiler, or in difficult environments with chirp sub-bottom profilers aboard autonomous underwater vehicles.
- Deep penetrating seismic and bathymetric-profiling should be conducted with modern versions of traditional low-fold multichannel seismic systems. Access to these systems by the community is limited, and should be supported as a community service.

5.4. Coring Expeditions and Process Studies

Traditional piston coring and detailed process-based studies should be conducted in concert with site surveying well before drilling expeditions. Long piston coring with the coring apparatus of the U.S. *RV Knorr* (or like vessel) has the potential to recover records extending back one to several glacial cycles. The *Knorr* long-core also does not have core-expansion issues like the long-coring system on the *Marion Dufresne* (e.g., Hillaire-Marcel & Turon, 1999). Piston cores will test the use of GIS and climate proxies during the last deglaciation when terrestrial records are available for comparison.

Gravity cores and multi-cores should also be collected. The former will be used for higher-resolution studies of the upper portion of the sediment sequence; the latter will be used to collect pristine samples of the sediment-water interface. Process studies for paleo-proxy validation can be conducted on these cores that can be compared to modern observations. Depth transects should thus be collected to document the modern patterns of sedimentation around Greenland and how it is transferred to the geologic record. Modern process-based proxy validation and the testing of proxies in the relatively recent geologic past are critical for successful reconstructions of the GIS and its environment further back in time.

5.5. Specific Drilling Sites

The workshop participants discussed and decided on the following locations as critical drilling objectives for assessing the paleo-history of the GIS (Fig. 3). This list is likely not comprehensive, and may be modified based on survey studies, but provides a plausible array of objectives for further study and refinement.

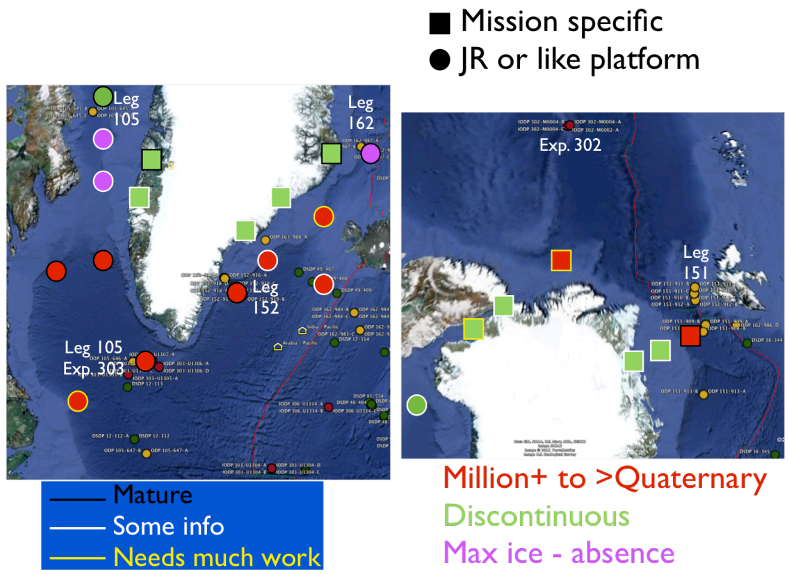

Fig. 3. Existing DSDP (red) ODP (yellow), IODP (green) drill sites (small symbols) and proposed new drilling locations (large symbols, circle=JR; square=MSP; extent of existing survey data indicated by color outside of symbol; symbol inside color shows type of record to be potentially retrieved). Note that the drilling target in the Lincoln Sea north of Greenland (red square, yellow outline) is a longer-term goal as current sea-ice conditions may make operations logistically difficult.

- Eirik Drift: Revisit sites targeted but because of weather not drilled during IODP Expedition 306 on northwest side of the drift to recover high resolution Pliocene to Miocene sediment sequences, which will address time-interval targets 1-4 & 6. Re-drill ODP Site 646 for better recovery to provide a complete Miocene to present record from the Eirik Drift. These sites may be ready to drill based on existing survey data.
- South of Davis Strait: These sites will document southwest GIS retreat and record water mass and ice-rafting changes into and out of Baffin Bay, addressing targets 2-6 (unlikely to retrieve Miocene-age sediment).
- Baffin Bay: This would include re-drilling ODP Site 645, which would provide information on the late Neogene evolution of the surrounding cyrosphere, and document the existence of a potential ice shelf during glaciations, addressing targets 1-5.
- Southwest of Denmark Strait: Sites from this area would record intervals of southeast GIS maximum extent and retreat, and when Greenland valley glaciers coalesced into a full ice sheet, addressing targets 1-4 & 6. These sites may also provide more local pollen records due to the blocking of the Westerlies by the island of Greenland. Areas to target would be to revisit ODP Leg 152 Sites 914-919 that were originally proposed, though not drilled during IODP Expedition 303, and sites closer to Denmark Strait.

- Scoresby Sund, Jakobshavn and Uminak Ice Stream Fans: These sites will provide information on when the GIS reached its maximum glacial extents and will exploit the use of new down hole logging tools. They will address targets 1-4 & 6.
- Northeast to north Greenland shelf and slope: These sites could contain a long record of the GIS obtainable by drilling oceanward-dipping strata (Berger & Jokat, 2008). The records may be discontinuous and down hole logging tools will be necessary, but targets 1-4 may be addressable.
- Outlet glaciers (Jakobshavn, Helheim, Kangerdlussuaq, Humboldt, Petermann, 79 North): Using a mission specific platform, these sites would provide information on local-scale instability to test the existence of bifurcation points. Records would be discontinuous, but with extensive seismic surveying, drilling of trough mouth fans and in fjords could potentially document the existence of instabilities in these different glacier systems as well as GIS response-time to a climate perturbation. Down hole logging tools would be necessary.
- More distal sites from Greenland: These will record the evolution of subsurface water mass properties, in particular temperature, which may impact the GIS directly or indirectly through the melting of ice shelves. Drill sites should allow for collection of depth transects in the northern North Atlantic, for example from the North American margin and the Reykjanes Ridge.
- Nares and Fram Straits: Records from these straits (and their inlets and outlets) would document the flow of water from the Arctic around Greenland, which plays an important role in governing ocean temperatures around the island. Down hole logging tools would be necessary, particularly for Nares Strait where recovery may be discontinuous.

5.6. Platforms and Drilling Approaches

The critical drilling targets identified by the workshop participants will require at least two different platforms (Fig. 3).

- Drilling sites around west to east Greenland, in Baffin Bay and at more distal locations will require the use of the *JOIDES Resolution* or like platform to obtain long, continuous records.
- Drilling sites near outlet specific glaciers, northeast to northwest of Greenland and in Nares and Fram Straits will require mission-specific platforms due to potential complications with sea ice (i.e., an ice breaker equipped with the Meeresboden-Bohrgerät (MeBo)[9] sea-floor drilling system, or through-ice drilling similar to ANDRILL[10]).

Our ability to document paleo-GIS behavior and address the process-oriented questions will depend on the quality of materials recovered through drilling. Where possible, advanced piston coring (APC) should be the primary objective. In potentially difficult lithologies, a range of strategies may be needed to optimize core recovery. Stronger non-magnetic core barrels that can be employed during APC drilling at all depths would also improve paleomagnetic records and therefore time control, improving chronologies for older parts of the GIS record.

[9] http://www.marum.de/en/Sea_floor_drill_rig_MeBo.html
[10] http://www.andrill.org/

6. Participants

Of the 49 participants, 19 were graduate students/postdocs; 5 were early-career scientists.

Attendee	Appointment	Institution	Attendee	Appointment	Institution
Ian Bailey	Post Doc	National Ocean Centre-Southampton	Alan Mix	Professor	Oregon State University
Henning Bauch	Professor	University of Kiel	Joseph Nicholl	Grad Student	Cambridge University
Anders Carlson*	Professor	University of Wisconsin-Madison	Laurence Padman	Scientist	Earth & Space Research
James Channell	Professor	University of Florida	Elizabeth Pierce	Grad Student	Lamont Doherty Earth Observatory
Stephanie Desprat*	Professor	University of Bordeaux	Ross Powell	Professor	Northern Illinois University
Robert DeConto	Professor	University of Massachusetts-Amherst	Fred Prahl	Professor	Oregon State University
Kelly Deuerling	Grad Student	University of Florida	Summer Praetorius	Grad Student	Oregon State University
Anne de Vernal	Professor	University of Quebec-Montreal	Alberto Reyes	Post Doc	University of Wisconsin-Madison
Eugene Domack	Professor	Hamilton College	Antony Rosell-Mele	Professor	University of Barcelona
Jason Dorfman	Grad Student	Oregon State University	Yair Rosenthall	Professor	Rutgers University
Aurora Elmore	Post Doc	University of New England	Andreas Schmittner	Professor	Oregon State University
Helen Evans	Scientist	Lamont Doherty Earth Observatory	Christian Schoof*	Professor	University of British Columbia
Carl Gladish	Grad Student	New York University	Fiona Siefert	Grad Student	Portland State University
Robert Hatfield	Post Doc	Oregon State University	Jeremy Shakun	Post Doc	Harvard University
Brian Haley	Scientist	Oregon State University	Jennifer Stanford*	Scientist	University of Southampton
Claude Hillaire-Marcel	Professor	University of Quebec-Montreal	Joseph Stoner	Professor	Oregon State University
Anne Jennings	Scientist	University of Colorado	Sarah Strano	Grad Student	Oregon State University
Alexandra Kirshner	Grad Student	Rice University	Marta Torres	Professor	Oregon State University
Gary Klinkhammer	Professor	Oregon State University	Anne Trehu	Professor	Oregon State University
Sebastian Koenig	Grad Student	University of Massachusetts-Amherst	Sam Van Laningham*	Professor	University of Alaska-Fairbanks
Matthew Konfirst	Post Doc	Ohio State University	Kelsey Winsor	Grad Student	University of Wisconsin-Madison
Anthony Koppers	Professor	Oregon State University	Stella Woodard	Post Doc	Texas A & M University
Shaun Marcott	Post Doc	Oregon State University	James Wright	Professor	Rutgers University
Ellen Martin	Professor	University of Florida	Chuang Xuan	Post Doc	Oregon State University
Jennifer McKay	Scientist	Oregon State University	* indicates an early-career scientist		

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