Ice-wedge stable isotopes at the Dmitry Laptev Strait (Northeast Siberian Arctic) – indications for Late Quaternary stratigraphy and paleoclimate

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1 Ice wedges as winter climate archives

- In permafrost regions, winter thermal contraction cracking of the ground and subsequent filling of frost cracks mostly by snow melt in spring lead to the formation of vertical ice veins
- Repetition of frost cracking and crack filling over time lead to the growth of ice wedges that shape the polygonal tundra surface (Figure 1)
- Ice wedges are considered as climate archive for meteorological winter and spring, i.e. the cold period of the year (DJFMAM, here referred to as winter; Meyer et al., 2015)
- Their isotopic composition (δ18O, δD) is interpreted as proxy for local surface winter temperatures
- Ice wedges can be directly dated by ^{14}C dating and the $^{36}Cl/Cl^-$ approach (Blinov et al., 2009), indirect age attribution is possible by dating the surrounding sediments using different methods or isotope-based cryostratigraphic correlation

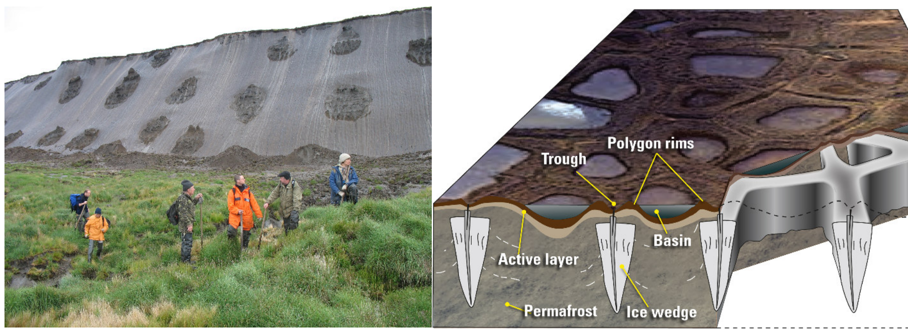
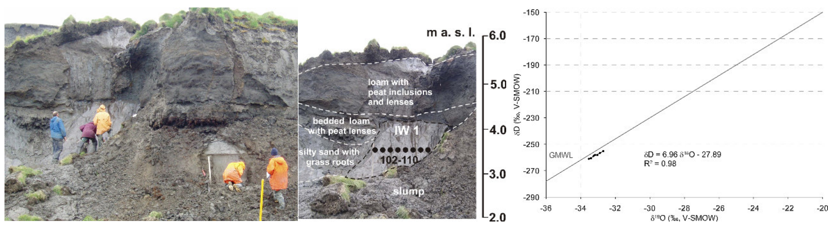


Figure 1 Yedoma Ice Complex wall in summer 2007 and schematic cut-away of ice-wedge polygons (R. Mitchell/Inkworks).

3 MIS5 Ice Complex (Buchchagy)

- Isotope-based cryostratigraphic correlation to ice wedge L7-15 IW1 at Bol'shoy Lyakhovsky Island, constrained to about 120 to 90 kyr (Wetterich et al., 2016)
- In contrast, OSL ages of about 80 kyr for sediments underlying ice wedge Oy7-07 IW1
- Stable-isotope values (mean δ18O -33‰) reflect very cold winter temperatures



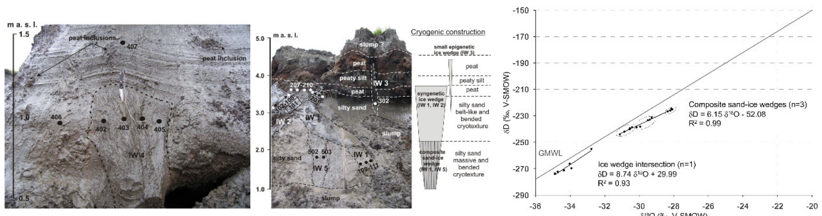
Oy7-07 IW1			
	δ18O	δD	d exc
Mean	-33.1	-258.3	6.7
Min	-33.5	-261.1	6.1
Max	-32.7	-255.1	7.2

Figure 4 Overview photograph, detailed photograph and co-isotope plot for Oy7-07 IW1.

4 MIS4 flood plain deposits (Kuchchugui)

- Sediment age information from OSL (about 70 to 80 kyr) and infinite ^{14}C ages (>43 kyr), ice-wedge ages from $^{36}Cl/Cl^-$ (68±31kyr and 98±31kyr; Blinov et al., 2009)
- Buried composite sand-ice wedges (CSIW) and multi-stage ice-wedge intersection (passing downwards into CSIW) (Figure 5)
- CSIW may show different formation conditions or stages of strong isotopic alterations
- Ice-wedge δ18O (mean -34‰) reflects coldest winter temperatures

→ Ice wedges may be initial stage of MIS 3 Yedoma Ice Complex?

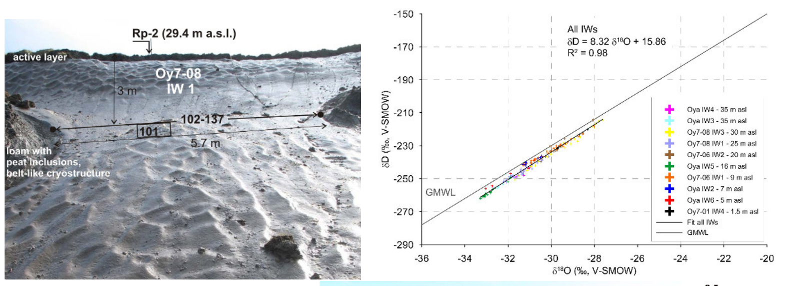


CSIW			
	δ18O	δD	d exc
Mean	-29.7	-234.7	2.7
Min	-31.1	-243.8	-0.4
Max	-28.1	-224.7	5.1
IW intersection			
	δ18O	δD	d exc
Mean	-34.1	-268.0	4.9
Min	-34.9	-273.6	1.8
Max	-32.8	-255.1	7.1

Figure 4 Photographs of composite sand-ice wedge, multi-stage ice wedge intersection, and co-isotope plots.

5 MIS3 Ice Complex (Yedoma)

- Sediment age information from ^{14}C dating reveals Ice Complex formation between at least 48.5 to 32.2 kyr (Schirrmeister et al., 2011)
- In places, Holocene development on top of the Ice Complex revealed by ^{14}C ages and Holocene ice-wedge isotope signatures, i.e. δ18O > -27.5‰, the corresponding data are not considered here
- δ18O of ten ice wedges (mean -29‰ to -33‰) reflect non-stable cold to very cold winter tempertures during the MIS 3



IC all ice wedges			
	δ18O	δD	d exc
Mean	-30.8	-240.2	5.9
Min	-33.3	-262.1	2.7
Max	-27.6	-214.2	10.2

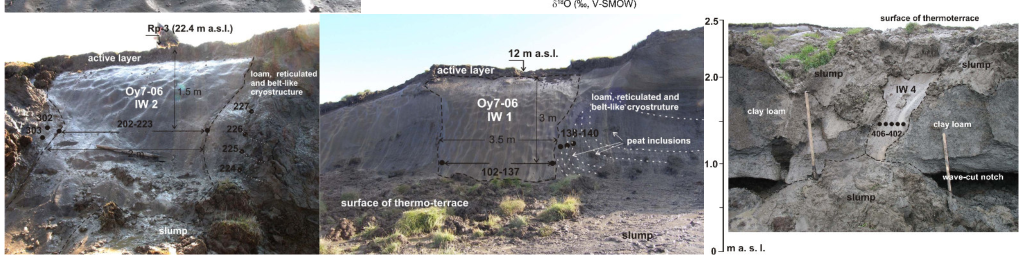


Figure 5 Photographs of selected ice wedges of the MIS3 Yedoma Ice Complex in different altitude levels (1 to 29 m asl) and corresponding co-isotope plot.

References: Blinov et al. 2009. Geochemistry, Geophysics, Geosystems 10, Q0AA03; Meyer et al. 2015. Nature Geoscience 8, 122-125; Meyer et al. 2002. Permafrost and Periglacial Processes 13, 91-105; Opel et al. 2011. Permafrost and Periglacial Processes 22, 84-100; Schirrmeister et al. 2011. Quaternary International 241, 3-25; Wetterich et al. 2016. Quaternary Science Reviews, doi:10.1016/j.quascirev.2015.11.016; Wetterich et al. 2014. Quaternary Science Reviews 84, 39-55. Wetterich et al. 2011. Quaternary Science Reviews 30, 3139-3151; Wetterich et al. 2009. Paleogeography, Paleoclimatology, Paleoecology 279,73-95.

2 Study region, stratigraphy and chronology

- Main study region at the Dmity Laptev Strait is the Oyogos Yar mainland coast (72.7°N, 143.5°E) opposite of Bol'shoy Lyakhovsky Island (Figure 2)

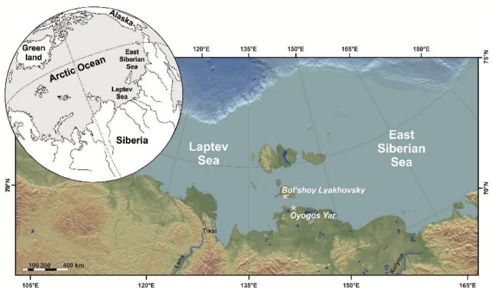


Figure 2 Study region at the Dmitry Laptev Strait.

- Sediment dating: ^{14}C, luminescence
- Ice-wedges dating: ^{14}C, $^{36}Cl/Cl^-$
- Cryostratigraphic correlation to Bol'shoy Lyakhovsky Island based on ice-wedge isotopes
- Studied ice wedges were attributed to four stratigraphic units (Table 1)

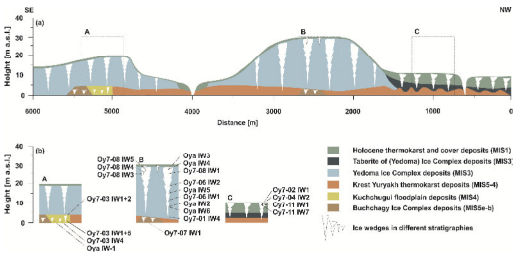


Figure 3 Schematic stratigraphic overview of the Oyogos Yar mainland coast permafrost outcrops.

MIS	Type	Local term	Poster section
MIS1	Thermokarst basin deposits	Alas (Laptev)	6
MIS3	Yedoma ice Complex deposits	Molotkov (Oyogos)	5
MIS4	Floodplain deposits	Kuchchugui	4
MIS5	Ice Complex deposits	Buchchagy (Kazantsevo)	3

Table 1 Stratigraphic units exposed at the Oyogos Yar mainland coast.

6 MIS1 Thermokarst basin ice wedges (Holocene+recent)

- Late Glacial thermokarst basin with Holocene sediment accumulation and syngenetic ice-wedge growth at least over the last two millennia revealed by ice-wedge ^{14}C ages (Opel et al., 2011) (Figures 6 and 7)
- Warmest ice-wedge δ18O derived winter temperatures at Oyogos Yar (up to -20‰)

Figure 6 Examples of recent ice wedges, i.e. modern ice-wedge rejuvenation stages.

Recent ice wedges			
	δ18O	δD	d exc
Mean	-20.7	-158.3	7.7
Min	-24.4	-186.4	4.7
Max	-18.2	-137.3	9.1

Holocene (profiles)			
	δ18O	δD	d exc
Mean	-25.0	-192.1	8.1
Min	-27.1	-207.8	4.8
Max	-20.7	-159.9	11.3

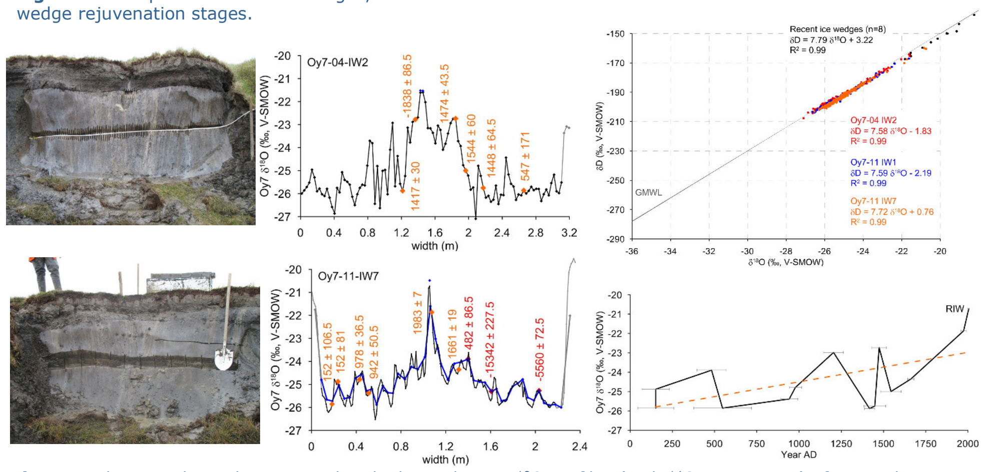


Figure 7 Photographs and corresponding high-resolution δ18O profiles (with ^{14}C ages in AD) of two Holocene ice wedges, co-isotope plot of Holocene and recent ice wedges, and stacked δ18O record based on dated δ18O samples.

7 Regional comparison to Bol'shoy Lyakhovsky Island

- Oyogos Yar ice-wedge isotopes correspond very well to that from Bol'shoy Lyakhovsky
- Not all generations were found at Oyogos Yar (i.e. MIS2 and MIS7a), whereas the attribution of MIS4 at Bol'shoy Lyakhovsky is still a matter of debate

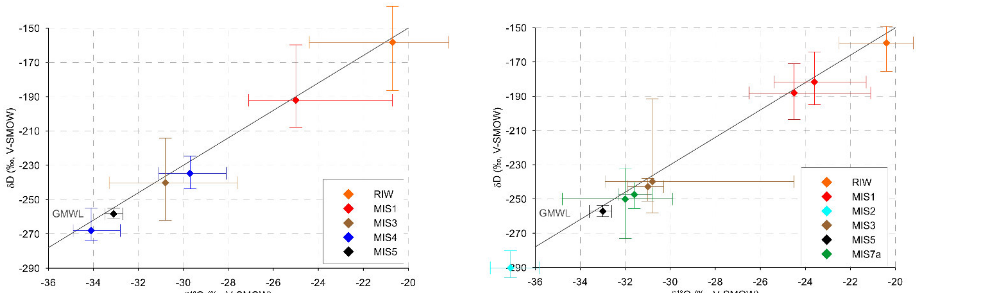


Figure 8 Co-isotope plots of Oyogos Yar mainland coast ice-wedge generations compared to ice-wedge generations at Bol'shoy Lyakhovsky Island (Meyer et al., 2002; Wetterich et al., 2009, 2011, 2014, 2016).

8 Conclusions

- **Stable isotope data of four ice-wedge generations at the Oyogos Yar mainland coast reflect variations in Northeast Siberian Arctic winter climate conditions on different time scales from MIS5 to today.**
- **MIS4 ice-wedge δ18O reflect coldest conditions, slightly colder than during MIS5.**
- **MIS3 ice wedges indicate a cold to very cold non-stable climate during Yedoma Ice Complex formation.**
- **Distinctly warmer conditions can be inferred for the Holocene as well as a Late Holocene warming trend with peak δ18O values for modern ice wedges.**
- **The attribution of ice wedges to distinct sedimentary units and direct ice-wedge dating is often challenging and requires particular attention and new chronological approaches.**