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Invited Review

Quaternary dinoflagellate cysts in the Arctic Ocean: Potential and limitations for stratigraphy and paleoenvironmental reconstructions

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A B S T R A C T

The Arctic Ocean is a siliciclastic depositional environment which lacks any rock-forming biogenic calcareous and siliceous components during large parts of its Quaternary history. These hemipelagic sediments are nevertheless suitable for the study of organic-walled microfossils of which the fossil remains of dinoflagellates - dinoflagellate cysts - are the most important group. Dinoflagellate cysts have become an important tool in paleoceanography of the high northern latitudes, but their potential for Quaternary biostratigraphy has remained largely unexplored.

Dinoflagellate cysts are the dominant marine palynomorph group which is more continuously present in the marginal seas (e.g. Barents Sea, Bering Sea) than in the Arctic Ocean itself throughout the Quaternary. Most species have long stratigraphic ranges, are temporary absent and show abundance variations on glacial-interglacial timescales. Of the more than 30 taxa recorded, only *Habibacysta tectata* and *Filisphaera filifera* became extinct in the Pleistocene. The highest persistent occurrence of *H. tectata* at ca. 2.0 Ma and the top of *F. filifera* acme at ca. 1.8 Ma can be used for supra-regional stratigraphic correlation between the Arctic Ocean and adjacent basins. These events corroborate a slow sedimentation rate model for the Quaternary section on the central Lomonosov Ridge, but a combination of different methods will have to be applied to provide a detailed chronostratigraphy. The occurrence of cysts of phototrophic dinoflagellates in certain stratigraphic intervals on Lomonosov Ridge supports published evidence of episodic opening of the multiyear Arctic sea ice cover during the Quaternary probably related to a stronger inflow of Atlantic water. This contradicts the hypothesis of a permanently ice covered central Arctic Ocean in the Quaternary.

1. Introduction

The Quaternary period (the last 2.58 million years; Gibbard and Head, 2010) experienced the substantial expansion of the high northern latitude cryosphere as a response to a significant atmospheric and surface ocean cooling (e.g. Shackleton et al., 1984; Raymo, 1994; Maslin et al., 1998 and references therein; Kleiven et al., 2002; Fedorov et al., 2013). Large ice sheets recurrently formed on the circum-arctic continents and continental shelves, and covered Eurasia, Greenland, North America and adjacent shelf seas during certain periods in the Quaternary (e.g., Svendsen et al., 2004; Ehlers and Gibbard, 2007; Knies et al., 2009; Alley et al., 2010; Laberg et al., 2010; Molodkov and Bolikhovskaya, 2010; Jakobsson et al., 2014; Bierman et al., 2016; Schaefer et al., 2016; see Ehlers et al., 2011 and chapters therein). As a consequence of waxing and waning ice sheets, sea level fluctuated considerably leading to frequently closing and opening of shallow gateways to the Arctic Ocean, such as the Bering Strait, resulting in the modification of the Arctic Ocean circulation (e.g., Backman et al., 2009; Matthiessen et al., 2009; O'Regan et al., 2010).

Reconstructing the glaciation history from terrestrial records is hampered by incomplete sedimentary sequences and reworking of deposits by subsequent glaciations (e.g., Svendsen et al., 2004). However, evidence for glaciations on the circum-arctic continents

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may be found in the marine environment because ice sheets advancing across the shelves calve icebergs into the oceans and/or form extensive ice shelves that release clastic sediments when melting, and also grounding of glacial ice leaves landforms on the sea floor (e.g., Clark et al., 1980; Polyak et al., 2001; Spielhagen et al., 2004; Krylov et al., 2008; Stein et al., 2010b; Niessen et al., 2013; Darby, 2014; Jakobsson et al., 2014, 2016). Additionally, marine sediments archive the oceanographic conditions in the past, including the variability of the arctic pack ice cover, providing a link between ice sheets and ocean conditions (e.g., Polyak et al., 2010; Cronin et al., 2010, 2013).

An important prerequisite for reconstructing Arctic paleoceanography and glacial history is a sound chronostratigraphy, but this is still lacking for the marine sedimentary archives in the central Arctic Ocean. Firstly, most marine time series only comprise Middle to Upper Pleistocene sediments because gravity and piston cores, collected over the past decades, do not extend to the base of the Quaternary (e.g., Weber and Roots, 1990; Thiede et al., 1990; Backman et al., 2004; Stein, 2008; Stein et al., 2010b; Polyak et al., 2013). Quaternary sediments have been extensively recovered at the margins of the Arctic Ocean (e.g., Myhre et al., 1995; Jansen et al., 1996; McNeil et al., 2001; Dixon et al., 2008), but the first scientific sites that cover a complete central Arctic Quaternary sequence were drilled on the Lomonosov Ridge only in 2004 (Fig. 1; IODP Expedition 302, "Arctic Coring Expedition" (ACEX), Backman et al., 2006). Secondly, a multitude of methods provide contradictory stratigraphic interpretations (see Section 2 below). Among the biostratigraphic proxies, marine palynology has been utilized to establish age models for short sediment cores (e.g., Mudie, 1985; Matthiessen et al., 2001) but has not been applied yet on the ACEX composite record at a higher resolution for the entire Quaternary.

Based on published and new data, we review the stratigraphic occurrence of marine palynomorphs in Quaternary sediments of the Arctic Ocean, and evaluate their potential for establishing a biostratigraphy. We provide an overview on the status of the Quaternary chronostratigraphy and the different methods applied to develop age models (Section 2) followed by a review of Quaternary dinoflagellate cyst biostratigraphy (Section 3). New palynostratigraphic data from the Lomonosov Ridge (IODP Expedition 302), the northern Barents Sea margin (ODP Leg 151) and the Bering Sea (IODP Expedition 323) are presented in Section 4. Possible processes that may influence the stratigraphic occurrence

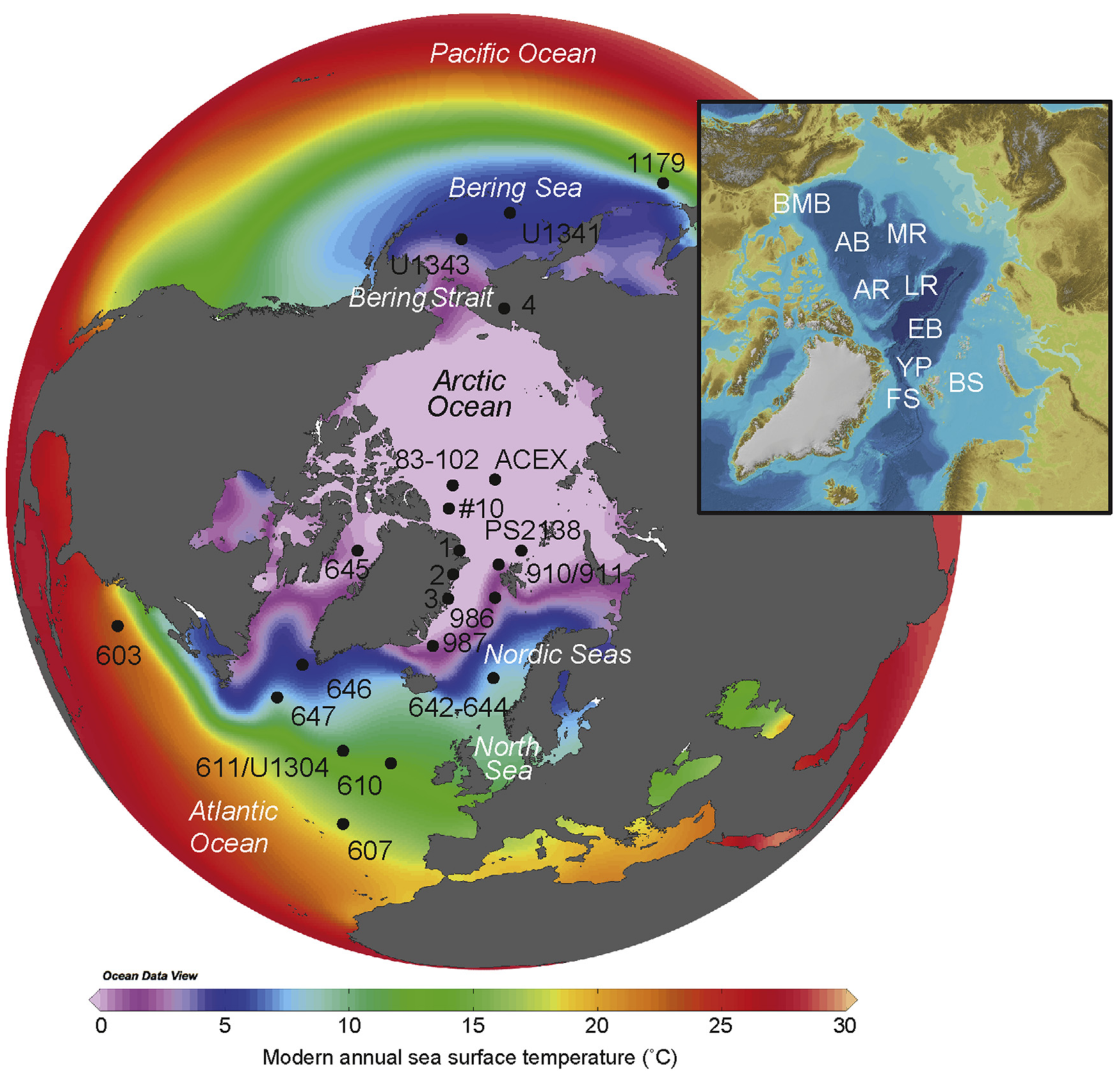

Fig. 1. Modern annual sea surface temperatures in the Northern Hemisphere (base map from De Schepper et al., 2015). All sites mentioned in the text are shown (1, Kap København Formation; 2, Île de France Formation; 3, Store Koldewey Formation; 4, Lake El'gygytgyn). Inset map (Jakobsson et al., 2012) shows geographic features mentioned in the text (abbreviations: AB, Amerasian Basin; AR, Alpha Ridge; BMB, Beaufort-Mackenzie Basin; BS, Barents Sea; EB, Eurasian Basin; FS, Fram Strait; LR, Lomonosov Ridge; MR, Mendeleev Ridge; YP, Yermak Plateau; #10, GreenICE #10).