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Late-Middle Quaternary lithostratigraphy and sedimentation patterns on the Alpha Ridge, central Arctic Ocean: Implications for Arctic climate variability on orbital time scales

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ABSTRACT

We use sediment cores collected by the Chinese National Arctic Research Expeditions from the Alpha Ridge to advance Quaternary stratigraphy and paleoceanographic reconstructions for the Arctic Ocean. Our cores show a good litho/biostratigraphic correlation to sedimentary records developed earlier for the central Arctic Ocean, suggesting a recovered stratigraphic range of ca. 0.6 Ma, suitable for paleoclimatic studies on orbital time scales. This stratigraphy was tested by correlating the stacked Alpha Ridge record of bulk XRF manganese, calcium and zirconium (Mn, Ca, Zr), to global stable-isotope (LR04-δ^{18}O) and sea-level stacks and tuning to orbital parameters. Correlation results corroborate the applicability of presumed climate/sea-level controlled Mn variations in the Arctic Ocean for orbital tuning. This approach enables better understanding of the global and orbital controls on the Arctic climate. Orbital tuning experiments for our records indicate strong eccentricity (100-kyr) and precession (~20-kyr) controls on the Arctic Ocean, probably implemented via glaciations and sea ice. Provenance proxies like Ca and Zr are shown to be unsuitable as orbital tuning tools, but useful as indicators of glacial/deglacial processes and circulation patterns in the Arctic Ocean. Their variations suggest an overall long-term persistence of the Beaufort Gyre circulation in the Alpha Ridge region. Some glacial intervals, e.g., MIS 6 and 4/3, are predominated by material presumably transported by the Transpolar Drift. These circulation shifts likely indicate major changes in the Arctic climatic regime, which yet need to be investigated. Overall, our results demonstrate applicability of XRF data to paleoclimatic studies of the Arctic Ocean.

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1. Introduction

Paleoenvironmental reconstruction in the Arctic Ocean is hampered by low sedimentation rates and difficulties in establishing reliable and accurate sediment chronologies, largely due to the poor preservation of biogenic components and a semi-isolated nature of the Arctic Ocean that complicates correlation of regional records to global reference stacks (e.g., Backman et al., 2004; Darby et al., 2006; Stein, 2008; Polyak et al., 2009; Polyak and Jakobsson, 2011). Stratigraphy is further complicated by a heavy impact of Pleistocene glaciations on the Arctic Ocean causing sedimentation hiatuses during glacial maxima and large influx of icebergs during glacial collapse events (e.g., Darby et al., 2006; Polyak et al., 2009; Polyak and Jakobsson, 2011). On the other hand, distinct variations in lithological and chemical composition, ice-rafted debris (IRD), foraminifera and ostracode abundances, stable isotopes, and attendant sediment properties have been useful for developing Arctic sediment stratigraphy tied to glacial-interglacial variability (Jakobsson et al., 2000; Polyak et al., 2004, 2009; Spielhagen et al., 2004; O'Regan et al., 2008; Stein et al., 2010a, 2010b; Marzen et al., 2016). We apply this approach, focusing on XRF scanning measurements of major elements displaying high variability (Mn, Ca, and Zr), combined with basic lithological and microfaunal data, to sediment cores from the Alpha Ridge, central Arctic Ocean. Sedimentation rates here have been estimated as especially low due to

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large distance from the margins and heavy sea-ice conditions in the Beaufort Gyre circulation system controlling this area (Polyak et al., 2009; Stein et al., 2010b). For better stratigraphic insight, in addition to Arctic correlations, Mn and attendant Ca and Zr records were stacked and tuned to global paleoclimatic and sea-level data (Lisiecki and Raymo, 2005; Rohling et al., 2014) and orbital parameters (Laskar et al., 2004). This approach not only aids constraining the age model, but also enables better understanding of the global and orbital controls on the Arctic climate.

2. Background

2.1. Arctic Ocean sediment stratigraphy

Lithological variability in sediment cores from the Arctic Ocean, including physical properties and sediment composition, has been widely used for regional and basin-wide correlations and reconstruction of sedimentary environments and provenance (e.g., Clark et al., 1980; Polyak et al., 2009; Stein et al., 2010a, 2010b). A common feature of this lithostratigraphy is cyclic interlamination of brown, Mn-rich, and greyish, Mn-poor layers (units). The widely accepted interpretation of this Mn-based cyclicity implies that Mn precipitated in Arctic Ocean sediments primarily during interglacial and major interstadial intervals, when relatively high sea levels and mild climate conditions facilitated Mn delivery from the margins to the Arctic Ocean interior (e.g., März et al., 2011; Löwemark et al., 2012, 2014; Macdonald and Gobeil, 2012; Meinhardt et al., 2016). Due to their inferred synchronous deposition and typically straightforward identification, Mn-rich layers are being widely used for stratigraphic correlation and paleoclimatic characterization of sedimentary records (e.g., Jakobsson et al., 2000; Polyak et al., 2004; O'Regan et al., 2008). However, Mn distribution in sediments is sensitive to diagenetic transformations as Mn (oxyhydr)oxides may become both dissolved and re-precipitated upon burial (März et al., 2011; Löwemark et al., 2014; Meinhardt et al., 2016). Therefore, stratigraphic application of Mn-based variations should be exercised with caution and verified with concurrent downcore distribution of other proxies.

Another widely distributed set of lithostratigraphic markers is formed by peaks of detrital carbonates, some of which can be readily identified in core lithology as pink-whitish (PW or W) layers (Clark et al., 1980; Darby et al., 1989; Phillips and Grantz, 2001; Polyak et al., 2004, 2009; Stein et al., 2010a, 2010b; Wang et al., 2013). These carbonates, predominantly dolomites, can be traced to Paleozoic carbonaceous rocks of the Canadian Arctic Archipelago, which have been repeatedly eroded by Pleistocene glaciations (Bischof et al., 1996; Stokes et al., 2005; Bazhenova et al., 2017). During glacial collapse events the eroded sediment was transported by icebergs over the western Arctic Ocean via the Beaufort Gyre circulation system and deposited as IRD. As biogenic carbonate content in Arctic sediments is typically low, total Ca in resulting sedimentary records closely approximates the downcore distribution of detrital carbonates (Polyak et al., 2009; Stein et al., 2010a, 2010b; Dong et al., 2017).

While Ca can be used as a tracer of inputs from the North American ice sheets, Zr could potentially approximate IRD derived from the Eurasian side as an element commonly associated with quartz that is deemed more indicative of Siberian than North American provenance in Arctic sediment cores (Vogt, 1997; Zou, 2016; Dong et al., 2017). While this pattern needs further investigation, it is corroborated by the initial XRF data, also showing an affinity of Zr to coarser sediment likely related to iceberg discharge (Schoster, 2005). The combined measurements of Mn, Ca, and Zr, thus, can be conveniently used for outlining the stratigraphy and sediment provenance in the Arctic Ocean.

Chronostratigraphy of Arctic Ocean sediments has not yet been firmly established, and the existing age models can only be considered as tentative. Where biogenic carbonaceous material is present, such as foraminifers, the uppermost stratigraphy (ca. 40 ka) can be constrained by means of AMS ^{14}C dating. Despite considerable gaps and uncertainties related to poorly understood reservoir mixing, as well as other potential complications (e.g., from subglacial hardwater), distribution of ^{14}C ages appears to make a consistent pattern. The surficial brown unit B1 is constrained across the Arctic Ocean to the Holocene (ca. 0–12 ka), and the next brown unit B2, in some areas identified as two subunits, B2a and B2b, to Marine Isotope Stage (MIS) 3, with most ages ranging from ca. 30 to 45 ka (e.g., Darby et al., 1997; Polyak et al., 2009; Hanslik et al., 2010; Poirier et al., 2012). Despite numerous attempts, absolute age beyond the range of ^{14}C dating has not been reliably constrained as various methods (e.g., magnetostratigraphy, biostratigraphy, stable isotopes) experience complications and biases in Arctic environments. For example, paleomagnetic records allow for differing interpretations and may not even represent actual variations of the paleomagnetic field (e.g., Channell and Xuan, 2009; Xuan et al., 2012).

Several biostratigraphic markers, typically species occurrence peak zones, have been identified in Quaternary Arctic Ocean sediments based on benthic and planktic foraminifers, ostracodes, and coccoliths (Ishman et al., 1996; Polyak et al., 2004; Adler et al., 2009; Backman et al., 2009; Cronin et al., 2013, 2014; Lazar and Polyak, 2016). These markers can be used as independent stratigraphic tools for verifying lithostratigraphic correlations, where respective microfossils are present. However, the distribution of these markers is mostly constrained to the Arctic Ocean, which limits their use for broader biostratigraphic correlations. Furthermore, preservation of fossil remains in Arctic Ocean sediments is variable and overall declines with age, especially in deposits older than the estimated Late Quaternary.

As multiple proxies, including physical properties, chemical composition, and paleobiological content, show apparent cyclic variability in Arctic Ocean sedimentary records, cyclostratigraphic approach has a potential to constrain sediment age by matching depositional variations to global paleoclimatic cycles and orbital parameters (e.g., Jakobsson et al., 2000; O'Regan et al., 2008; Adler et al., 2009). A reasonable integration of orbitally tuned Quaternary section of the ACEX borehole from the central Lomonosov Ridge to a longer Cenozoic record constrained by zonal biostratigraphy (O'Regan et al., 2008) gives credibility to this approach and encourages further applications of cyclostratigraphic tuning.

2.2. Study area

The Alpha Ridge is one of the major Arctic submarine ridges that extends northwards from the Ellesmere Island, Canadian Arctic, and rises to ~1200 m above the surrounding ocean bottom of an average 3000 m depth. The study area covers the basin-ward part of the Alpha Ridge, where it approaches the junction with the Mendeleev Ridge that further extends across the western Arctic Ocean to the Siberian margin (Fig. 1). The Lomonosov Ridge, another major submarine Arctic structure, ~500 km away from the Alpha Ridge, divides the Arctic Ocean into the eastern (Eurasian) and western (Amerasian) parts (basins). Seafloor in the study area, thus, characterizes the northernmost sedimentary environments in the western Arctic Ocean, apart from the basins, which are filled by turbidites (e.g., Backman et al., 2004).

Surface oceanic circulation over the Alpha Ridge is predominated by the clockwise Beaufort Gyre that carries ice with entrained sediment, and surface water, mostly from the North American margin (Fig. 1). Closer to the Mendeleev Ridge area the Beaufort

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