Near-shore Arctic Subsea Permafrost in Transition

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Models and geophysical data indicate that large areas of the Arctic shelves are underlain by subsea permafrost. As a result of their exposure during the last glacial maximum, the shelves are thought to be almost entirely underlain by permafrost from the coastline down to a water depth of about 100 m. Subsea permafrost is still poorly understood, mainly due to the lack of direct observations. Large volumes of methane in gas hydrate form can be stored within or below the subsea permafrost and the stability of this gas hydrate zone is sustained by the existence of permafrost. Degradation of subsea permafrost and the consequent destabilization of gas hydrates could significantly if not dramatically increase the flux of methane to the atmosphere.

New evidence from a coastal and offshore drilling program in the western Laptev Sea confirms the existence of frozen sediments on the shelf. Based on geocryological, thermal and pore water/ice salinity data it is possible to understand the evolution of subsea permafrost during and after inundation. The boundary between upper unfrozen and lower frozen sediments rapidly decreases in elevation with increasing distance from the coast. The subsea permafrost is warm and saline above the phase boundary. The presence of unfrozen and saline permafrost suggests that permafrost may not be as cold or thick as predicted by thermal modeling.

The formation and distribution of subsea permafrost

"Subsea permafrost" describes sediment or rock that has remained below 0 °C for two or more years. Freezing point depression by saline pore solution can result in unfrozen permafrost (Osterkamp 2001). Thus, subsea permafrost may be ice-bonded (cemented by ice), ice-bearing (containing some ice) or ice-free. We use “frozen” and “unfrozen” to refer to the presence and absence of ice.

Subsea permafrost is generally created by the flooding of terrestrial permafrost due to sea level rise or coastal retreat. The distribution of this relict permafrost depends on regional glacial and sea level histories. Subsea permafrost is thought to be common on the shallow Siberian shelves, which were not glaciated during the last glacial cycles and were subject to a severe, continental climate during low sea level periods (Figure 1). Seawater temperature and sediment salinity control the current thermal state of subsea permafrost. Negative mean annual sea temperatures can result in the formation of new subsea permafrost.

Current data on the distribution of subsea permafrost is mostly derived from thermal modeling (e.g. Hubberten and Romanovskii 2003, Lachenbruch 1982) and geophysical data (Rekant et al. 2005) but some offshore drilling results are available as well (e.g. Dallimore 1991, Osterkamp et al. 1989).

New evidence from offshore drilling

In April 2005 a coastal and offshore drilling program entitled COAST took place in the western Laptev Sea (Figure 1). Five boreholes were drilled and cored along a transect running perpendicular to the coastline. The transect extended from onshore (core C1) to 12 km offshore (cores C2 to C5), where the water depth reached 6 m. A dry drilling technique and a casing prevented sea water infiltration. We present geocryological core descriptions, borehole temperatures and pore water/ice salinities. Supplementary data include oxygen and hydrogen isotope concentrations of the pore ice and IR-OSL

(Infrared Optical Luminescence) age determinations of sediment from the deepest borehole (C2).

The transect was located in the western Laptev Sea for three reasons:

(1) Warm and less saline river water has little influence on this part of the Laptev Sea due to the absence of larger rivers.

(2) The coastal onshore region has been intensively studied. Sediments are generally ice-rich (>80% by volume) permafrost deposits of the Pleistocene Siberian Ice Complex.

(3) Permafrost has been modeled for the region. Recent results suggest that ice-bearing continuous permafrost with a thickness of 400-600 m can be expected in the coastal offshore zone, whereas the coastal onshore permafrost should be 700-1000 m thick (Romanovskii et al. 2005). Coring at this location thus provides a test for model results.

Figure 1 illustrates the results of the drilling program. All offshore cores (C2-C5) contained frozen sediments, and the phase boundary elevation decreased with increasing distance from the shore. Sediments are mostly sandy except for the lowermost section of C2 (below 64.7 mbsl) which consists of fine-grained mud. Sediment that has remained frozen since inundation was encountered in C2 at a depth of 35.5 m below sea level (mbsl). The typical cryogenic structures (ice veins) of ice-bonded terrestrial permafrost deposits are clearly seen in Figure 2, which shows a photograph of a segment of C2 from 44.8 mbsl and terrestrial permafrost sediments obtained from C1 (50 m depth). Pore ice samples from C2 at 42-45 mbsl have $\delta^{18}O$ values of -28.2 to -26.7 and δD values of -220 to -208 (‰ vs. SMOW). The low isotope values agree well with values from the Siberian Ice Complex, and indicate that the ice was formed from winter precipitation during cold Pleistocene climate conditions (Meyer et al. 2002).

Considering the model data summarized above, a surprising result is that C2 encountered almost completely unfrozen sediments below a depth of 64.7 mbsl (Figure 1). This observation raises the question of whether present models hold true for subsea permafrost thickness and distribution throughout the whole Laptev Sea shelf.

Salinity and temperature distribution of subsea permafrost

Figure 3 illustrates temperature and pore water/ice salinity profiles. Borehole temperatures decrease from the coast offshore. The temperature was -12.4 °C in the deepest part of the terrestrial borehole C1 (not shown) and lay between -1 and -1.5 °C in the lower section of C2. The bottom water temperatures and salinities correspond to the freezing point of sea water (-1.5 to -1.7 °C and 29-32 ‰, Figure 3). Except for C5, pore water salinities of the upper unfrozen sediments are similar to bottom water and drop to almost 0 ‰ at the phase boundary. In C2 this drop is less abrupt and occurs a few meters above the boundary, in the absence of a change in sediment texture. This could be the result of mixing between downward moving saline pore water and upward moving freshwater from the thawing permafrost below, or indicate a transition from convective to molecular diffusion (Hutter and Straughan 1999).

Based on isotope data, the lowermost unfrozen sediments in C2 (below 64.7 mbsl) contain marine pore water with salinities reaching 30 ‰. At temperatures of -1 to -1.5 °C these marine sediments remain unfrozen. IR-OSL age determinations of 111.1 ± 7.5 ka for the lowermost section of core C2 (77 mbsl) indicate that these marine sediments could be of Eemian age (Marine Isotope Stage 5e). The Eemian was the second-to-latest interglacial phase. A similar sequence of interbedded frozen and unfrozen layers has been described for the Canadian Beaufort Sea (Blasco 1995).

Borehole C5 was drilled from sea ice frozen to the beach sediments. Nevertheless, 8-10 hours after drilling the borehole filled with water at a temperature of -5 to -7°C and a salinity of over 100 ‰. Sea ice and bed freezing, salt exclusion and downward brine movement created an unfrozen layer between 2 and 2.8 mbsl. Such hypersaline, partly unfrozen layers (cyropegs) within ice-bonded permafrost have also been described for the region off Prudhoe Bay (Osterkamp et al. 1989).

Subsea permafrost does not necessarily represent a rocklike ice-bonded layer but is sometimes ice-free. In the presence of negative seabed temperatures, sufficiently saline pore waters are required for subsea permafrost to thaw and, as their salinity increases, the thawing rate increases. The boundary between unfrozen and underlying frozen sediments declines in elevation more rapidly off the coast than expected based on modeling predictions. Based on modern coastal erosion rates, the results of the present study show that the upper surface of the frozen sediments may reach 35 mbsl (30 m below sea floor) after only 2500 years of inundation.

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Figure Captions

Figure 1. Location and geometry of the COAST drilling transect. The map insert shows the distribution of subsea permafrost according to Brown et al. 1998.

Figure 2. Subsea permafrost deposits retrieved from borehole C2 (lower core; 12 km off the coast, 44.8 mbsl) showing the typical cryogenic structures (ice veins) of ice-bonded terrestrial permafrost. Terrestrial permafrost deposits obtained from borehole C1 (upper core; 50 m depth) are shown for comparison.

Figure 3. Salinity and temperature profiles of the boreholes C2-C5. See text for explanation. Boreholes were completed on April 14, 19, 20, 22 and 25 (C1 to C5, respectively). Temperatures were measured between 1 and 9 days after drilling with an accuracy of better than 0.1 °C.

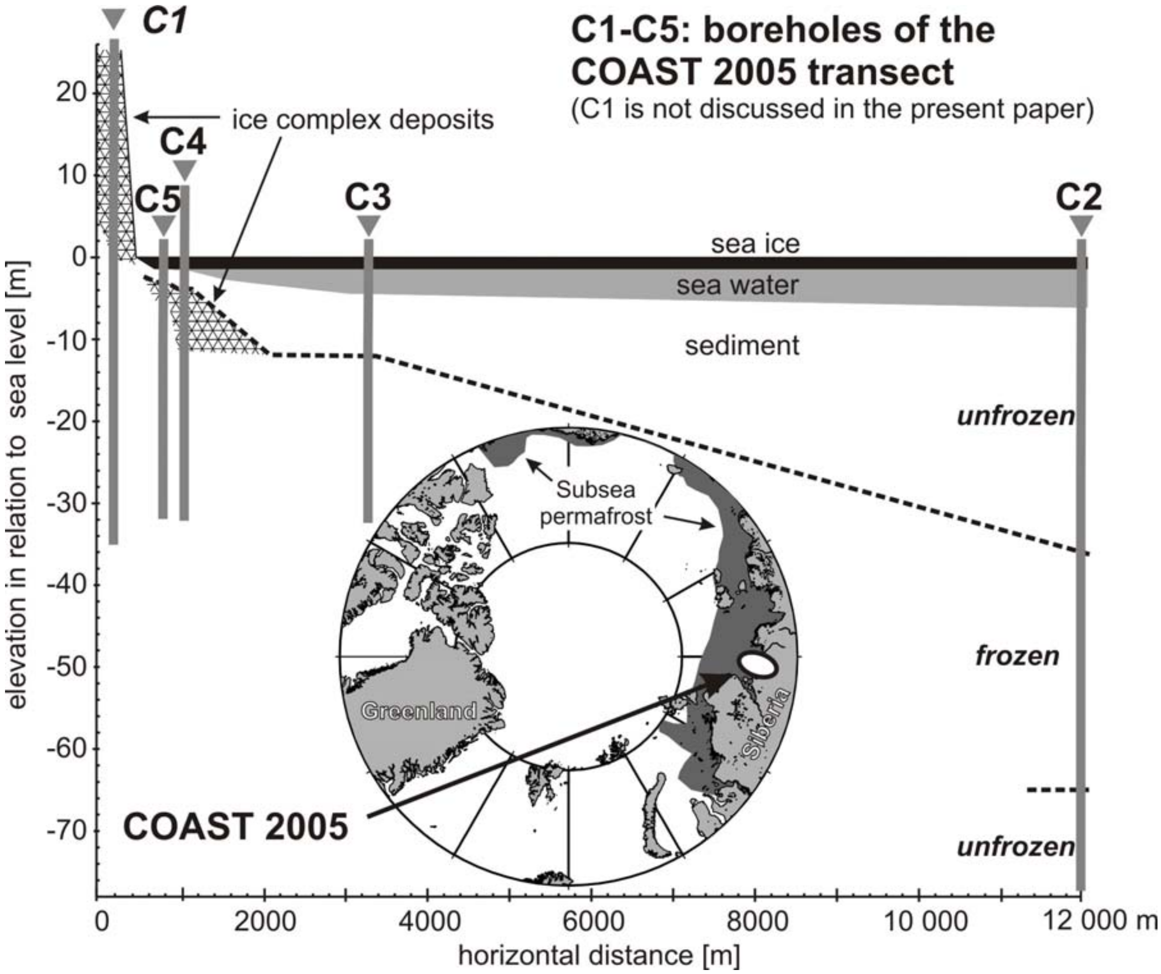
C1
C1-C5: boreholes of the
COAST 2005 transect
(C1 is not discussed in the present paper)
ice complex deposits
C4
C5
C3
C2
sea ice
sea water
sediment
unfrozen
frozen
unfrozen
Subsea
permafrost
Greenland
Siberia
COAST 2005
elevation in relation to sea level [m]
horizontal distance [m]
0
2000
4000
6000
8000
10 000
12 000 m
20
10
0
-10
-20
-30
-40
-50
-60
-70

Figure 1


1 - 2005
C-1
Run#:
of core:
cm in bag:
50.0 m
125 126 127
COAST 1 - 2005
C-2
Date:
Run#:
Length of core:
Bag#:
cm in bag:
44.8 m

Figure 2

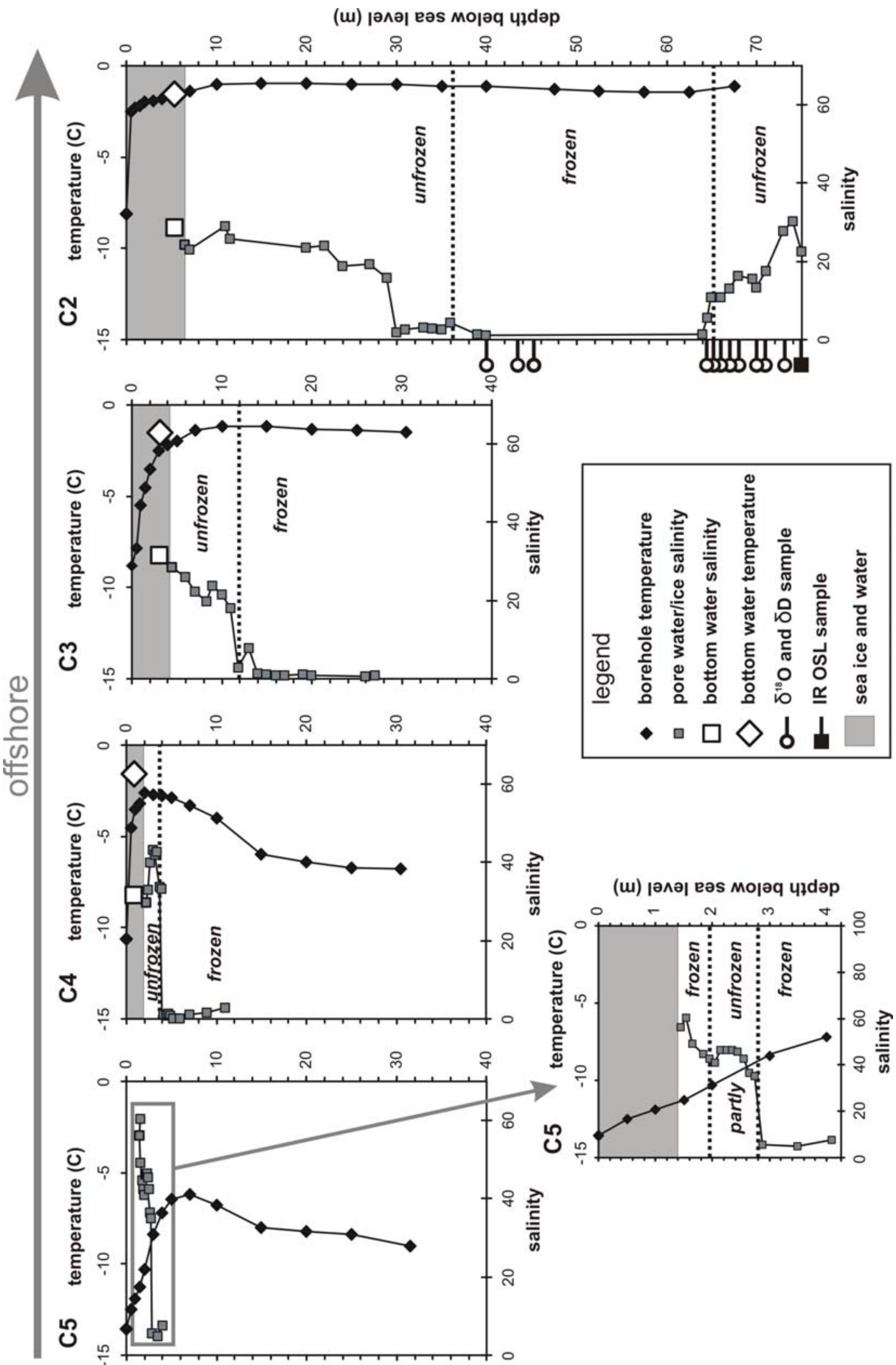
offshore
C5
C4
C3
C2
temperature (C)
salinity
depth below sea level (m)
unfrozen
frozen
partly
legend
borehole temperature
pore water/ice salinity
bottom water salinity
bottom water temperature
δ18O and δD sample
IR OSL sample
sea ice and water

Figure 3