Ice-wedge based permafrost chronologies and stable-water isotope records from Arctic Siberia

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1 Permafrost and fossil ice-wedge polygons


Figure 1. Yedoma Ice Complex wall in summer 2014, photograph by M. Fuchs

In permafrost regions, decreasing winter air temperatures in winter promote **thermal contraction** of the exposed ground and **frost cracking**. Snow, hoar frost and spring meltwater fill in the cracks to form vertical ice veins that may grow into **syngenetic ice wedges** after numerous freeze-thaw cycles (Figure 2). Physical self-organization leads to the typical pattern of **polygon tundra** with ice wedges below the rims and sedimentary centers.

Ice wedges are thought to be the **most common ground** ice type in permafrost and serve as **paleoclimate archives** to be studied by means of stable-water isotopes. The isotopic composition of each single ice vein is linked to winter snow, and, therefore, indicative of the climate conditions during the corresponding cold season. The **$\delta^{18}O$ and δD** of wedge ice (in ‰ vs. V-SMOW) are related to the condensation temperature of the precipitation and interpreted as **mean winter air temperature** proxy at the study site.

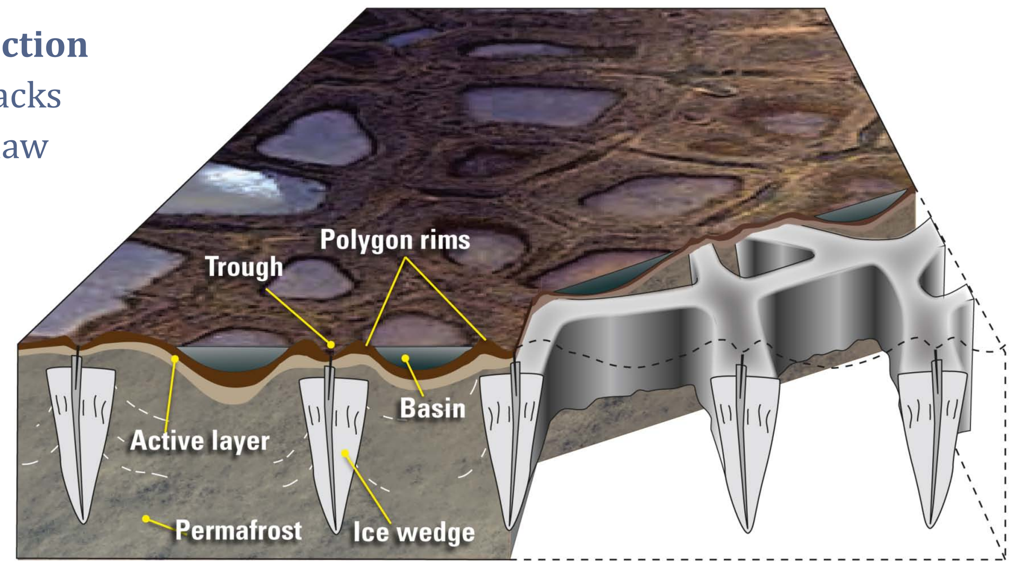

Figure 2. Schematic cut-away of ice-wedge polygons (R. Mitchell/Inkworks for U.S. Fish and Wildlife Service)

The d excess ($d = \delta D - 8\,\delta^{18}O$) is indicative for the evaporation conditions (i.e. relative humidity, sea surface temperature) in the moisture source region.

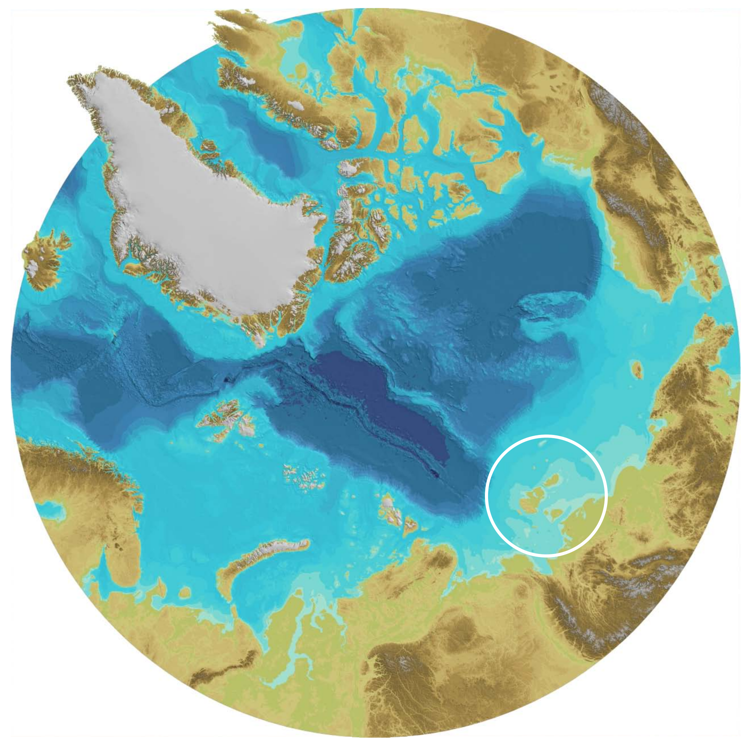
Figure 3. Study region in eastern Siberia (IBCAO, 2012).

2 Study area, dating and local stratigraphy

Mid- and late **Pleistocene** tundra-steppe environments of western Beringia are preserved and described as **Ice Complex** (IC) deposits. Those are differentiated in four IC generations as recognized at the coasts of the **Dmitry Laptev Strait**, on Bol'shoy Lyakhovsky Island and partly on the Oyogos mainland coast (Figures 3 and 4).

Direct **dating** of ice wedges, in particular for the pre-Holocene is challenging as there is (a) only little particulate organic material for **radiocarbon dating** preserved in ice wedges, and (b) the ages are often close to the age limit of radiocarbon dating. New promising dating tools are in development and comprise radiocarbon dating of air-bubble CO_2 and dissolved organic carbon from ground ice as well as **cosmogenic $^{36}Cl/Cl$ dating** for mid- to late Pleistocene ground ice. Most often syngenetic ice wedges are stratigraphically attributed to their embedding frozen sediments with known geochronological information from radiocarbon, luminescence and radioisotope disequilibria ($^{230}Th/U$) dates.

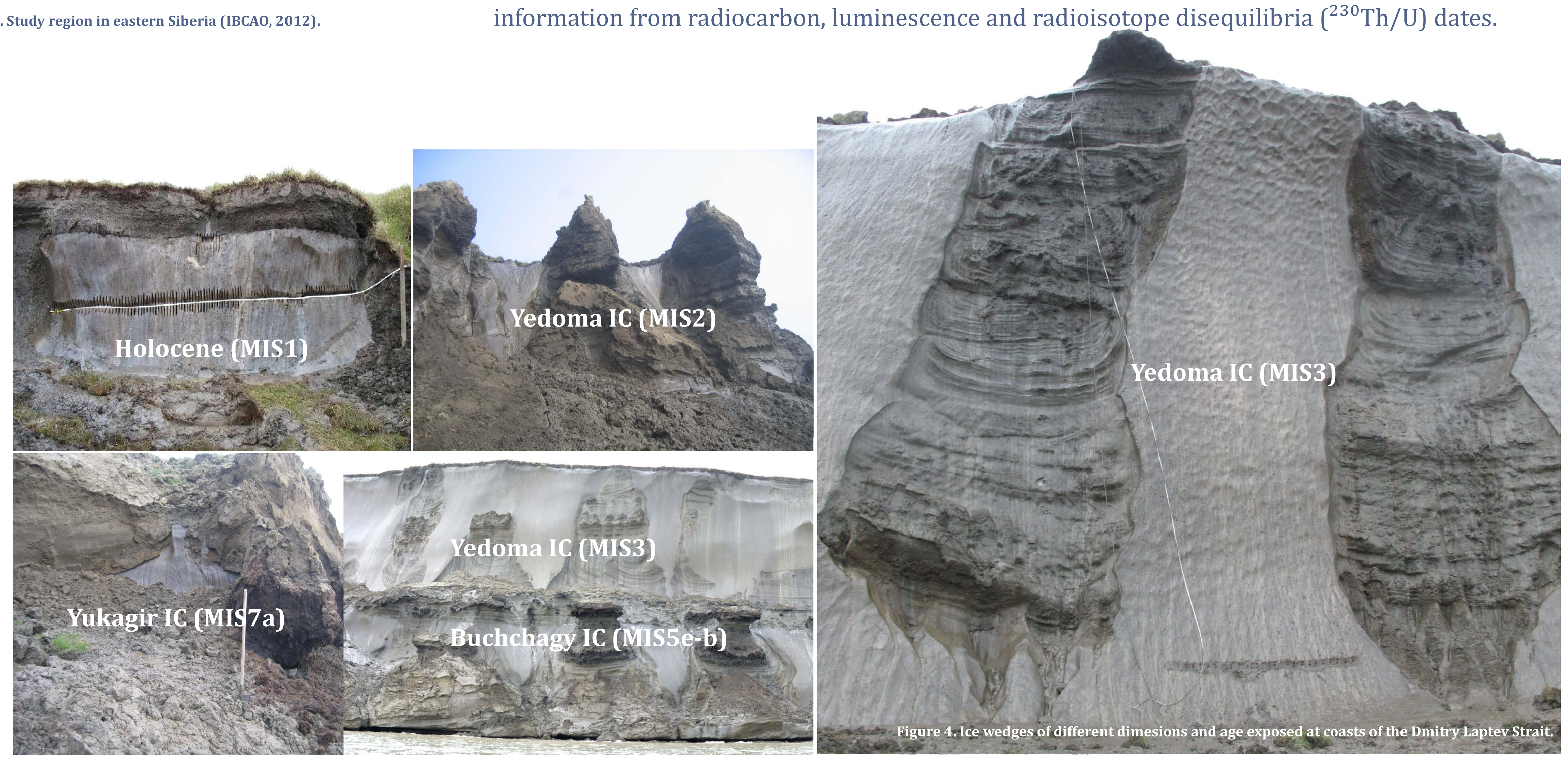

Figure 4. Ice wedges of different dimesions and age exposed at coasts of the Dmitry Laptev Strait.

3 Exemplarely Holocene wedge-ice stable water isotope records

The **internal stratification** of syngenetic ice wedges is best seen along **horizontal transects** (Figure 5). Ice-wedge growth over time in width andheight captures change in isotopic composition of **winter precipitation**. $\delta^{18}O$-δD cross plots are commonly used to to assess the paleoclimatic significance by comparison with the Global Meteoric Water Line (GMWL, $\delta D = 8\delta^{18}O + 10$, Craig 1961). Radiocarbon dates of ice-enclosed organic matter provide age control and may enable the development of time series (Meyer et al. 2015).

Slope and intercept values are used to assess the deviation from the GMWL or LMWL as result of **secondary fractionation** processes after precipitation of snow (in the snow cover by sublimation or hoar frost development), during melting and refreezing and during ice-sediment exchange.

D excess may indicate significant changes in **moisture sources** such as Atlantic vs. Pacific vs. regional (e.g. polynya) and/or **SST and humidity conditions** in the moisture source regions.

Further reading: EGU2016-3892, CL1.07, X3.41
Opel et al. *Late Holocene stable-isotope based winter temperature records from ice wedges in the Northeast Siberian Arctic*,
Hall X3 on Friday, 22 Apr 2016, 17:30-19:00.

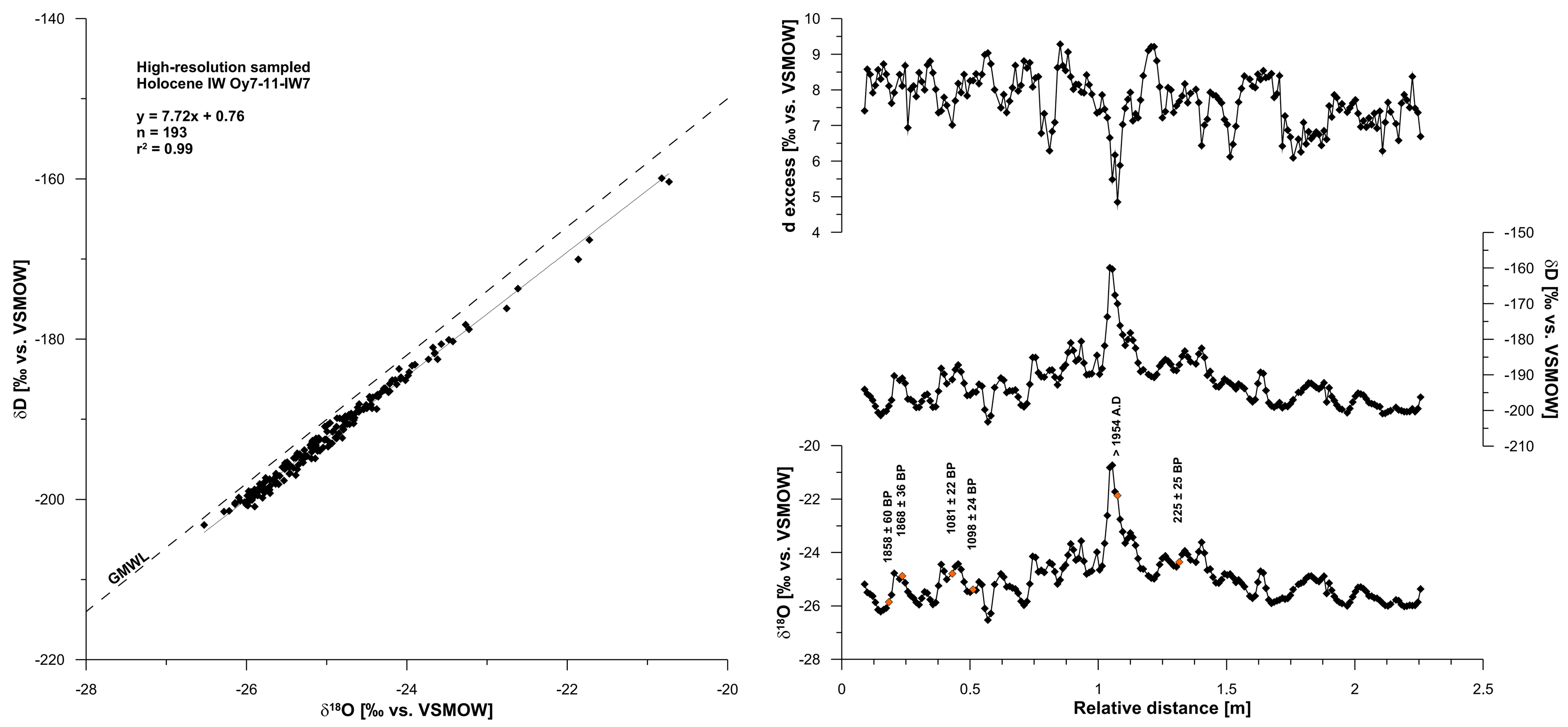

Figure 5. Holocene syngenetic ice wedge data from coastal exposure Oy7-11-IW7 of the Oyogos Yar mainland coast (Opel et al. 2011).

4 Paleoclimate implications

If comparing ice-wedge data from both coasts of the Dmitry Laptev Strait those records of the same stratigraphic unit reveal the similar paleoclimatic information. **Interstadial** periods of the late Pleistocene show (MIS7a, MIS5e-b, MIS3) mean values from **-33 to -30 ‰ for $\delta^{18}O$** and from **-260 to 240 ‰ for δD** (Figure 6). **The Last Glacial Maximum** (MIS2) reveals coldest winter conditions as mirrored by mean values of **-37 ‰ for $\delta^{18}O$** and **-290 ‰ for δD.** Warmest winter conditions are obvious in **Holocene** (MIS1) records by mean values of more than **-25 ‰ for $\delta^{18}O$** and more than **-190 ‰ for δD**.

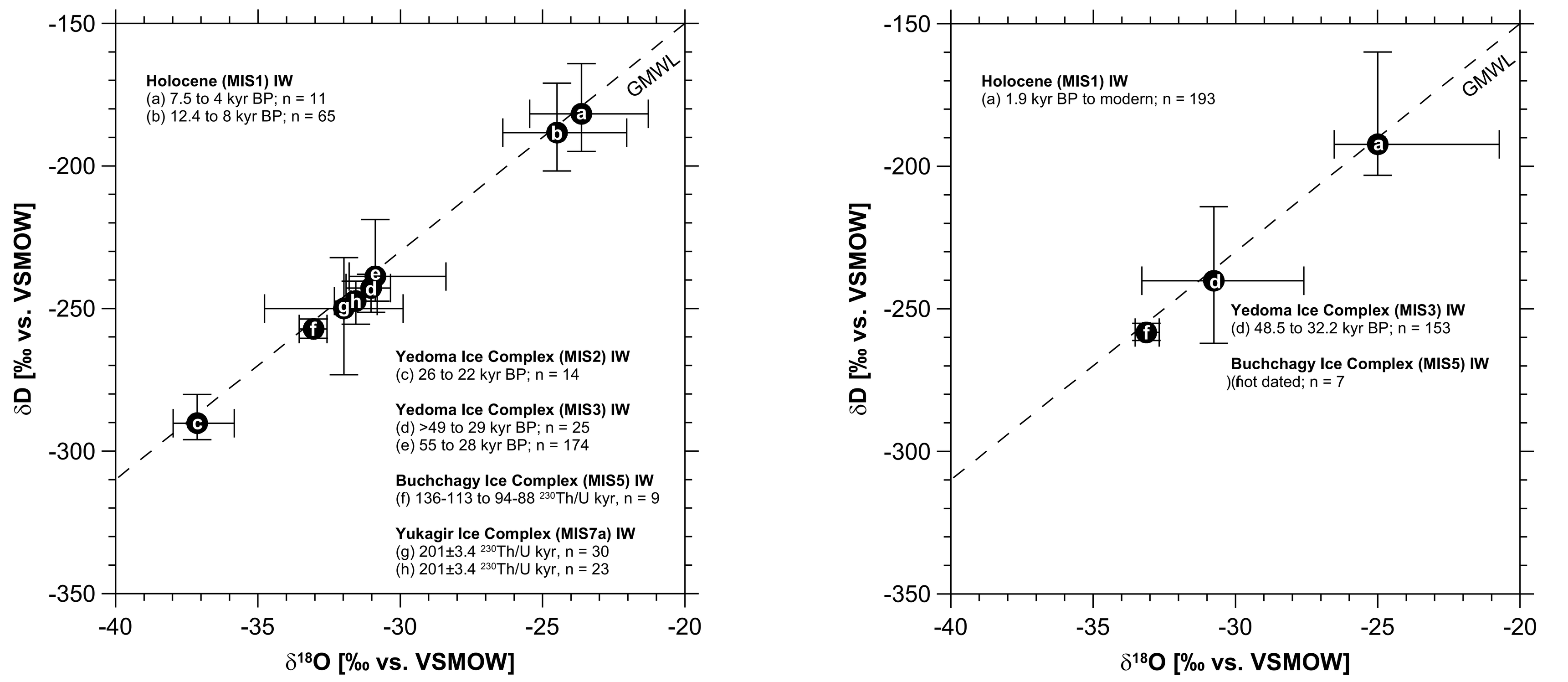

Figure 6. Cross-plot compilation of stable-water isotope data ($\delta^{18}O$, δD) in several generations of syngenetic ice wedges (IW) exposed (a) at the southern coast of Bol'shoy Lyakhovsky Island and (b) at the Oyogos mainland coast. Ice-wedge data sources: MIS1 (Meyer et al. 2002, Opel et al. 2011, Wetterich et al. 2009), MIS2 (Wetterich et al. 2011); MIS3 (Meyer et al. 2002; Wetterich et al. 2014); MIS5 (Wetterich et al. in press); MIS7a (Meyer et al. 2002).

Ongoing research in ice-wedge based paleoclimatology deals with (a) the (further) development of **dating** approaches, (b) the construction of **high-quality time-series** for certain time slices (e.g. Holocene), (c) the **calibration** of $\delta^{18}O$ to local **temperatures** and (d) an improved interpretation of d excess.

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