The relation between sea ice stratigraphy and particle concentration in an Alaskan coastal lagoon

Masato Ito[1], Andrew R. Mahoney[2], Chris M. Polashenski[3,4], Takenobu Toyota[5], Sumito Matoba[5] and Takashi Kikuchi[1]
[1]*Japan Agency of Marine-Earth Science and Technology, Yokosuka, Japan*
[2]*Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA*
[3]*Thayer School of Engineering, Dartmouth College, Hanover, NH, USA*
[4]*U.S. Army Cold Regions Research and Engineering Laboratories, Hanover, NH, USA*
[5]*Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan*

Incorporation, transport and release of particulate matters by sea ice associated with sea ice formation, drift and melt significantly play important roles in material cycle in polar oceans. In particular, sediment-laden ice, so-called dirty ice, is widespread over the whole Arctic Ocean (Nürnberg et al., 1994; Eicken et al., 2005; Darby et al., 2011). This ice potentially contributes to dispersal of pollutants (Pfirman et al., 1995; Cooper et al., 1998). The entrainment process of particulate matters into sea ice have not been well understood. Campbell and Collin (1958) proposed underwater interaction of resuspended sediment with frazil ice under turbulent conditions with heavy waves or swells before freeze-up. This mechanism is referred as suspension freezing. A few field measurements reported that high sediment concentration was found in granular ice layers which are formed through consolidation of frazil and grease ice (Osterkamp & Gosink, 1984; Eicken et al, 2000, 2005; Stierle & Eicken, 2002). Mooring observations with acoustic instruments suggested that suspension freezing can occur in shallow polynya or sea-ice edge regions (Ito et al. 2017, 2019). In spite of these efforts of field works, more field observations are required in order to reveal the general process to supply particulate matters with sea ice and the source of the matters. In late spring of 2017 and 2019, we sampled sea ice cores and snow on the ice in Elson Lagoon located at the northernmost part of Alaska. This study analyzes sea ice stratigraphy and size distribution of particulate matters inside sea ice and snow.

Figure 1 shows a typical example of photograph and thick and thin section of the sea ice core. This core included a sediment-laden layer from the top to 1.40 m (Fig. 1a). Thin ice sections obviously show that the sediment-laden layer coincide with granular ice (Fig. 1c). Below the sediment-laden layer was clear layer of columnar ice (Figs. 1a and 1c). This fact strongly indicates that sediment was incorporated into sea ice associated with frazil ice formation and subsequent consolidation. For 2019 observation, five sediment-laden cores were obtained within the area of 2 km distance, and the thickness of sediment-laden layers was 0.27 – 1.41 m. All sediment-laden layers completely corresponded to granular ice, and these layers presented around the top or middle of the cores. The grain size of granular ice for sediment-laden layer was same over the all five cores. The thickness difference of granular ice is likely attribute to dynamical ice growth processes before freeze-up such as rafting of pancake ice, implying turbulent conditions with heavy waves. This situation can induce sediment resuspension and frazil ice formation, and is suitable to generate suspension freezing. Thus, we interpret that seafloor sediment was entrained into sea ice through suspension freezing.

Size distributions of particulate matters contained in sea ice were analyzed with the Coulter counter (Beckman, Maltisizer 3). Regardless of sea ice stratigraphy, ~90% of the particulate inclusions are very fine silt and fine silt (diameter < 16 μm). The particle number decreases exponentially with an increase in the diameter. On the other hand, larger particles well contribute to total inclusion volume due to their relatively large own volume. For the sediment-laden layers, in particular, fine silt (8 μm ≤ diameter < 16 μm) and coarse silt (16 μm ≤ diameter < 31 μm) particles mainly dominate the total inclusion volume. Although the size distribution of particulate inclusion is strongly dependent on that of seafloor sediment, silt size particles are likely main contributor to cycling particulate matters associated with sea ice form and decay as suggested by early studies (e.g. Darby et al., 2011).

Both of particle number and volume concentration for sediment-laden layers were 1 order higher than those for columnar ice or 2 orders higher than snow accumulation on the ice. This fact indicates that seafloor sediment is major source of particulate inclusion of sea ice and it is mainly entrained into sea ice through suspension freezing. Sea ice is not likely to entrain particulate matters which originate from seafloor sediment during downward thermal ice growth. There was a gap of particle concentration at the boundary between granular ice (sediment-laden layer) and columnar ice, implying that particulate inclusions are not redistributed inside sea ice. Columnar ice included more particles than snow accumulation in this case. Remineralization occurred in brine can contribute to supply particulate matters with sea ice as mentioned by Nomura et al. (2010). Skeletal layer with ~0.1 m in thickness was formed from the bottom of the ice (Figs. 1a, 1b and 1c). Particle concentration for this layer was same order as that for sediment-laden layer, even though the concentration was higher for sediment-laden layer. Seawater exchanged between bottom skeletal layer and underlying ocean. Suspended particle matters can entrain into skeletal layer associated with this process.

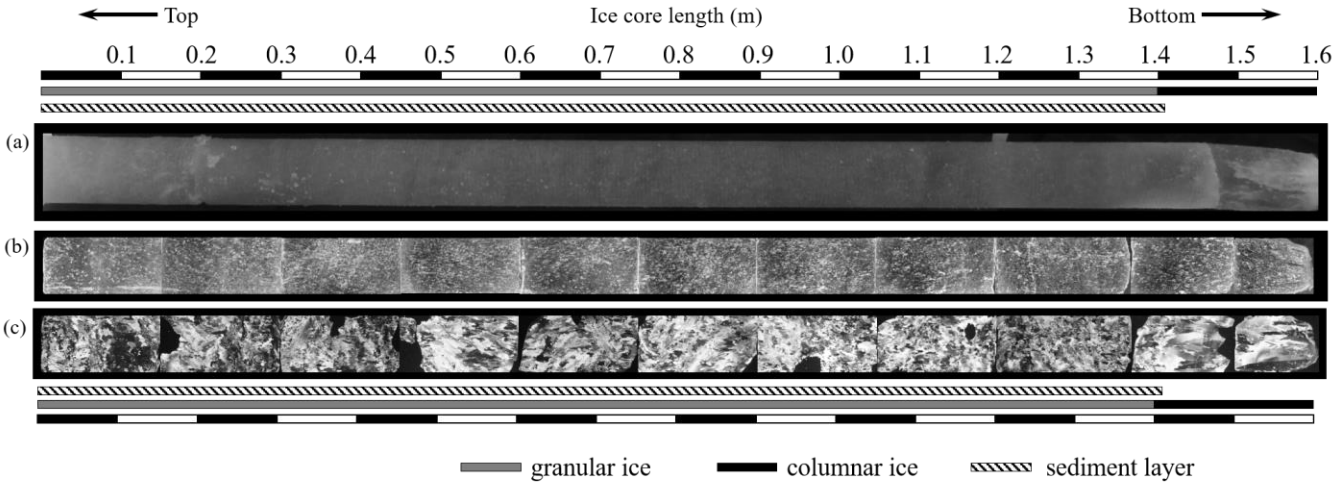

Figure 1. Typical example of (a) sediment-laden sea ice core and (b and c) its thick and thin sections. Bars above (a) and below (c) indicate ice stratigraphy and sediment-laden layer. The core thickness was 1.60 m, and the core was extracted through full-thickness.

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