



Identification of contrasting seasonal sea ice conditions during the Younger Dryas



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ABSTRACT

A palaeo sea ice reconstruction for northern Norway for the interval ca 13.8–7.2 cal ka BP has been performed using a combined organic geochemical proxy-based study of a marine sediment core (JM99-1200) obtained from Andfjorden (69° 15.95' N, 16° 25.09' E) and the outcomes compared with a series of other palaeoclimate studies carried out previously. Within this study, particular emphasis has been placed on the identification of the sea ice conditions during the Younger Dryas and the application of different biomarker-based proxies to both identify and quantify seasonal sea ice conditions. Firstly, the appearance of the specific sea ice diatom proxy IP₂₅ at ca 12.9 cal ka BP in the sedimentary record has provided an unambiguous but qualitative measure of seasonal sea ice and thus the onset of the Younger Dryas stadial. The near continuous occurrence of IP₂₅ for the next ca 1400 yr demonstrates seasonal sea ice during this interval, although variable abundances suggest that the recurrent conditions in the early-mid Younger Dryas (ca 12.9–11.9 cal ka BP) changed significantly from stable to highly variable sea ice conditions at ca 11.9 cal ka BP and this instability in sea ice prevailed for the subsequent ca 400 yr, during which, an extremely short interval of permanent or near-permanent sea ice was observed at ca 11.75 cal ka BP. At ca 11.5 cal ka BP, IP₂₅ disappeared from the record indicating ice-free conditions that signified the beginning of the Holocene. The IP₂₅ concentrations were also combined with those of the open water phytoplankton biomarker brassicasterol to generate P_BIP₂₅ data from which more quantitative measurements of sea ice were determined. P_BIP₂₅ data were consistent with, consecutively, seasonal then infrequent sea ice cover for the early-mid and late Younger Dryas, while further comparisons of the P_BIP₂₅ data with the outcomes of previous correlations with modelled sea ice concentrations suggested that these intervals were characterised by ca 60–90% and ca 0–60% sea ice cover, respectively. Both qualitative and quantitative sea ice records were also consistent with sea surface temperature and other palaeoclimate estimates derived previously from various other proxy studies. The contrasting seasonal sea ice conditions during the Younger Dryas were further verified through a comparison of the concentrations of IP₂₅ with those of another highly branched isoprenoid (HBI) alkene that is di-unsaturated and believed to also be produced by sea ice diatoms. The ratio of the HBI diene to IP₂₅, termed DIP₂₅, is believed to provide a useful indicator of stability or variability in sea ice conditions and complements the outcomes from the IP₂₅ and P_BIP₂₅ index data. The identification of contrasting seasonal sea ice conditions during the Younger Dryas will likely contribute to the debate regarding the climatic impacts that took place during this intriguing interval.

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1. Introduction

The Younger Dryas stadial represents an intriguing and much studied short-term (ca 1400 yr) event that occurred during the transition from the Last Glacial to the current interglacial (the Holocene) and was characterised by significant and extended

cooling across higher latitude regions of the northern hemisphere. Interest in the Younger Dryas stems, in part, from the predictions of significant economic and ecological impacts that may be induced during abrupt climate changes (Alley et al., 2003). Numerous studies have investigated the details of the Younger Dryas through Greenland ice records (e.g. Alley et al., 1993; Mayewski et al., 1993; Taylor et al., 1997; Alley, 2000), marine and lake sediment records from Europe (e.g. Isarin et al., 1998; Brauer et al., 2008) and Arctic and sub-Arctic areas (e.g. Gulliksen et al., 1998; Seppä et al., 2002; Vorren and Plassen, 2002; Ebbesen and Hald, 2004; Bakke et al.,

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2009; Aagaard-Sørensen et al., 2010), yet the exact causes that triggered this abrupt event are still under debate. One explanation is based around a reduced North Atlantic Meridional Overturning Circulation, which probably resulted from a massive release of meltwater into the North Atlantic (e.g. Gildor and Tziperman, 2000; Broecker, 2003; Knutti et al., 2004; McManus et al., 2004; Jennings et al., 2006). A combination of outbursts from Lake Agassiz (North America) and re-routing of continental drainage from the Mississippi river into the North Atlantic Ocean at the onset of the Younger Dryas has generally been considered to be responsible for initiating this abrupt climate change (Clark et al., 2001). More recently, however, it has been shown that the re-routing of Arctic meltwater in a north westerly direction through the Mackenzie Valley made an additional and significant contribution (Teller et al., 2002, 2005, 2006; Tarasov and Peltier, 2005; Murton et al., 2010). Alternatively, a model involving extensive winter sea ice cover, that resulted from more extreme seasonality compared to modern times and would have dramatically altered the heat exchange between the ocean and the atmosphere, has also been proposed (Denton et al., 2005; Lie and Paasche, 2006). Central to the debate, however, remains the occurrence and impact of sea ice to the Younger Dryas stadial. Since reconstructions of sea ice are often made by extrapolation of other proxy-based climate measurements such as sea surface temperature (SST) and sea surface salinity (SSS), there is a clear need to develop proxies that provide more direct evidence for the past occurrence of sea ice. Further, if such proxies are also able to discriminate between different sea ice scenarios, then there is an additional potential to improve on the somewhat generic terms that are frequently used to describe past sea ice conditions (extreme, extensive, etc) which, while understandable given the nature of the proxies from which they are derived, are not especially informative. In the particular case of the Younger Dryas, the application of sea ice-specific proxies that also provide more specific details of the sea ice conditions should further help to identify or confirm the role of seasonality during abrupt climate changes (Manabe and Stouffer, 2000; Gildor and Tziperman, 2003; Denton et al., 2005; Lie and Paasche, 2006).

To date, numerous palaeo sea ice reconstructions have been carried out for the Arctic and the majority of these have been based on the application of a wide range of environmental proxies (For a recent review see Polyak et al., 2010). Within the sedimentary marine environment, for example, the presence/absence of calcareous microfossils such as foraminifera has been used to deduce sea ice cover in the Arctic as well as to reconstruct past SST (Pflaumann et al., 2003; Sarnthein et al., 2003). However, this approach can be somewhat limited by dissolution of aragonite/carbonate foraminifera as a result of increased organic carbon input (e.g. Wollenburg and Kuhnt, 2000). The presence of sea ice diatoms in marine sediments has also been used to elucidate past sea ice coverage (e.g. Justwan et al., 2008), while one of the most frequently adopted approaches to infer past sea ice conditions is based on the abundances and distributions of dinoflagellates cysts (e.g. de Vernal et al., 2000, 2005; Mudie et al., 2001). In addition to these biological proxies, the use of ice rafted debris (IRD) has also been used as a tracer of Arctic drift ice (e.g. Geirsdóttir et al., 2002; Moros et al., 2004; Andrews and Eberl, 2007; Andrews, 2009; Andrews et al., 2009).

In recent years, a new proxy for palaeo sea ice reconstructions in the Arctic has been reported, which is based on the presence of a mono-unsaturated C₂₅ highly branched isoprenoid (HBI) alkene biosynthesised by Arctic sea ice diatoms during the spring (IP₂₅; Fig. 1; Belt et al., 2007; Brown et al., 2011) and is deposited in underlying sediments following ice melt. This biomarker, termed IP₂₅ (Belt et al., 2007), has been detected in Arctic sea ice and in marine sediments from a large number of diverse regions across

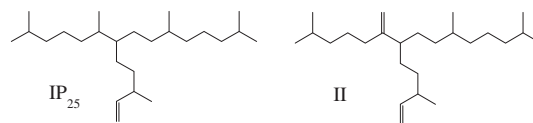


Fig. 1. Structure of the sea ice biomarker IP₂₅ and diene II.

the Arctic (Belt and Müller, 2013) and the selectivity of IP₂₅ towards a sea ice diatom origin, coupled with its stability in sediments over long timescales, makes it a suitable biomarker to study and quantify for palaeo sea ice reconstructions. To date, the presence and relative abundances of IP₂₅ have been used in a number of palaeo sea ice reconstructions representing different Arctic regions over a range of timescales (for a review, see Belt and Müller, 2013). Further biomarkers, including sterols, have also been used as indicators of different algal communities reflecting contrasting oceanographic conditions. For example, 24-methylencholesterol was previously reported as the main sterol in sea ice diatom communities during the spring bloom in McMurdo, Antarctica (Nichols et al., 1993), although this biomarker is not source specific and is also produced by some dinoflagellates and prasinophytes (Volkman et al., 1998). A structurally related sterol, brassicasterol, is produced by a large number of phytoplankton and has been used as a geochemical indicator of open water conditions. Indeed, sedimentary brassicasterol concentrations have been combined with those of the sea ice biomarker IP₂₅ to generate the so-called PIP₂₅ index, which potentially provides more quantitative measures of palaeo sea ice conditions (Müller et al., 2011). Finally, a number of IP₂₅-based sea ice reconstructions have been successfully incorporated into multi-proxy and large-scale climate modelling studies (e.g. Antoniadou et al., 2011; Axford et al., 2011; Kinnard et al., 2011; Miller et al., 2012), so there is further motivation to conduct such investigations, especially those that are high resolution and pan-Arctic.

The main aim of the current study was to use the presence of the IP₂₅ sea ice proxy and other biomarkers to identify, unambiguously, sea ice occurrence during the Younger Dryas stadial in northern Norway, to better define the nature of the sea ice conditions, to identify any fluctuations within these and to make any sea ice determinations more quantitative by comparing the biomarker-based proxy data with predictions of sea ice concentrations derived from modelling approaches carried out previously (Müller et al., 2011). In addition, these outcomes had the potential to provide insights into the mechanism(s) responsible for initiating the Younger Dryas and for establishing a more detailed understanding of the oceanographic transitions that occurred within this stadial. In order to achieve these aims, we chose to investigate a sediment core for which a reasonably comprehensive suite of other oceanographic proxy and geochemical data had already been collected and discussed (Knies et al., 2003, 2005; Ebbesen and Hald, 2004).

2. Regional setting

Two water masses, the Atlantic water of the North Atlantic Current (NAC) and the coastal water of the Norwegian Coastal Current (NCC), dominate the oceanographic regime in the study area. The warm (>2 °C) and saline (>35‰) NAC (Hopkins, 1991) flows northward adjacent to, and beneath, the less saline (32–35‰) NCC by following the bathymetry of the northern Norwegian shelf (Loeng, 1991). The shelf topography, which is dominated by relatively shallow to intermediate glacial troughs, strongly steers the in- and out-flow of both water masses (Moseidjord et al., 1999). Due to the open ocean connection, the water column is well-

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