Investigations of past climate and sea-ice variability in the fjord area by Station Nord, eastern North Greenland

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The marine record of the Independence–Danmark fjord system extending out to the Wandel Hav in eastern North Greenland (Fig. 1A) is little known due to the almost perennial sea-ice cover, which makes the region inaccessible for research vessels (Nørgaard-Pedersen *et al.* 2008), and only a few depth measurements have been conducted in the area. In 2015, the Villum Research Station, a new logistic base for scientific investigations, was opened at Station Nord. In contrast to the early exploration of the region, it is now possible to observe and track the seasonal character and changes of ice in the fjord system and the Arctic Ocean through remote sensing by satellite radar systems. Satellite data going back to the early 1980s show that the outer part of the Independence–Danmark fjord system is characterised by perennial sea ice whereas both the southern part of the fjord system and an area 20–30 km west of Station Nord are partly ice free during late summer (Fig. 1B). Hence, marine-orientated field work can be conducted from the sea ice using snow mobiles, and by drilling through the ice to reach the underlying water and sea bottom.

Earlier studies have shown that the last deglaciation of the region occurred in the early Holocene (Funder 1989; Nørgaard-Pedersen *et al.* 2008) and the sea subsequently inundated the fjord system. Based on onshore evidence from eastern North Greenland, beach ridges and frequent deposition of drift wood during the Holocene Thermal Maximum at about 8000–5000 years BP indicate a period of open water and a mean summer temperature higher than today (Funder *et al.* 2011).

During the first field season in 2015 at the new station, a number of field-based research projects were carried out coordinated by the Arctic Science Partnership (ASP, http://www.asp-net.org/) and the Arctic Research Centre (ARC) at Aarhus University, Denmark. The Geological Survey of Denmark and Greenland (GEUS) and ARC carried out the fjord sediment coring project described here. The main objective of the marine geoscience field work was to collect sediment cores, which can be used to reconstruct past sea-ice variability through recent centuries and millennia. A major aspect was also the impact of sea ice on primary production, mainly diatoms and dinoflagellates and on biogeochemical cycles and the Arctic ecosystem.

This paper presents preliminary results of the sediment coring work and also new information on the bathymetry in the fjord area up to 50 km from Station Nord. A time-series of satellite radar images of sea-ice types in the fjord system provided by the Danish Meteorological Institute (DMI) for the last decade is discussed to better understand the recent sea-ice dynamics in the area. An introduction to the ongoing laboratory work and data processing is also included.

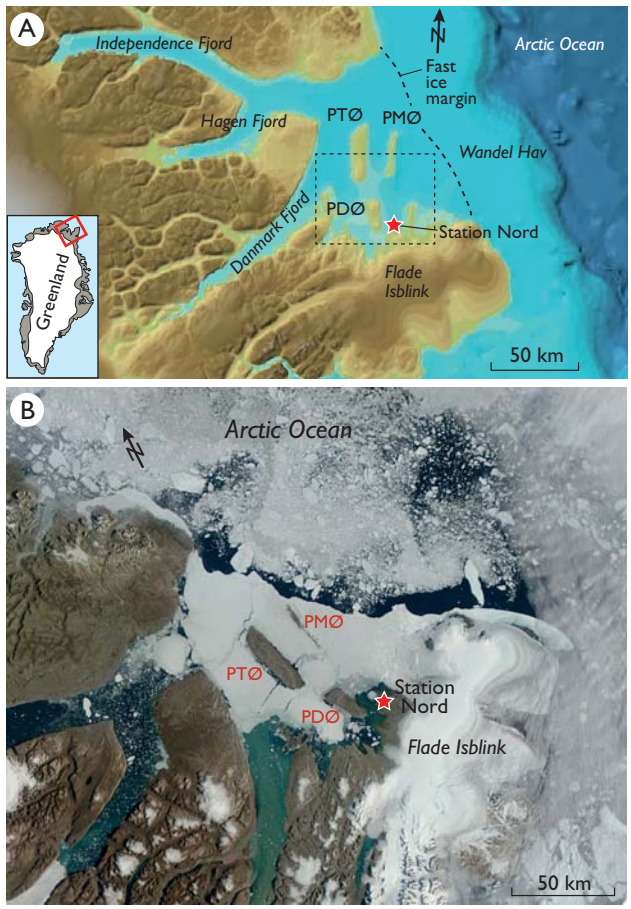

Fig. 1. **A**: Study area (framed area) near Station Nord and Villum Research Station (red star), eastern North Greenland. The average position of the fast-ice edge toward the Arctic Ocean pack-ice drift is indicated. Map source: IBCAO vers. 3.0 (Jakobsson *et al.* 2012). **B**: Satellite image (DMI AQUA) of the area from 15 August 2015. **PDØ**: Prinsesse Dagmar Ø. **PTØ**: Prinsesse Thyra Ø. **PMØ**: Prinsesse Margrethe Ø.

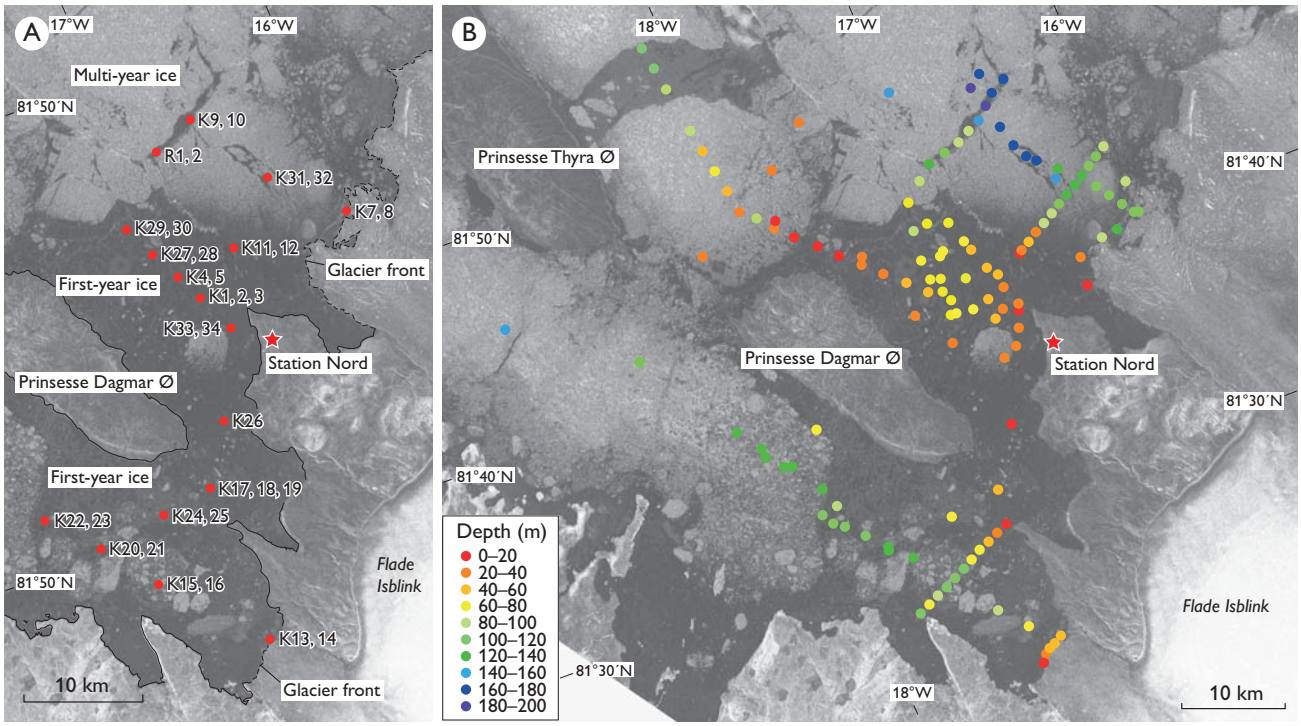

Fig. 2. **A**: Radar satellite image of the study area (SAR Sentinel-1 from 29.01.15), showing areas of seasonal (dark grey) and multi-year ice (light grey). There is no open water. High resolution SAR image (courtesy of Leif Toudal, Danish Meteorological Institute). Red dots: core sites. **K**: Kajak core. **R**: Rumohr core. Stippled lines: marine-terminating margins of Flade Isblink. **B**: Bathymetry data points with colour code for 20 m depth intervals overlain on SAR satellite image. Depth data sources are from the 2015 ASP field season (echo soundings and CTD based data) supplemented by data collected in 2006 by Naja Mikkelsen (GEUS), Yngve Kristoffersen (University of Bergen, Norway), and René Forsberg (DTU Space, Denmark).

Ice conditions

Satellite data show that the northern hemisphere has experienced a significant decrease in sea ice during the past *c.* 35 years, with a late summer sea-ice net loss in excess of 10% per decade, in addition to decreases seen in ice extent, thickness and age (Perovich & Richter-Menge 2015). Older (>4 years) and thicker sea ice is now only dominant in northern Arctic Canada and off northern Greenland. The large Independence–Danmark fjord system in eastern North Greenland is characterised by a semi-permanent fast-ice cover (Wadhams 1986) in the outer part and in the inner more southern part by a seasonal ice cover, which breaks up and partly melts during August–September (Fig. 1A). A coastal open water lead (polynya) is often observed between the northern margin of the fast ice and the drifting Arctic pack ice. The fast ice in the outer fjord system is protected by three large islands (the 'Prinsesse islands'; Figs 1, 2), which make it stable for a number of years before parts of it break up (Wadhams 1986 and available satellite data). Very thick and old ice of the 'sikkussak' type has, therefore, been observed earlier at the mouth of the fjord system (Wadhams 1986). During exceptionally warm summers the outer fast-ice cover has broken up, for example as observed in mid-August 2003 (Rasmussen 2004). The 2003 event coincided with break-up of the thick fast ice off the large NE Greenland ice stream in 2002 and 2003.

While planning our field work we used synthetic aperture radar (SAR) and visible band images (AQUA, TERRA) captured over the last decade from DMI (http://ocean.dmi.dk/arctic/nord.uk.php) in order to characterise the multi-year ice dynamics of the fjord system and to select the sampling sites. Sea-ice radar reflectivity is sensitive to the roughness of the ice and the presence of saltwater droplets within newer ice. Thus, older and more deformed multi-year ice appears white or light grey (more reflection), whereas younger, first-year ice appears dark grey or black (less reflection). Hence, it is possible to identify areas characterised by first-year ice and distinguish these from multi-year ice covered areas (Fig. 2). Moreover, by examining the ice-cover character on SAR images from DMI from 2009 onwards, it is possible to date different patches of fast-ice cover. Ice tongues of glacier ice and icebergs debouching out to the sea from the ice cap of Flade Isblink can be identified north-east and south-west of Station Nord (Fig. 2).

The SAR and visible band image record for the past decade reveals that the oldest fast ice in the study area is found

in the Wandel Hav. This ice appears to be at least 6 years old and may date back to 2004 following the total break-up in 2003. A similar area of older ice patches is situated between the Prinsesse Thyra Ø and Prinsesse Margrethe Ø (Fig. 2). In mid-August 2012, the fast-ice cover at the mouth of the Independence Fjord and Danmark Fjord broke up, creating a wide-open connection to the Arctic Ocean in the area north-west of Prinsesse Thyra Ø. Freeze-up later in 2012 created the constellation of multi-year ice coverage persisting until today. Only the outer rim of the old fast-ice cover may occasionally be eroded by loss of ice fragments, which drift away with the Arctic pack-ice drift.

The Flade Isblink ice cap is mainly drained by two outlets along its western margin. A comparison of earlier maps (Higgins 1991) and 2015 satellite-derived data indicates that the outlet immediately north of Station Nord has retreated about 13 km southwards between 1991 and 2015. Higgins (1991) estimated the average flow speed of the outlet glacier to be of a few hundred metres per year. Satellite radar data from the last decade confirm this estimate, but also indicate that the outlet glaciers have been surging (Joughin *et al.* 2010).

Field work

We collected sediment cores from 11 April to 2 May 2015 in the ice-covered fjord area (Figs 2, 3). Sampling took place up to about 30 km from the station along several transects determined according to ice conditions and existing knowledge of bathymetry. We used two snow mobiles with sledges (3–4-person team) for transport. We selected sampling sites based on a geo-referenced high-resolution radar satellite image (Sentinel-1 SAR from 31.01.2015) revealing areas of first and multi-year ice as well as glacier-front positions and larger icebergs (Fig. 2). Whenever possible, we targeted sites with thin first-year ice (about 1.0–1.2 m) and avoided sites covered by thick (>3 m) multi-year ice, which was very arduous to drill through.

At each core site, we first removed the snow cover, which was usually at least 1 m thick, and used a 9 inch ice-auger to drill two or more overlapping holes in the ice, sufficiently large for the coring devices (Fig. 3). At most locations, we measured water depths with an echo sounder, but at oceanographic stations we used CTD data (conductivity, temperature and depth). We sampled sediment with a Kajak Sediment Corer (25–75 cm long tube, 45 mm inner diameter), a Rumohr Lot Corer (50–100 cm long tube, 75 mm inner diameter), and at a few stations, with a Van Veen Grab Sampler (top 10 cm surface sediment). We used a tripod with a top-mounted hydraulic winch (Pot Hauler) connected to a petrol-driven power pack to retrieve the *c.* 60 kg Rumohr Corer, whereas Kajak cores were retrieved with a hand winch (Fig. 3). Drilling large holes through 1–3 m of sea ice was time-consuming, and we found that Kajak coring was the most efficient approach. We collected duplicate or triplicate Kajak cores at most coring sites and one Kajak core from each site was subsampled at 1 cm intervals at the Villum Research Station. Sea-ice cores were collected using a Kovacs Ice Corer System for biochemical and taxonomic studies of the sea-ice algal communities.

Fig. 3. Recovering a Kajak core with seabed sediments. Photograph: Jesper Hoffmann.

Bathymetrical data

Apart from a single study of short sediment cores and water-depth measurements south-west and north-west of Prinsesse Dagmar Ø close to Station Nord (Nørgaard-Pedersen *et al.* 2008) very little is known about the bathymetry and sedimentation record of this remote area. Bathymetrical datasets from the limited earlier field projects in the area have, for this study, been updated by new data from the 2015 ASP field season. Earlier data consist of echo soundings carried out in 2006 and reconnaissance data. The 2015 field season dataset consists of echo sounding data and CTD-derived bathymetry data. As the CTD data are corrected for water-column velocity differences (due to water masses with different salinities and temperatures), these may be considered the most accurate. Water depths increase from *c.* 20 m near Station Nord to >150 m 20–30 km northwards (Fig. 2B). In front of the glacier outlet margin 10–15 km north-east of Station Nord, a trough is found with depths up to 100–150 m right up to the glacier margin at 81°40′N. There is a shallow area between Prinsesse Dagmar Ø and Prinsesse Thyra Ø with water depths between 20 and 30 m, but the depth increases

to >100 m towards the north. South of Prinsesse Dagmar Ø, a trough possibly connected to the mouth of the Danmark Fjord shows depths in the range of 130–150 m. The trough axis rises to about 115 m *c.* 10 km from the glacier outlet margin and reaches depths of maximum 50 m at the glacier margin.

Preliminary results and outlook

A total of 37 sediment cores were retrieved from 17 sites along transects up to *c.* 30 km from Station Nord (Fig. 2A). Many of the Kajak cores are only a few decimetres long. However, we recovered cores exceeding 0.5 m from more water-rich mud close to glacier margins and at the few Rumohr core sites.

A spatial study of sea-ice and productivity proxies including dinoflagellate cysts, diatoms, foraminifera, biomarker IP25 (a proxy for sea ice) and biogenic silica is currently being conducted for the 17 sampling sites, to establish a baseline of recent conditions that will serve as modern analogues for reconstructions of sea-ice variability and changes in oceanographic conditions during earlier time periods.

Selected sediment cores are being analysed for ^{210}Pb and ^{137}Cs content to estimate sedimentation rates at the study sites and establish a chronology for the topmost part of the cores. The first dating results show sedimentation rates in the order of 0.04–0.06 cm/y. Preliminary investigations of the microfossil content of the sediments revealed calcareous benthic foraminifera and a few ostracods, particularly at the deeper sites, which allows for the possibility to use ^{14}C dating to establish a robust chronology for the sediment records. Furthermore, studies of the sites located north of Station Nord show a stronger marine influence, whereas the sites towards the north-west and south have a clear signal of freshwater or glacial influence. Complementary to the climate proxy work, a characterisation of the protist communities is being undertaken by germination, growth tests, and molecular analyses (DNA) targeting the two main groups of primary producers: diatoms and dinoflagellates. Investigations of the sampled sea-ice cores showed that during the early part of the season's field work the sea ice was barren of algae. This is attributed to light attenuation by the snow (average snow thickness of 1 m). *In situ* light measurements, and fluorescence measurements on 25 sea-ice core samples (bottom 5 cm) using a phytoplankton analyser showed no detectable photosynthetic activity (information from the Phytobiology Team, Aarhus University).

The field work provided us with some first insights into an ice-covered, very remote and large fjord system of eastern North Greenland. The preliminary data confirm presence of biogenic remains and sedimentary signatures which can be used as proxies for palaeo-environmental reconstructions and deciphering of the younger part of the Holocene climate history in this region.

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