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Entrainment of fine-grained surface deposits into new ice in the southwestern Kara Sea, Siberian Arctic

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ABSTRACT

The entrainment of bottom deposits (silt and clay) into newly formed ice was investigated in the Amderma/Vaygach flaw lead in the southwestern Kara Sea, Siberian Arctic. Fine-grained bottom deposits and sea ice sediments (SIS) were analyzed by granulometry, scanning electron microscopy and X-ray diffractometry. On average, SIS contain by a factor of four times more silt than the shelf deposits (66.7% vs. 16.3%), and the SIS clay percentage is more than three-fold of the bottom value (31.2% vs. 9.1%). Sand-sized particles are significantly less abundant in SIS compared to bottom sediment (2.1% vs. 74.6%). The preferred entrainment of silt into ice is underpinned by the enhanced silt-to-clay-ratio in SIS compared to bottom deposits. Though silt is preferably entrained into SIS, no evidence was found for preferential ice-entrainment of any silt sub-fraction (coarse, medium or fine). However, sub-angular- and angular-discoidal silt particles are favorably entrained into local sea ice. Clay mineral assemblages in SIS and shelf surface sediments match very well revealing that no individual clay mineral is preferably enriched in SIS or reduced at the bottom. The general textural, compositional and statistical match of fine-grained shelf surface deposits and SIS proves that bottom sediment is the principle source for ice-entrained material in the study area. We propose e.g. wave action and thermohaline convection to take sediment particles upward from the bottom nepheloid layer into the well-mixed 10–40 m deep water column of the Amderma/Vaygach flaw lead, and the turbulent process of suspension freezing to bring sediment particles and frazil crystals into contact, finally leading to the formation of sediment-laden ice. The role of SIS entrainment and export for local/regional shelf erosion and coastal retreat is of minor importance in the SW Kara Sea compared to other circum-Arctic shelf seas. However, the characteristic clay mineral assemblage of local SIS and bottom deposits can help identify the origin of SIS both on regional and Arctic-wide scales.

1. Introduction

Insights on the entrainment of fine-grained particulate material into newly formed sea ice, based on field investigations, have been gained for most of the shallow western Arctic, Siberian and Russian Arctic shelves over the past three decades (Osterkamp and Gosink, 1984; Kempema et al., 1988; Reimnitz et al., 1992, 1993, 1998; Nürnberg et al., 1994; Eicken et al., 1997, 2000, 2005; Dethleff et al., 2000; Stierle and Eicken, 2002; Darby, 2003; Ogorodov et al., 2004; Dethleff, 2005). However, knowledge of turbulent entrainment processes and related hydrodynamic mechanisms particularly in the Siberian Kara Sea are still very meager, and widely rely on modeling efforts (Harms et al., 2000; Sherwood, 2000; Smedsrud, 2003).

Minimum concentrations of sea ice sediments (SIS) in the Arctic are a few $mg\,l^{-1}$, while turbid sea ice mostly contains about ~50–500 $mg\,l^{-1}$ with maximum concentrations of as much as 1000–3000 $mg\,l^{-1}$ (Osterkamp and Gosink, 1984; Larssen et al., 1987; Kempema et al., 1988; Reimnitz et al., 1993; Stierle and Eicken, 2002). Sedimentological, clay mineralogical and geochemical aspects of sediment entrainment and processes of SIS transport in the Arctic Ocean were discussed e.g. by Nürnberg et al. (1994), Eicken et al. (1997), Reimnitz et al. (1998), Dethleff et al. (2000), Darby (2003), and Dethleff (2005). Based on numerical drift simulations and clay mineral investigations, Pfirman et al. (1997) and Harms et al. (2000) identified parts of the eastern Kara Sea and the entire Laptev Sea as the main contributors to Arctic SIS transport toward the ablation areas of Fram Strait. Evidence was found that also Canadian Arctic Seas contribute to SIS today, and over geological time scales (e.g. Darby et al., 2002; Darby, 2008).

According to Campbell and Collin (1958) and Reimnitz et al. (1992), the process of suspension freezing is the most effective

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entrainment mechanism for SIS. Supercooling of the water during cold and stormy weather conditions leads to the formation of frazil ice, which may intensively interact with sediment particles in the turbulent water column at shallow locations in open water areas like flaw leads (long-extended openings between coastal fast ice and drifting ice) and polynyas (circular openings in sea ice) (Darby, 2003; Dethleff, 2005). The water column mixes down to the shelf bottom (~50 m at maximum), and turbulent scavenging and filtration of (re)-suspended particulate matter by rising ice crystals promote the entrainment and enrichment of particles in newly forming ice (Osterkamp and Gosink, 1984; Reimnitz et al., 1993).

Kempema and Dethleff (2006) and Dethleff and Kempema (2007) proposed Langmuir circulation as one of the main turbulent hydrodynamic mechanisms contributing to the process of suspension freezing, which promotes the entrainment of silt and clay-sized particulate material into the newly forming ice cover. This fine-grained material generally represents >90% of the sediment found in Arctic SIS samples (Wollenburg, 1993; Reimnitz et al., 1998; Dethleff, 2005). In this study, we focus on the silt and clay fractions from SIS and shelf sediment samples collected in the Kara Sea.

The Kara Sea is a semi-enclosed Siberian Arctic shelf sea bordered by Novaya Zemlya to the west and north, and by the Severnya Zemlya Archipelago to the east (Fig. 1). From November to June, the sea is generally ice covered. New frazil and grease ice are produced in shallow open water like flaw leads and polynyas throughout the winter (Martin and Cavalieri, 1989; Cavalieri and Martin, 1994; Kern et al., 2005; Kern, 2008). The Amderma/Vaygach flaw lead (Fig. 1) borders the narrow band of coastal fast ice off the coast of the Yugorskyi Peninsula and Vaygach Island. Water depths at this location extend down to ~40 m. According to the present knowledge, turbulent entrainment of shelf surface deposits into newly formed ice occurs most effectively at least down to this depth (Reimnitz et al., 1993; Dethleff, 2005), though there is evidence for much deeper convective circulation over the shallow Siberian shelf (Pavlov et al., 1994).

The purpose of this study is to compare bottom deposits and SIS from shallow sites in the restricted southwestern Kara Sea Amderma/Vaygach flaw lead in order to provide sedimentological and mineralogical evidence for the entrainment of fine-grained particulate material into locally formed lead ice. We compare the bulk composition (sand/silt/clay = S/S/C) of samples, but

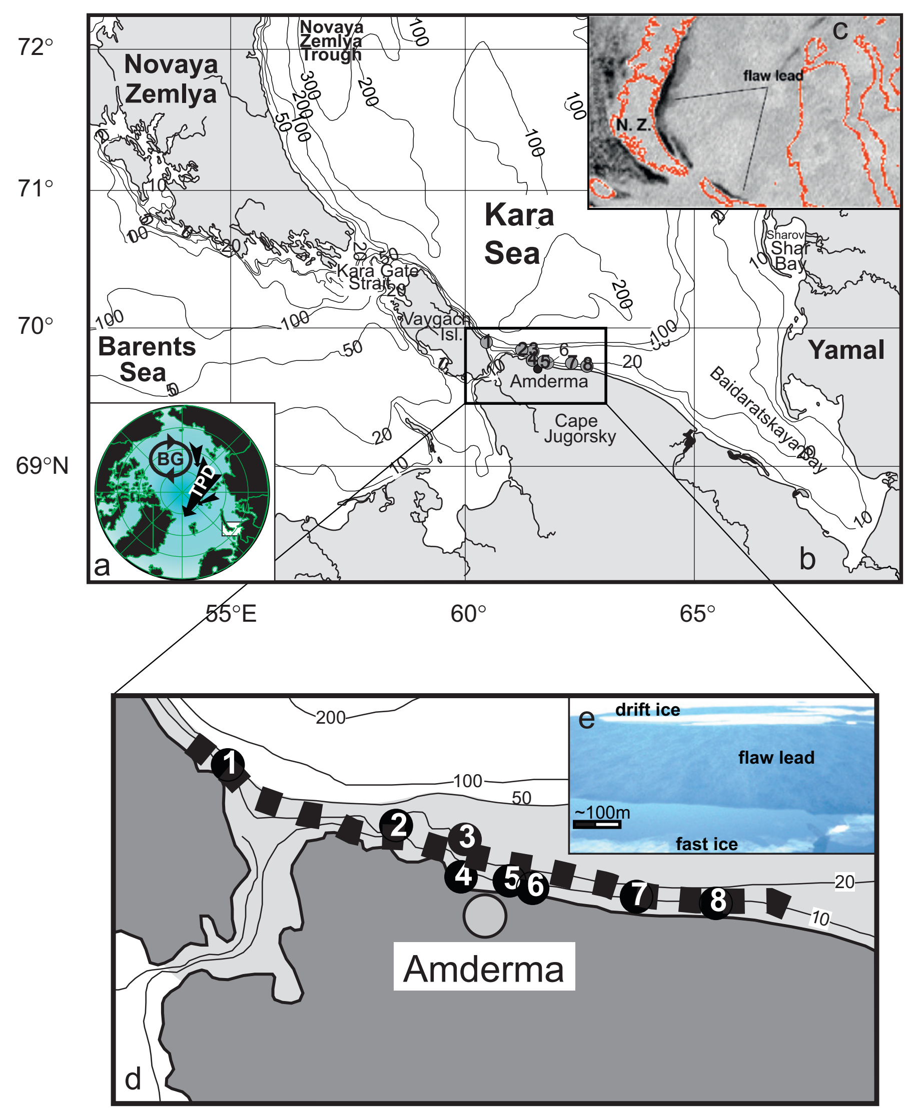

Fig. 1. (a) Showing the main Arctic ice drift patterns with BG denoting "Beaufort Gyre" and TPD representing "Transpolar Drift" and (b) illustrating the Kara Sea map. (c) Shows the coastal flaw leads in the Aderma/Vaygach region and along the eastern coast of Novaya Zemlya (photo courtesy NOAA; NOAA-12 satellite, 10th April 1993). Southern Kara Sea map (d) displays sampling sites and shelf regions available for turbulent SIS entrainment (light grey area). The black dotted line indicates the Vaygach/Amderma flaw lead, which is also shown in the photograph inlet from aerial view (e).