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Imprint of late Pleistocene continental processes visible in ice-rafted grains from the central Arctic Ocean

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ABSTRACT

Ice-rafted quartz sand grains of sediment samples representing marine isotope stages (MIS) 3 and 4 from the Lomonosov Ridge, Arctic Ocean, are here analysed with a scanning electron microscope (SEM) to characterise processes in the sediment source area. The microtextural characteristics of the grains were observed and their microtexture frequencies calculated. Specific sets of microtextures were identified and classified (Group I–III) using principal component analysis (PCA) and cluster analysis. The statistically analysed microtextural data were used to identify signals of continental processes that operated during the late Pleistocene (MIS 4 to MIS 3) in the Eurasian Arctic. The microtextures of Group I generally formed as a result of prolonged fluvial/alluvial or aeolian transport. The glacial microtextures of Groups II and III indicate subglacial conditions and transport. Based on the data, two principal components seem to characterise late Pleistocene continental environmental conditions – glacial and non-glacial. There is a signal of non-glacial continental processes in the ice-rafted grains at around 62, 64 and 67 ka ago. A signal of subglacial processes was observed in the grains at around 26, 34, 42 and 45 ka and, concurrent with non-glacial, at around 62 and 64 ka ago. We suggest that these signals in MIS 4 sediments are related to deglaciation with an increased supply of glacial sediment to the Arctic Ocean, whereas during MIS 3 they were probably related more to iceberg calving from the oscillating Barents-Kara ice sheet.

1. Introduction

Multiproxy data from marine sediments can provide valuable information for understanding the environmental evolution and dynamics of the ice sheets on the continents (Knies et al., 2000, 2001, 2009; Spielhagen et al., 2004; O'Regan et al., 2008, 2010). Multiproxy data from sediment cores from the Arctic Ocean, for example, indicate that major ice-rafted detritus (IRD) and meltwater events occurred at certain time intervals during the last glaciation, and this data linked with geological data from terrestrial sediment sequences has been applied to reconstruct the glaciation history of the Eurasian north during the last glaciation (e.g., Svendsen et al., 2004; Larsen et al., 2006) (Fig. 1a and b). Based on this approach, a relatively clear picture has emerged of the history of the Eurasian ice sheets during the last Weichselian glaciation (cf. Larsen et al., 1999; Thiede, 2004; Kjær et al., 2006a,b). It is presently widely accepted that the Barents ice sheet and especially the Kara ice sheet were most extensive during the Early Weichselian (c. 100–80 ka), occupying the Arctic Sea shelf areas and the northern parts of mainland Russia, while the extent of the Scandinavian ice sheet was limited to Scandinavia and Finnish Lapland (cf. Svendsen et al., 2004; Larsen et al., 2006). It is also well established that the Scandinavian ice sheet was at its largest during the Late Weichselian (c. 20–17 ka), when the extent of the Kara and Barents ice sheets was smaller compared with their Early Weichselian glacial maximum (cf. Svendsen et al., 2004; Larsen et al., 2006). However, there is some controversy over the exact timing of the Barents and Kara ice sheet expansions and ice-free intervals during the Early and Middle Weichselian (Fig. 1b). Particularly, the Kara and Barents ice sheet history during the Middle Weichselian—a time span correlating with the marine isotope stages (MIS) 3 and 4 (c. 74–25 ka)—is still disputed. Based on comprehensive data from onshore sediment sequences and the correlation between terrestrial data and results obtained from marine sediment cores from the Arctic Ocean (Spielhagen et al., 2004), Svendsen et al. (2004) concluded that the western Barents Sea area became covered by the Barents Ice Sheet during MIS 4 (74–59 ka). Svendsen et al. (2004) also concluded that the Barents Ice Sheet reached the shelf edge in the youngest part of MIS 4 (c. 65 ka) and the ice

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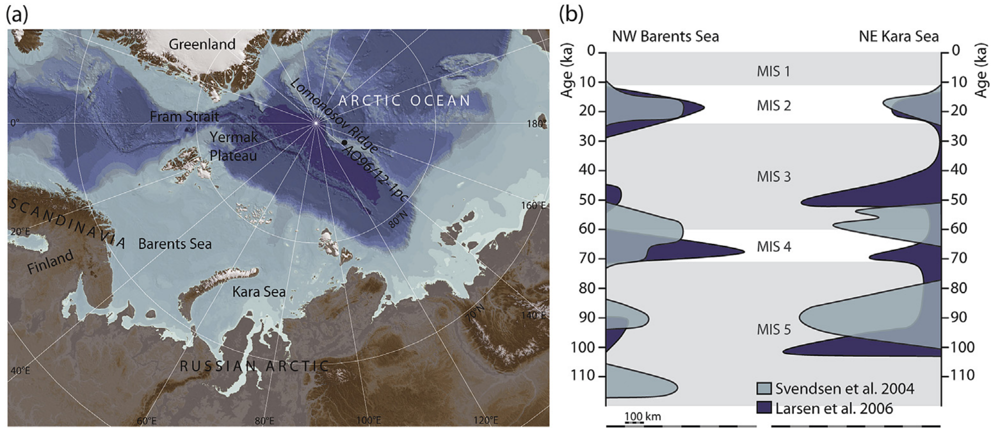

Fig. 1. (a) Map showing the location of the Eurasian Arctic. Coring site AO96/12-pc is also indicated. The bathymetric portrayal is based on the International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0 (Jakobsson et al., 2012). (b) The Weichselian glaciation curves for the Barents Sea and the Kara Sea areas according to Svendsen et al. (2004) and Larsen et al. (2006).

remained there until the oldest part of MIS 3 (c. 57 ka). According to them, the Kara Ice Sheet started to grow slightly later than the Barents Ice Sheet, and the Kara Ice Sheet attained its largest extent between c. 65–50 ka, after which the glaciers deglaciated prior to their re-growth in the Late Weichselian (MIS 2).

Using data obtained from sediment sequences on land and comparing these data with marine IRD and meltwater event data presented by Spielhagen et al. (2004) and Siegert et al. (2001) from the eastern Arctic Ocean and NW Barents Sea, Larsen et al. (2006) revised the Middle Weichselian ice sheet history by Svendsen et al. (2004). In the Larsen et al. (2006) reconstruction the Barents Ice Sheet started to grow in the early part of MIS 4 at around 72 ka and attained its largest extent at c. 65 ka and then deglaciated rapidly by 60 ka, while the Kara Ice Sheet remained relatively small between 70 and 65 ka. After the subsequent ice-free period, Kara Sea-dominated glaciation took place in MIS 3 between c. 55–45 ka when the Kara Ice Sheet was thought to expand to the shelf edge in the north and onshore northern Russia to the south (Larsen et al., 2006). Therefore, the major difference between these two Middle Weichselian ice reconstructions in the Eurasian north is that the data from Larsen et al. (2006) suggest major Kara Sea glaciation at c. 55–45 ka with no or relatively little ice in the Barents Sea area, whereas Svendsen et al. (2004) conclude that the major glaciation centre was in the Barents Sea area at 65–57 ka and the Kara Ice Sheet was at its largest at c. 58 ka (Fig. 1b).

Sediment core data from the central Arctic Ocean, the Fram Strait and the Yermak Plateau indicate that conspicuous IRD-rich layers were deposited in the youngest part of MIS 4 and the oldest part of MIS 3 (Jakobsson et al., 2000, 2001; Vogt et al., 2001; Spielhagen et al., 2004). These layers are often interpreted as glacial debris derived from calving ice sheets, thus being related to the growth and decay of the Eurasian ice sheets, since it is generally assumed that the North American and Greenland ice sheets had minimal input to IRD deposition in the Eurasian Basin or the Lomonosov Ridge (e.g. Haley et al., 2008a; Haley et al., 2008b). However, the origins of the IRD material have not been studied in detail so far. Therefore, in this study, we used quantitative quartz grain microtextural analysis of IRD sediments obtained from marine core material from the Lomonosov Ridge (Fig. 1a) first to determine the microtextural characteristics of the quartz sand grains and then to define the proportions of the characteristic microtextures. This was done to shed light on glacial/non-glacial continental processes that were responsible for the microtextural characteristics of the quartz grains. This data was subsequently applied to reveal the presence/absence of glacier ice on land in the Eurasian Arctic during the Middle Weichselian between c. 70–25 ka (i.e. MIS 3 and 4).

2. Materials and methods

2.1. Sediment core and lithology studied

A sediment piston core 96/12-1pc (Fig. 1a) was obtained from the Lomonosov Ridge crest (144°46.4′E, 87°05.9′N) during the 1996 Arctic Ocean expedition (AO96). An age model for the upper 2.2 mbsf of the core is based on nannofossil biostratigraphy (Jakobsson et al., 2000). According to this age model, the core interval from 0.425 mbsf (the uppermost sample of this study) to 1.576 mbsf (the lowermost sample of this study) covers c. 41 ka during MIS 3 and MIS 4. The uppermost part of the sediment core is composed of yellowish-brown to yellowish-grey silty clay with some millimetre-scale sand layers at the bottom. A sharp contact at 1.15 mbsf distinguishes these sediments from an underlying 48-cm-thick layer of homogenous dark grey silty clay (Jakobsson et al., 2000, 2001) which also contains a significant component of sand (20–40 wt %). This layer has a sharp lower contact with underlying olive grey silty clay from 1.63 to 1.86 mbsf, which then grades downwards to alternating light and dark brown clay.

2.2. Sample preparation and analysis

Thirteen sediment samples with approximately 10-cm intervals were wet-sieved to separate the grain-size fractions, which ranged from 250 to 600 μm. The separation methods were adopted from McManus (1988). The samples were prepared for scanning electron microscopic (SEM) analysis according to Trewin (1988). A total of 520 quartz grains, 40 grains from each sample, were randomly selected and their surface microtextures were analysed using a Jeol JSM-6400 SEM at the Center of Microscopy and Nanotechnology at the University of Oulu. An Inca energy dispersive spectrometer (EDS) was calibrated for cobalt and used for the elemental analysis to confirm whether the grains were composed of silica.

2.3. Microtextural description and statistical analyses

The grain shape, surface type and microtextural content of each grain were observed based on the SEM photomicrographs. The magnifications varied in the range of x100–x300. The surface microtexture classification, interpretation and terminology are predominantly based on previous studies (Mahaney et al., 1996,