Interactive comment on "Ground-ice stable isotopes and cryostratigraphy reflect late Quaternary palaeoclimate in the Northeast Siberian Arctic (Oyogos Yar coast, Dmitry Laptev Strait)" by Thomas Opel et al.

M. Kanevskiy (Referee)

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Dear Mikhail Kanevskiy,

Thank you for your thorough review which has raised a couple of good points to improve our manuscript. Please find our replies to your referee comments below in → blue italics.

REVIEW

Thomas Opel, Sebastian Wetterich, Hanno Meyer, Alexander Yu. Dereviagin, Margret C. Fuchs, and Lutz Schirrmeister "Ground-ice stable isotopes and cryostratigraphy reflect late Quaternary palaeoclimate in the Northeast Siberian Arctic (Oyogos Yar coast, Dmitry Laptev Strait)"

This manuscript is focused on reconstruction of palaeoclimate and palaeonvironmental conditions in the Northeast Siberian Arctic over the last 200,000 years. It is based on complex study of perennially frozen Quaternary deposits of the Dmitry Laptev Strait region. The study included descriptions and sampling of coastal exposures, estimation of ice content, radiocarbon and IRSL dating, and stable-isotope analysis.

This study was performed by highly qualified and experienced team of researchers who have published numerous outstanding papers on cryostratigraphy of Quaternary deposits and paleoecology of Northeast Siberia. The paper makes a valuable contribution to our knowledge of permafrost history of this region and provides unique information on structure and properties of Quaternary deposits.

The manuscript is clearly written, the results of study are properly interpreted, and I strongly support publication of this paper. However, it requires some revision. My comments and recommendations are listed below (more comments and suggestions are provided in the attached file).

→ Thank you for this positive evaluation!

General comments:

My major concerns are related mostly to terminology and descriptions of cryostructures.

1. In the manuscript, you often use the terms "Ice Complex" and "Yedoma" but didn't give definitions of these terms, which are commonly considered to be synonyms (e.g., Schirrmeister et al., 2013, in Encyclopedia of Quaternary Science). I understand that here you have to use both terms to describe similar deposits of different ages (following Tumskoy, 2012) but it should be explained. I recommend to discuss these terms in the Introduction, Page 2, after Line 6.

→ The term 'Yedoma' is through the paper only used in stratigraphic terms as Yedoma Ice Complex. We added a general explanation of the Ice Complex as follows in the Introduction (section 1): "Ice

Complex (IC) deposits formed in polygonal tundra environments with syngenetic ice-wedge growth during different periods of the late Quaternary in non-glaciated Beringia (Tumskoy, 2012; Schirrmeister et al., 2013). The most prominent IC of late Pleistocene age is named Yedoma IC (MIS4-3), but older IC formations are known such as the Yukagir IC of MIS7 age (Schirrmeister et al., 2002) and the Buchchagy IC of MIS5 age (Wetterich et al., 2016).“

2. Through the manuscript, you often use the term “stable-water isotope composition of ice”, but I don’t think you should mention “water” since you’re talking about ice. I recommend to use “stable-isotope composition of ice” instead.

→ We deleted „water“ accordingly.

3. I recommend you not to use the term “Permafrost deposits” (e.g., Page 2, Lines 2 and 4). It’s better to use either “permafrost” or “perennially-frozen deposits.”

→ We changed the terms and use only “permafrost” instead of “permafrost deposits”.

4. I recommend you not to use the term “thermokarst deposits” (e.g., page 4, Line 20). It’s better to use either “thaw-lake” or “thermokarst-lake” deposits.

→ We changed the terms and use now “thermokarst-lake deposits” and “thermokarst basin palustrine deposits” to differentiate between lacustrine and boggy deposition regimes and units.

5. I recommend you not to use the term “texture ice” (it is used everywhere in the paper). This term is probably originated from “teksturoobrazuyushchiy (texture-forming) ice,” which is common in Russian literature, where it is associated with the term “cryotexture.” The latter is widely used in Russia, but not in the international literature, where the term “cryostructure” is used instead (see van Everdingen 1998). I recommend you to use “ice lenses” or “pore and segregated ice” or just “segregated ice” instead of “texture ice.”

→ Thank you for this advice. We followed your suggestion and replaced “texture ice” by “pore and segregated ice”.

6. Cryostratigraphic descriptions are not very detailed (though there is “cryostratigraphy” in the title of your manuscript), and it will be good to illustrate them with close-up photos.

→ Following your recommendation, we extended the cryostratigraphic descriptions by more details in the Results section 4.1 although close-up in high quality suitable for publication are unfortunately not available for all studied units. We therefore feel unable to provide illustrations as suggested.

7. Descriptions of cryostructures are not consistent. You stated (Page 5, lines 4-5) that your descriptions are based on classification suggested by French and Shur (2010) (actually, this classification was proposed by Murton and French, 1994, and I also recommend you to cite Murton, 2013, in Treatise on Geomorphology), but sometimes you use different terms (e.g., massive cryostructure, lens-like reticulated cryostructure).

→ Changed accordingly. We added the recommended references by Murton and French (1994) and Murton (2013) in Fieldwork section 3.1. We furthermore made the descriptions consistent to the referred literature.

8. I don't recommend you to use the Russian term "massive cryostructure" because it may be mixed up with massive ice. It is equivalent to "structureless cryostructure" (Murton and French 1994); French and Shur 2010), or "pore cryostructure" (Shur and Jorgenson 1998). I recommend you to name this cryostructure "pore (structureless)" after Murton 2013, and mention that such sediments do not contain any inclusions of ice visible by naked eye.

→ Changed accordingly.

9. For the ice content of different units (Section 4.1), you give only the range of values. It will be good to add a table with the ice-content data for each unit, including the average values ± SD, number of samples, etc.

→ We followed your suggestion and added a table (Table 2) with minimum, mean, maximum values, standard deviation and number of samples per stratigraphic unit.

10. Several times you mentioned pollen-based temperature reconstructions (with references to previous studies), but did not provide any information. I believe the manuscript will benefit if you add a short summary or a table with the pollen data for each unit (such table may be based on Table 2 from Andreev et al. 2011).

→ Pollen data are unfortunately not available for all units of the Oyogos Yar study site, only for some (Wetterich et al., 2009, 2016). All other pollen information originates from Bol'shoy Lyakhovsky Island. Therefore, we decided not to include detailed pollen information into this study. As the focus of this study is the ground ice (stable isotopes and cryostructures), we believe that references to previous studies are sufficient.

11. Your descriptions of different units (Section 4.1) are not consistent and in many cases incomplete. I recommend you to use the following pattern, uniform for all units: 1) description of sediments (soil type and origin, color, thickness, lamination, inclusions, etc.); 2) ground ice: a) prevailing cryostructures (type, if possible – thickness of ice lenses and spacing between them, and/or photos of cryostructures; gravimetric ice content and, if possible, visible-ice content), b) massive-ice bodies (for ice wedges: width, vertical extent, color, bubbles, inclusions, type – syn- or epigenetic, if possible – volumetric content of wedge ice); 3) age of sediments.

→ See also our reply to point 6 above. We extended the cryostratigraphic descriptions and followed the recommended structure to ensure consistency and enhance readability.

Specific comments and suggestions:

Page 2, Lines 25-27. ". . .ice. . .originates from freezing of soil moisture in the seasonally thawed active layer" – This statement applies only to syngenetic permafrost. ". . .melt water of the active layer ice" – do you mean "from the degrading upper permafrost?" (water of the active layer usually forms from summer and winter precipitation, and you already mentioned these sources in the same sentence).

→ As suggested in the edited supplement we added "in syngenetic permafrost" to the first sentence. We decided to keep the second sentence in its current form as melt water of the thawed active layer contributes to the soil moisture as well as winter and summer precipitation (we just added a

"thawed" to active layer). The soil moisture resulting from the different sources is then subject to evaporation and freeze-thaw cycles.

Page 3, Lines 29-32 – Page 4, Lines 1-6. Since you are talking about more than 100 years of studies, it will be good to add several more references, e.g. Bunge 1887, Toll 1897, and of course Romanovskii 1958.

→ We added references to Bunge 1887, Toll 1897 and Romanovskii 1958.

Page 4, Lines 7-8. I recommend you to rewrite this sentence – it is not very clear.

→ We removed the sentence from the text.

Page 4, Lines 9-11. You mentioned here such terms as "thermokarst" and "taberite" but did not provide any references (for "taberite," I recommend Kaplina 1987, 2009, Romanovskii 1993 or other Russian sources).

→ Changed accordingly. We added the reference of Kaplina (2009) which is at least available online and contains a comprehensive overview of Soviet and Russian literature on thermokarst and taberites.

Page 4, Lines 13-14. I recommend you to rewrite this sentence – it is not very clear.

→ We rephrased the sentence to make it clearer.

Page 7, Line 11. I recommend you to replace "cryolithological" units with "cryostratigraphic."

→ Changed accordingly.

Page 8, Line 4. Please check spelling: according to Tumskoy 2012, it is Bychchygyi (or Bychchygyiskaya – if you transliterate it from Russian) Suite.

→ We would prefer to keep the term as spelled in the English publication of Wetterich et al. (2016) co-authored by V. Tumskoy.

Page 8, Line 22 (and at several other places). Lens-like reticulated cryostructure – does it mean poorly developed reticulate cryostructure? The term "coarse" should be explained, otherwise you can just present thickness of ice lenses and spacing between them (range in mm). Close-up photos of typical cryostructures will be very useful.

→ According to Murton and French (1994), we changed the term "lens-like reticulated" to "irregular reticulated" in the revised cryostratigraphic descriptions. The term "coarse" refers ice lens thickness > 1 mm. We added accordingly this information in brackets to the descriptions. As written in our reply to point 6 close-up in high quality suitable for publication are unfortunately not available for all studied units. We therefore feel unable to provide illustrations as suggested.

Page 9, Lines 17-18. "Unit V is completed by a paleosol layer . . ." – Do you mean this paleosol layer is located on top of Unit V?

→ Yes, the paleosol layer is the topmost layer of Unit V. We rephrased this sentence to make this clearer.

Page 9, Line 25. There should be ice wedges in this unit, at least epigenetic (see Fig.2)

→ Yes, partly the toes of epigenetic ice wedges (related to Unit VII) could be found. We added this information.

Pages 9-10. 4.1.7 Unit VII. Description of this unit is incomplete. Please describe the peat horizon and present its thickness (Page 10, Line 7).

→ Changed accordingly.

Page 10, Lines 4-5. I recommend you to rewrite this sentence – it is not very clear.

→ We rephrased this sentence.

Page 10, Lines 10-11. "Unit VIII was only found in places and associated with initial thermokarst." – Please clarify.

→ We refer to the fillings of small initial thermokarst ponds (bylary). We rephrased the sentence accordingly.

Page 10, Line 12. How could you identify syngenetic wedges? Small wedges on top of Yedoma sections are mainly epigenetic. What was the vertical extent of these wedges? Anyway, the thickness of this unit is so small that it's really difficult to recognize the nature of wedges (syngenetic vs epigenetic).

→ The small syngenetic ice wedges were related to the fillings of small initial thermokarst ponds (bylary) and therefore easy to identify. We rephrased the sentence

Page 10, Lines 13-15. "Moreover, Holocene cracking activity characterised by milky white ice veins was also observed in the upper parts of the huge ice wedges of the Yedoma Ice Complex". You already mentioned (see the previous sentence) that the Holocene ice wedges penetrate into the Yedoma wedges. If you mean something different, you should clarify this.

→ We found in the ice wedges of the upper part of Unit IV (Yedoma IC) several milky-white ice veins of Holocene origin (i.e. epigenetic to the Yedoma Ice Complex ice wedges). We rephrased this sentence. This finding could be confirmed by the respective stable-isotope values.

Page 14, Line 18. A presence of what? Zyryanian floodplain deposits?

→ Yes. We rephrased this sentence.

Page 14, Lines 25-34. Please clarify: are you talking about the gap in sedimentation or presume that Yedoma formation continued till the end of the Pleistocene, but the upper part of the sequence was eroded later (or consider both options).

→ Both options seem to be possible. Based on our available data it is not possible to solve this question entirely. We rewrote this paragraph and referred to Cape Mamontov Klyk and Bykovsky Peninsula as sites with Yedoma IC formation until the end of the Pleistocene.

Page 15, Lines 3-4. "Dated taberal Ice Complex deposits of unit V and the overlying lacustrine deposits of units VI and VII prove widespread permafrost degradation related to the development of vast thermokarst basins during the last deglaciation." – Dates from taberal deposits are not related to thermokarst development and reflect only the time of Yedoma formation.

→ You are of course right. We changed the sentence to correct this.

Page 15, Lines 13-14. "A predominantly lateral ice-wedge growth in the last two millennia can be concluded from radiocarbon ages of actively growing ice wedges of unit VII (Table 4) indicating rather stable surfaces in the thermokarst basins with low accumulation." – First, it is not very clear, how did you come to this conclusion. Do you have the data on radiocarbon ages of peat in thaw-lake basins? Second, in Table 4, there is no information on depth of sampling.

→ All samples were taken in a similar depth (about 1-1.5 m below surface). We added this information to the figure caption. Five out of 19 samples had to be excluded as they represented redistributed material. The remaining samples indicate the lateral ice-wedge growth (oldest samples in the outer parts, youngest samples in the central parts of the studies ice wedges). Together with the youngest age of palustrine deposits (3.6 kyr b2k) and the shape of the ice wedges this leads to the conclusion of rather stable surface conditions and a predominantnly lateral ice-wedge growth.

We rewrote the paragraph and added a reference to a paper addressing this in more detail (Opel et al., 2017).

Page 16, Lines 2-5. This explanation looks rather strange. Do you mean that the entire 6-m-thick layer was freezing from below just in one event? If so, I don't think this explanation is correct. Syngenetic permafrost formation is going rather slowly, step by step, and only small portions of the active layer (its basal horizon) join the permafrost at a time, following a slow rising of the permafrost table.

→ You are right. It is very unlikely that the entire layer was freezing from below in just one event. There may have been a lot of events as well freezing from above. However, as this issue is not finally resolvable using our data we decided to remove the hint to the freezing direction and just state that the distinct $\delta^{18}O$/δD minimum and the respective d excess maximum are the result of freezing and does not reflect climate signals.

Page 16, Lines 10-12. I recommend you to rewrite this sentence – it is not very clear.

→ We deleted this sentence.

Page 16, Lines 20-21. In case of very slow sedimentation, and especially gaps in sedimentation, age offsets may be much more than few hundreds to few thousands years.

→ We changed the wording slightly to make clear that we discuss age offsets between host sediments and syngenetic ice wedges with reference to a distinct altitude level within a unit such as the Yedoma Ice Complex (Unit IV). However, considering the mentioned very slow sedimentation or gaps in sedimentation, we agree that age offsets may be much bigger.

Page 16, Lines 27-28. I'm not sure think this explanation is correct. If deposition occurs at the floodplain, we may presume that frost cracks are filled mainly during the spring flooding, so amount of snow is not so important.

→ We assume that frost cracks may be already filled before spring flooding. Nevertheless, we agree that the availability of sufficient sedimentary material may be more important than the amount of snow. We therefore deleted the reference to dry conditions.

Page 16, Line 31. What do you mean by "rounded"? Concave, convex?

→ We added convex.

Page 17, Line 7. What do you mean by “. . .indicate very cold winter climate for the initiation of ice-wedge genesis. . .?” Cold climate during the early stage of ice-wedge formation?

→ Yes, we accepted your suggestion.

Page 17, Lines 22-23. “The variability of stable-isotope values with respect to altitude indicates changing conditions from very cold to moderate winter temperatures.” – For what unit(s)? Fig. 5 doesn’t show big changes in stable-isotope values for Unit IV.

→ This statement refers indeed to Unit IV (Figure 5) that shows significantly varying stable-isotope compositions. We added a reference to Figure 5 to this sentence as well as our tentative classification scheme based on $\delta^{18}O$ values (extremely cold: -38‰ to -35‰, very cold: -35‰ to -32‰, cold: -32‰ to -29‰, moderate -29‰ to -26‰, warm: -26‰ to -23‰, very warm: -23‰ to -20‰) to the discussion.

Page 18, Line 2. I recommend you to explain that mean values for Unit VII (Fig. 6a) were calculated without taking into account values obtained from modern and recent wedges, which are shown in this figure separately.

→ This is not the case as the high-resolution horizontal ice-wedge profiles contain also recent and modern ice veins. Therefore, we decided not to follow your suggestion.

Page 19, Lines 33-34. I recommend you to rewrite this sentence – it is not very clear.

→ We rewrote this sentence to make it clearer.

Page 21, Lines 35-36. Please transliterate the title of this paper.

→ Changed accordingly.

Page 26, Line 3 and Table 1. I recommend to present information on epigenetic ice wedges as well.

→ We haven’t considered epigenetic ice wedges in this study due to their complicated chronological attribution. Therefore we decided not to follow your recommendation for Table 1. However, in the description of Unit III and Unit V we added the information on epigenetic ice wedges, presumably related to Unit IV and Unit VII, respectively.

Page 29, Table 4. Depth of sampling (or height asl) is not shown.

→ All samples were taken in a similar depth (about 1-1.5 m below surface). We added this information to the figure caption.

Page 30, Table 5, title. “Ice wedges marked with an asterisk contain samples attributed to Unit IV and Unit VIII, respectively.” – What does it mean? You didn’t mention segregated ice in the title, though you present the values in the table (texture ice).

→ As pointed out in section 4.1.8 we observed Holocene ice veins in two ice wedges of the Yedoma Ice Complex (Unit IV). As described in section 4.2.3 we attributed samples with a Holocene stable-isotope composition (i.e. $\delta^{18}O$ values higher than -28‰) to Unit VIII. Samples of the respective ice wedges (Oy7-06 IW2 and Oy7-08 IW3) are therefore attributed to Unit IV and Unit VIII and the two ice wedges are marked with an asterisk in Table 5. We added the reference to section 4.2.3 to the table caption. We additionally added “pore and segregated ice” to the caption.

Page 32, Figure 1. I recommend to add a larger scale geomorphic map of the Oyogos Yar coast (based on satellite imagery) showing yedoma remnants and alases, and the position of the coastal exposure presented in Fig. 2.

→ Thanks for this suggestion. We added such a map to Figure 1.

Page 36, Figure 6. I recommend you to explain (in the caption or in the main text) that mean values for Unit VII (Fig. 6a) were calculated without taking into account values obtained from modern and recent wedges, which are shown in this figure separately.

→ This is not the case as the high-resolution horizontal ice-wedge profiles contain also recent and modern ice veins. Therefore, we decided not to follow your suggestion.

MORE COMMENTS AND SUGGESTIONS ARE PROVIDED IN THE ATTACHED FILE.

Good luck!

→ Thank you!

Mikhail Kanevskiy, Institute of Northern Engineering University of Alaska Fairbanks

Please also note the supplement to this comment:

http://www.clim-past-discuss.net/cp-2017-1/cp-2017-1-RC1-supplement.pdf

→ Thanks for these detailed comments. We accepted most of them during revision of the manuscript.

Interactive comment on "Ground-ice stable isotopes and cryostratigraphy reflect late Quaternary palaeoclimate in the Northeast Siberian Arctic (Oyogos Yar coast, Dmitry Laptev Strait)" by Thomas Opel et al.

T.J. Porter (Referee)

trevor.porter@utoronto.ca

Dear Trevor Porter,

Thank you for your thorough review which has raised a couple of good points to improve our manuscript. Please find our replies to your referee comments below in → blue italics.

General comments:

Water isotopes from ice cores are one of the most important climate proxies in Quaternary paleoclimate research. But long ice core records have significant spatial limitations. Relict ground ice in continuous permafrost regions has great potential to fill spatial and temporal gaps in the water isoscape. The manuscript reviewed here, in my view, represents an important contribution to the Quaternary literature. It provides new relict ice isotope data from Oyogos Yar (Dimitry Laptev Strait region) and compares with existing data from the nearby Bol'shoy Lyakhovsky Island locality. Together this regional dataset offers an impressive cross-section of climate-isotope variability over the last ~ 200 ka. Many of the deposits pre-date the limits of the radiocarbon method, and are notoriously challenging to constrain. The authors have done a commendable job establishing a regional chronostratigraphic framework that is both well illustrated and simple to understand. The manuscript was generally well written – some editorial type corrections are needed as outlined below. The data appear to be of high quality and were thoughtfully interpreted, and reasonable conclusions were ultimately drawn. I have only a few specific comments that I feel the authors should address. Following the suggested revisions, I would strongly recommend this manuscript is accepted.

→ Thank you!

Specific comments:

- Abstract describes 'cold to very cold', 'very cold to moderate', 'very cold' and 'extremely cold' winter conditions during several key timeslices, but the benchmark is not clearly defined. Please state what the paleoclimate end members are (e.g., LGM to Late Holocene).

→ For this climate interpretation we use the following tentative classification of mean ice wedge $\delta^{18}O$ values with six classes (extremely cold: -38‰ to -35‰, very cold: -35‰ to -32‰, cold: -32‰ to -29‰, moderate -29‰ to -26‰, warm: -26‰ to -23‰, very warm: -23‰ to -20‰). This classification uses roughly the Last Glacial Maximum and modern climate conditions as end-members.

We added this information to the discussion (section 5.2).

- P14, L10: What is meant by '. . .fits good to a maximum in modelled summer temperatures. . .'? Are you referring to how the water isotope data match the modelled temperatures? If so, this comparison is perhaps unjustifiable since the ice wedge isotope values are from snowmelt and should therefore be compared with modelled winter temperatures. Considering uncertainties of age and seasonality (all winter months, or just some) of the relict ice, the data seem to compare reasonably well with modelled winter temperatures. I would recommend revising this bit so that the reader is not confused about the seasonality of the water.

→ In this paragraph we do not discuss ice-wedge isotope data. Instead we discuss the presence of extensive thermokarst lakes dated to 102.4±9.7 kyr (MIS5c), formerly ascribed to the Eemian (MIS5e). Nevertheless, the general warm temperatures inferred from the presence of the thermokarst lake deposits coincide with a maximum in modeled summer temperatures around 105 kyr b2k.

We changed the wording accordingly.

- P15, L24-25: This statement is a bit too strong and lacks accuracy – as it is currently written, it appears to say the primary signal in texture ice relates to secondary fractionation. However, the subsequent sentence contradicts that. Alternatively, you might say that climatic interpretation of water isotopes in texture ice is confounded by partial overprinting of the original meteoric signal by secondary fractionation processes associated with active layer freeze-thaw cycles, and that the degree of overprinting may depend heavily on the environmental context given contrasting variances across different units.

→ Thanks for this advice. We changed the sentence using to your suggestion.

- In section 5, tentative links are made between isotope variations in the Siberian study region and some of the high-amplitude (Dansgaard-Oeschger 'style') fluctuations in North Greenland, NGRIP ice core record. I would caution the authors about doing this so liberally. First, NGRIP is a different seasonality. Second, Greenland is a very special place, and most of these very strong climate oscillations in the NGRIP record are linked to local variability in the vigor of the North Atlantic heat pump (AMOC). While I can understand the appeal in making this comparison, since it may help to explain why the Siberian isotope data do not always compare well with the local modelled temperatures, I think more care is needed when attempting to correlate paleoclimate in the North Atlantic and East Siberian Arctic. My proposed solution would be to acknowledge these complex issues, re: seasonality, and also correlating high-amplitude events across such large distances. Finally, I would also suggest re-iterating that age uncertainties in the Siberian data are sufficient in most cases to bring the data in accord with the modelled temperatures.

→ You are completely right. It is challenging and probably to straightforward to compare the different datasets without referring to different seasonality, climate regime and age uncertainties. Nevertheless we think that comparing the different datasets add additional value for palaeoclimatic interpretation.

We added a sentence acknowledging the mentioned issues.

Technical corrections:

- P3, L17: no need for 'see e.g. discussion in' – this is already implied by citing the paper.

→ Changed accordingly.

- P3, L31-32: I understand the intended meaning of this sentence, but as it is currently written it suggests humans have been conducting field studies in this region since the mid-Pleistocene.

→ *Changed accordingly.*

- P4, L4: should be ‘less extensively’

→ *Changed accordingly.*

- P4, L12: should be ‘spatially and temporally’

→ *Changed accordingly.*

- P4, L26: mounds = colluvium?

→ *Thermokarst mound (baydzherakh) refers to the remaining sedimentary polygon center filling after melting of ice wedges surrounding an ice-wedge polygon.*

We added this explanation.

- P6, L17-18: is 12.5% (+/-0.5%) potassium content is a reasonable assumption? Please elaborate.

→ *Of course K contents in feldspars vary considerably, but due to our sample processing including feldspar flotation and density separation, we are confident to have extracted K-rich feldspar. In the cited study, Huntley and Baril (1997) found a K content for K-feldspars of 11.5 – 13.5% within a confidence interval of 95%. Based on that, the value of 12.5% ± 0.5% became a standard value used in IRSL dating. The need for more precise values arises when measuring single grains, because then the varying K content plays a role for statistical analyses of results, but in our study we used multiple grain aliquots that average over 100 – 500 grains approximately.*

- P6, L20-21: revise sentence structure, or break into 2 sentences. Example. The equilibrium technique was used to prepare ice-wedge and texture-ice samples for stable isotope analysis. Stable oxygen and hydrogen isotope ratios were measured on a Finnigan 215 MAT Delta-S at AWI Potsdam.

→ *Changed accordingly.*

- P6, L24: It is odd that the measurement precision hasn’t changed in 17 years (i.e., since Meyer et al., 2000). Perhaps a more recent citation would be appropriate here, or simply ask the IRMS lab manager at AWI what the value is today, and report that.

→ *The measurement precision of mass spectrometry has actually not changed within the last 17 years for water isotopes. The equilibrium technique is still the most precise on the market and not been surpassed by new developments in the field of mass spectrometry (i.e. the gas bench). So, there is actually no need for a newer reference. The new laser-optical techniques may reach similar precision, but these have not been used for our paper. Hanno Meyer is the lab manager and co-author of this manuscript.*

- P10, L13-15: Communication error. ‘Holocene cracking’ was not observed in the Yedoma Ice Complex. Rather, ‘milky white ice veins’ were observed in the YIC. Please revise the sentence.

→ *Changed accordingly.*

- P10, L22: when specific units are referred to (e.g., Unit II), ‘Unit’ should be capitalised. There are many instances of this spelling error throughout section 4. Please correct in the final manuscript.

→ *Changed accordingly.*

- P13, L25: revise to "…and have isotopic values that are depleted compared to ice wedges on Bol'shoy. . .'

→ *Changed accordingly, but … "less depleted"…*

- P14, L8-9: revise to "The IRSL age for Unit III (102.4+/-9.7 kyr) points to a MIS5c origin rather than MIS5e (Eemian) as suggested previously (Wetterich et al., 2009; Kienast et al., 2011).'

→ *Changed accordingly.*

- P14, L20-21: I am not sure what is meant here. Please clarify this sentence.

→ *We rewrote the sentence and followed the suggestion of Reviewer 1.*

- P15, L1: '. . .factors such as. . .'

→ *Changed accordingly.*

- P16, L2-3: revise to 'As soil water migrates to a freezing front, the first ice. . .'

→ *We changed the wording considering your suggestion.*

- P16, L10-12: I am not sure what is meant here. Please clarify this sentence.

→ *We deleted this sentence.*

- P16, L24: '. . .according to. . .'

→ *Changed to "corresponding".*

- P19, L1-3: if it adds value, why not add the Laskar winter insolation curve?

→ *We added the insolation curves for both summer (JJA) and extended winter (NDJFMA) to Figure 7 and changed the text and figure captions accordingly.*

- P19, L13: 'All in all, *our* data. . .'

→ *Changed accordingly.*

- P19, L23: '. . .pollen data from. . .'

→ *Changed accordingly.*

- P19, L34-35: please rephrase the sentence beginning with 'However,. . .' As it is currently written, I am not entirely sure what is meant.

→ *We rewrote the sentence.*

- P20, L1: please remind the reader (in brackets) how much d-excess increased.

→ *We added the numbers (about 1‰ for Bol'shoy Lyakhovsky Island and about 2‰ for Oyogos Yar).*

- P20, L12: '. . .in addition *to* and. . .'

→ *Changed accordingly.*

– Figure 7: Please specify if the standard error bars are 1 or 2 sigma.

→ *The age uncertainties refer to the maximum age range from Table 1 (i.e. refer to respective minimum and maximum age not to standard error).*

This is now stated in the figure caption.

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G. Iwahana (Referee)

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Dear Go Iwahana,

Thank you for your thorough review which has raised a couple of good points to improve our manuscript. Please find our replies to your referee comments below in → blue italics.

This paper describes very complicated suites of permafrost deposits. The authors analyzed a number of rare samples from remote Arctic field sites and provided new valuable dating information, then summarized and extracted essence of paleoclimate and paleoenvironmental conditions of the targeted region. This work was done systematically by highly experienced team especially for paleo-environmental studies using permafrost. Selection of sampling profiles were carefully made in the complicatedly distributed Ice-complex and thermokarst-affected terrains so that they can recover past events happened in this region. The paper was will-organized and most necessary components of the study was written precisely in details. I believe that this paper helps and guides wide range of precedent researchers who want to further explore and understand history and future not only in the Dmitry Laptev Strait area but also in other ice-rich permafrost regions. The results show that permafrost deposits on the both sides of the Dmitry Laptev Strait indicate comparable records of climate change if we consider uncertainty in age determination of older deposits. This results strengthen usage of permafrost as an important proxy of past climate and environmental change in periglacial regions. Two IRSL dating points provided large contribution to paleo-environmental study of old permafrost that cannot determine ages by radiocarbon method. I recommend this manuscript be published with minor revisions. Below, I included some suggestions that I believe they will improve the presentation of this work and help readers to grasp the authors results and conclusions.

→ Thank you for your positive evaluation!

(Minor comments, suggestions, and questions)

First two paragraphs in Introduction: There is no mention about hoar development in cracks as a possible main ice-wedge forming process and fractionation due to evaporation/sublimation after the meteoric sources of ice-wedge (snow-melt water or hoar) deposited on land surface. It would be good to interested readers to have brief explanation here why the authors excluded or didn't mention about those processes here or in later discussion.

→ Thank you for this suggestion. Indeed, climate and site-specific environmental conditions play an important role for ice-wedge formation, i.e. frost-crack filling. It is, however, commonly accepted that snowmelt is the most important crack-filling source. Minor sources may include varying proportions of densified snow or hoar-frost accretion (St-Jean et al., 2011; Boereboom et al., 2013). The effects of isotopic fractionation processes in the snow cover and during snowmelt prior to frost-crack filling on the stable-isotope composition of wedge ice are yet neither fully understood nor well constrained. Both issues are considered to be negligible for the purpose of this study but should be subject of more detailed studies in the future.

Following your recommendation, we added some information to the first two paragraphs of the Introduction (section 1).

Section 3.1 and discussion: There was limited information about relative locations of horizontal sampling profiles within the sampled ice-wedges and surrounding sediments. I understand it is extremely difficult to know the 3-dimentional distribution of ice-wedge network. Although sampling widths were shown in Tables, additional information about relative location of sample line edges and ice-sediment boundary in the cross sections would be helpful to infer representativeness of the samples for individual ice-wedge. In other words, how much your horizontal sampling profiles cover the actual ice-wedge widths?

→ We sampled horizontal ice-wedge profiles that cover the entire widths of the studied ice wedges. However, the sampling resolution was different between ice wedges (but constant within individual ice wedges) and varied from 1 cm for Holocene ice wedges (quasi-continuous sampling) to about 30 cm (single point sampling) for ice wedges of the Yedoma Ice Complex, depending on field conditions, sampling tools and research questions. The width of individual samples was between about 1 cm and 3 cm, depending on sampling tool (chain saw, axe and ice screw). When sampling with ice screw and axe, we usually took the first sample about 10 cm apart from the ice-sediment boundary to minimize the effects of post-depositional fractionation processes between sediment and ice. When sampling with the chain saw, we took the first sample directly at the sediment-ice boundary (but in several cases had to remove these samples from interpretation because the showed clear indications of secondary fractionation processes between the wedge ice and the surrounding ground). Furthermore, sampling took place perpendicular to ice veins. We are, therefore, quite confident, that our stable-isotope datasets are representative for individual ice wedges, in particular for Holocene ice wedges.

We added some of this information to section 3.1 (Fieldwork).

How did you distinguish individual ice-wedge from the vast massive of Yedoma Ice complex (especially Unit IV)? It looks continuous thick ice network within the 30m thick deposit in the photos (Fig. 3).

→ The ice wedges of the Yedoma Ice Complex (Unit IV) were sampled between two respective sedimentary polygon fillings, carefully selected either at the bottom of the headwall of the thaw slump or from above (ground surface). All sampled Yedoma ice wedges were at least several tens of meters apart from each other and in most cases at different altitude levels (see Table 5).

P. 2 / L. 25: You started here to use intra-sedimental texture ice, and used “texture ice” afterword. I recommend to state your usage of “texture ice” for ice for pore ice as well as segregated ice lenses and layers in this sentence.

→ Based on the very detailed referee comments of reviewer 1 we changed the terminology and use now “pore and segregated ice” instead of ”texture ice”.

P. 3 / L. 13: Why you mention about CO_2 in air-bubble and DOC here if carbon-dead ages are topic of the sentence?

→ This information was given just to show that there is some methodological progress in the application of wedge ice in paleoclimatic research. Even though we use only POC in this study we

prefer to have this information included. We slightly changed its position and moved it into an earlier sentence in the Introduction (section 1).

P. 4 / L. 21: The Kuchchugui Suite is MIS5 in Table 1 in contrast to MIS6; Tumskoy (2012). Is this correct?

→ Yes, this is correct. Tumskoy (2012) interpreted the Kuchchugui Suite as MIS6. Table 1 includes new IRSL dates from our study pointing to Kuchchugui formation during MIS5.

P. 5 / L. 7: "... Values higher than 100wt% indicate ice over-saturation. . ."; is this true only for your samples in this study? Did you extract texture-ice water only from those samples with supernatant water, and the results are only for them?

→ Yes, this is valid for all permafrost samples. Yes, we took samples of water for pore and segregated-ice stable isotopes only from thawed sediment samples with supernatant water. Hence, not all sediment samples resulted in a pore and segregated -ice stable-isotope sample.

We changed the wording accordingly.

P. 5 / L. 17: This means the sampling lines were not horizontally or parallel to the ground surface line? The frost cracking veins were not always near vertical?

→ No, the sample lines were horizontally (=parallel to the ground surface). Furthermore, ice wedges were selected where the exposure and consequently the possible sampling profiles perpendicularly cut frost-cracking direction and hence, ice veins. In general, the ice veins were near-vertically oriented

We changed the sentence accordingly.

P. 13 / L. 17: Refer Table 3 after the radiocarbon ages.

→ Changed accordingly.

P. 13 / L. 10: Please briefly explain why there is a possible attribution of unit I in the eastern part of the study region to the Zyryanian.

→ We believe you are referring to P.13 / L. 20. The main reasons are (1) that we do not have a good age control for ice wedges of Unit 1 below the Buchchagy Ice Complex deposits in the eastern section and (2) the sediments are similar to the (dated) Kuchchugui sediments of Section B and to the Zyrianian stadial floodplain deposits on Bol'shoy Lyakhovsky Island (roughly about 60 to 80 kyr b2k).

The sediment radiocarbon ages are infinite and/or close to the limit of the method whereas the ice wedge $^{36}CL/Cl^{-}$ ages reveal large uncertainties that might also allow an attribution to the Zyrianian stadial instead of an attribution to Unit 1 (Kuchchugui). We could not compare ice-wedge isotopes of the section A ice wedges with ice wedges of Unit 1 (Kuchchugui) in Section B because we did not observe the latter. So, the attribution in the eastern Section A is based on the litho- and chronostratigraphy of Section B.

P. 14 / L. 15: What do you mean a temporal coexistence of Ice Complex accumulation plains, thermokarst, and floodplains in the same region during MIS5? This means all three processes existed at different time frames during MIS5 or they coexisted at the same moment during MIS5, or something else?

→ All three landforms and related processes may have coexisted at the same time in the same region (i.e. several km^2), but not in the very same study location. Similar situations may be observed today. Based on the available age determinations, this cannot be resolved. Further information of our understanding of MIS5 periglacial landscapes is given in Wetterich et al. (2016), referred in the paper. The crucial point, however, are large uncertainties in the available and applicable dating (Th/U of peats).

We slightly changed the wording.

P. 14 / L. 23: Table 4 ! Table 3?

→ Table 1 is correct as no ages from Bol'shoy Lyakhovsky Island are reported in detail in this manuscript. See Table 1 for according references.

P. 15 / L. 16: Except for Unit IV?

→ We meant mean stable-isotope compositions for which our statement is valid.

We changed the sentence accordingly and add a reference to Table 5.

P. 15 / L. 28: Refer to Fig. 4 and Table 5.

→ Changed accordingly.

P. 15 / Section 5.2: It would be kind to briefly explain about secondary fractionation processes. Somehow, it should be connected to the sentence beginning from L. 32.

→ The information on secondary fractionation processes such as evaporation and freeze-thaw cycles is given in the next lines of this paragraph.

We added some information on the effects of evaporation and freezing.

P. 18 /L. 20-23: Is it possible to display and compare the results from other areas listed here to OY and BL data in Fig. 7? Even though they cover down to MIS3 or 4, it will help to discuss spatial representability of ground-ice stable-isotope records.

→ This is indeed an interesting idea. However, we decided not to include the additional ice-wedge isotope data because the chronologies and isotope values for MIS4 to MIS1 are quite similar to our data and would be confusing in the figure (in particular with the new colour coding according to your suggestion below).

P. 18 / L. 30: Please add reference for the pollen study (Andreev et al., 2004?).

→ We added the missing reference (Andreev et al., 2004) and slightly changed the wording.

P. 19 / L. 1: I recommend to refer to Unit I after Kuchchugui ice wedges.

→ Changed accordingly.

P. 19 / L 33-34: I couldn't understand this sentence well.

→ *We rephrased the sentence.*

P. 20 / L. 6-9: This is interesting and provides strong support for your discussion about IW as winter climate proxy.

→ *Thank you. More on this in Meyer et al. (2015) and Opel et al. (in press).*

Table 1: Check the reference for unit III, "hi"

→ *Should be "h". Changed accordingly.*

Table 3: To which sequence the samples from Field campaign 2002 is attributed?

→ *The samples from 2002 can be attributed to the sequences A and B. We added this information to Table 3.*

Figure 2: the green colors for Unit VII and VIII are hardly distinguishable. Could you make them more contrasted between two?

→ *Changed accordingly.*

Figure 3: CSIW is different from CW?

→ *Should be CW. Changed accordingly.*

Figure 4: Please make grey crosses larger because some points overlapping with black dots are not clearly distinguishable for me.

→ *Changed accordingly.*

Figure 7: Please consider to use colors for markers here as used in Fig. 6. It helps readers to connect the markers to discussed Units.

→ *Thank you for this great idea. We changed the figure accordingly and considered the color coding of Figure 6.*

Ground-ice stable isotopes and cryostratigraphy reflect late Quaternary palaeoclimate in the Northeast Siberian Arctic (Oyogos Yar coast, Dmitry Laptev Strait)

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Abstract.

To reconstruct palaeoclimate and palaeoenvironmental conditions in the Northeast Siberian Arctic, we studied late Quaternary permafrost deposits at the Oyogos Yar coast (Dmitry Laptev Strait). New infrared stimulated luminescence ages for distinctive floodplain deposits of the Kuchchugui Suite (112.5±9.6 kyr) and thermokarst thermokarst-lake deposits of the Krest Yuryakh Suite (102.4±9.7 kyr), respectively, provide new substantial geochronological data and shed light on the landscape history of the Dmitry Laptev Strait region during the Marine Isotope Stage (MIS) 5. Ground ice stable-isotope data are presented together with cryolithological information for eight cryostratigraphic units and are complemented by data from nearby Bol'shoy Lyakhovsky Island. Our combined record of ice-wedge stable isotopes as proxy for past winter climate conditions covers the last about 200 thousand years and is supplemented by texture ice stable isotopes of pore and segregated ice which contain reflect annual climate conditions overprinted by freezing processes. Our ice wedge stable-water isotope data indicate substantial variations in Northeast Siberian Arctic winter climate conditions during the late Quaternary, in particular between Glacial and Interglacial but also over the last millennia to decadescenturies. Stable isotope values of Ice Complex ice wedges indicate cold to very cold winter temperatures about 200 kyr ago (MIS7), very cold winter conditions about 100 kyr ago (MIS5), very cold to moderate winter conditions between about 60 and 30 kyr ago, and extremely cold winter temperatures during the Last Glacial Maximum (MIS2). Much warmer winter conditions are reflected by extensive thermokarst development during the MIS5c and by Holocene ice-wedge stable-isotopes. Modern ice-wedge stable isotopes are most enriched and testify the recent winter warming in the Arctic. Hence, ice-wedge based reconstructions of changes in winter climate conditions add substantial information to those derived from paleoecological proxies stored in permafrost and allow for distinguishing between seasonal trends of past climate dynamics. Future progress

in ice-wedge dating and an improved temporal resolution of ice-wedge derived climate information may help to fully explore the palaeoclimatic potential of ice wedges.

1 Introduction

The wide tundra areas of the Northeast Siberian Arctic lowlands are characterized by deep permafrost ~~deposits~~ that result from cold continental climate conditions in West Beringia during the Late Pliocene and Pleistocene when this region remained non-glaciated (Schirrmeister et al., 2013). Ice Complex (IC) deposits formed in polygonal tundra environments with syngenetic ice-wedge growth during different periods of the late Quaternary in non-glaciated Beringia (Tumskoy, 2012; Schirrmeister et al., 2013). The most prominent IC of late Pleistocene age is named Yedoma IC (MIS4-3), but older IC formations are known such as the Yukagir IC of MIS7 age (Schirrmeister et al., 2002a) and the Buchchagy IC of MIS5 age (Wetterich et al., 2016). The ice-rich permafrost ~~deposits~~ in this area contains huge amounts of ground ice. Syngenetic ice wedges are the major component. Vertically foliated ~~I~~ice wedges are formed by polygonal frost cracking due to thermal ~~ground~~ contraction of soils in winter and the subsequent ~~crack~~ filling of cracks with water in spring (e.g. Leffingwell, 1915; Lachenbruch, 1962). Snow melt is the main source for the water that enters the frost crack, quickly refreezes there due to the negative ground temperatures and forms a vertical ice vein. Depending on climate and site-specific environmental conditions minor sources may include varying proportions of densified snow or hoar-frost accretion (St-Jean et al., 2011; Boereboom et al., 2013). The periodic repetition of frost cracking and ice-vein formation ~~let~~ results in ice wedge~~s~~ growth in width and, if synchronous to sedimentation at the surface (syngenetic ice wedges), also in height.

~~The vertically foliated i~~Ice wedges may serve as paleoclimate archives (e.g. Mackay, 1983; Vaikmäe, 1989; Meyer et al., 2002b; Vasil'chuk, 2013), in particular in regions with limited availability of climate archives. They can be studied by means of stable~~ water~~ isotopes (Mackay, 1983). Due to rapid freezing in the frost crack preventing fractionation (Michel, 1982), the isotopic composition of each single ice vein is directly linked to atmospheric precipitation, i.e. winter snow, and, therefore, indicative for the climate conditions during the corresponding cold season. However, isotopic fractionation in the snow cover might impact the stable-isotope composition of wedge ice as well but is considered to be negligible for the purpose of this study. Hence, t~~T~~he stable isotope ratios of oxygen ($\delta^{18}O$) and hydrogen (δD) of wedge ice (in ‰ vs. V-SMOW) are related to the condensation temperature of the precipitation (Meyer et al., 2015) and are, therefore, interpreted as proxies for the mean winter air temperature at the study site~~ (Meyer et al., 2015)~~. More negative values reflect colder conditions and less negative values reflect warmer conditions. The *d* excess ($d=\delta D-8\delta^{18}O$) (Dansgaard, 1964) is indicative for the evaporation conditions (i.e. relative humidity, sea surface temperature) in the moisture source region (Merlivat and Jouzel, 1979). In the last years, stable-isotope data from ice wedges have been progressively used to reconstruct past climate changes in Arctic permafrost regions in Northern Siberia (Meyer et al., 2002a; Meyer et al., 2002b; Opel et al., 2011; Wetterich et al., 2011; Vasil'chuk and Vasil'chuk, 2014; Wetterich et al., 2014; Meyer et al., 2015; Streletskaya et al., 2015; Wetterich et al., 2016;

Opel et al., 2017) as well as in Alaska (Meyer et al., 2010b; Lachniet et al., 2012; Schirrmeister et al., 2016) and in Canada (Fritz et al., 2012; Porter et al., 2016) on different timescales and with different temporal resolutions.

In contrast, intra-sedimental texture ice forming cryostructures (pore ice as well as segregated ice lenses and layers) in syngenetic permafrost originates from freezing of soil moisture in the seasonally thawed active layer. Soil moisture is fed by varying proportions of different water sources such as summer rain and winter snow as well as melt water of the thawed active layer ice (Mackay, 1983; Vaikmäe, 1989). Additionally, soil moisture is subject to evaporation processes and numerous freeze-thaw cycles before it enters the perennially frozen state. Hence, the stable isotope composition of pore and segregated texture ice has undergone several fractionation processes until the final freezing during permafrost aggradation. It therefore cannot be straightforward interpreted as climate proxy (Wetterich et al., 2014; Wetterich et al., 2016). Nevertheless, the texture-ice isotopic composition of pore and segregated ice has been successfully interpreted in terms of general climate trends such as long-term warming or cooling (Schwamborn et al., 2006; Dereviagin et al., 2013; Porter et al., 2016).

In the Siberian Arctic Laptev Sea region, comprehensive studies of ice-wedge and partly pore and segregated texture-ice stable isotopes of stratigraphic units accessible in coastal exposures have been carried out in the last years at the Mamontova Khayata section of the Bykovsky Peninsula (Meyer et al., 2002a) and at the south coast of Bol'shoy Lyakhovsky Island close to the Zimov'e River mouth (Meyer et al., 2002b). Selected stratigraphic units have been studied at Cape Mamontov Klyk (Boereboom et al., 2013), at Bol'shoy Lyakhovsky Island (Wetterich et al., 2011; Wetterich et al., 2014; Wetterich et al., 2016), at the Oyogos Yar Coast (Opel et al., 2011), and in the Lena River Delta (Schirrmeister et al., 2003b; Wetterich et al., 2008; Schirrmeister et al., 2011a; Meyer et al., 2015). To verify the obtained palaeoclimate results on different timescales and to assess their spatial and temporal representativity, additional extensive ground-ice stable-isotope records are needed.

As for all climate archives, reliable chronologies are crucial for ground-ice based palaeoclimate studies. However, direct dating of ice wedges (Vasil'chuk et al., 2000) is challenging, in particular for the pre-Holocene. Mostly there is only little particulate organic material for radiocarbon dating preserved in ice wedges. Therefore, also air-bubble CO_2 and dissolved organic carbon enclosed in ice wedges have been used for radiocarbon dating to overcome this issue Moreover, the ages of late Pleistocene ice wedges are often close to or beyond the age limit of radiocarbon dating (Lachniet et al., 2012). However, new dating tools are in development and comprise radiocarbon dating of air-bubble CO_2 and dissolved organic carbon enclosed ice wedges (Lachniet et al., 2012), Uranium isotopes (Ewing et al., 2015) as well as $^{36}Cl/Cl^-$ dating for Mid- to Late Pleistocene ground ice (Blinov et al., 2009). In many cases, syngenetic ice wedges are therefore only indirectly dated by age determination of the surrounding host sediments. The attribution of host sediments and ice wedges to stratigraphic units with distinct chronological information is often complicated and, hence, regional stratigraphic correlations are challenging (Wetterich et al., 2014).

To address the issue of temporal and spatial representativity of ground-ice stable-isotope records, we present in this paper new data from different Late Quaternary stratigraphic and chronological units at the Oyogos Yar Coast of the Dmitry Laptev Strait. Based on new geochronological and cryolithological information we discuss the cryostratigraphy. We interpret the variability of new ice-wedge and pore and segregated texture-ice stable isotope data and discuss the relevance of ground-ice stable isotopes in terms of paleoclimate and environmental history. We relate our ground-ice stable-isotope data to previously published data from Bol'shoy Lyakhovsky Island in order to generate a Dmitry Laptev Strait ground-ice isotope record and compare it to large-scale climate changes. Furthermore, we shed light on the potential of ice-wedge isotope data as tools for stratigraphic correlations between different study sites.

2 Regional Setting

The Dmitry Laptev Strait connects the Laptev and East Siberian seas (Figure 1) and its coasts have been subject of geographical and geological research for more than 100 years (Bunge, 1887; von Toll, 1897; Romanovskii, 1958c, a, b). The north shore of the Dmitry Laptev Strait, i.e. the south coast of Bol'shoy Lyakhovsky Island represents one of the best-studied Quaternary permafrost sites in Northeast Siberia. Extensive studies of the exposed frozen sediments and ground ice have been carried out to To reconstruct environmental dynamics of West Beringia since the mid-Pleistocene extensive studies of the exposed frozen sediments and ground ice have been carried out (Arkhangelov et al., 1996; Kunitsky, 1996; Meyer et al., 2002b; Schirrmeister et al., 2002a; Andreev et al., 2004; Andreev et al., 2009; Wetterich et al., 2009; Andreev et al., 2011; Schirrmeister et al., 2011b; Wetterich et al., 2011; Tumskoy, 2012; Wetterich et al., 2014; Wetterich et al., 2016 and references therein). In addition, the permafrost exposures of the Oyogos Yar mainland coast at the south shore of the Dmitry Laptev Strait have been studied, but less extensively (Ivanov, 1972; Gravis, 1978; Konishchev and Kolesnikov, 1981; Kaplina and Lozhkin, 1984; Tomirdiaro, 1984; Nagaoka et al., 1995; Wetterich et al., 2009; Kienast et al., 2011; Opel et al., 2011; Schirrmeister et al., 2011b; Rudaya et al., 2015 and references therein).

Stability of permafrost deposits depends basically on climatic conditions during formation, past relief conditions, and the decoupling from seasonal thawing and freezing processes. Warmer interglacial Interglacial and interstadial warm periods promote extensive permafrost thaw and subsequent surface subsidence mainly due to ground-ice melt. Such processes termed thermokarst (e.g. Kaplina, 2009) have substantially influenced the study area during the Last Interglacial and since the Lateglacial-Holocene transition. Thawed and refrozen deposits are named as taberite or taberal deposits (Kaplina, 2009) and underlie lacustrine thermokarst-lake deposits (Figure 2). Due to varying deposition regimes over time as well as spatially and temporally and spatial variable patterns of permafrost degradation (and also aggradation) during warm periods, permafrost sequences are often not continuous. This often complicates geochronological interpretations as representatives deposits of consecutive late Quaternary periods may not be found superimposed upon each other but be found at laterally different positions and in different altitudes.

Following Tumskoy (2012), permafrost perennially frozen deposits exposed at the Dmitry Laptev Strait span from the MIS7 to the Holocene (Table 1). Yedoma Ice Complex deposits (MIS 3-2) are preserved in sections elevated up to 35 m a.s.l. high while thermokarst basins up to 15 m a.s.l. high exhibit lacustrine and palustrine deposits of the Lateglacial and Holocene periods. Lacustrine deposits of the Krest Yuryakh Suite, which are commonly attributed to the Last Interglacial (Wetterich et al., 2009; Kienast et al., 2011; Tumskoy, 2012) as well as the Buchchagy Ice Complex (MIS 5e-b; Wetterich et al. (2016)) are preserved either below Yedoma Ice Complex or below Lateglacial to Holocene thermokarst-lake and thermokarst basin palustrine deposits (Figure 2). The stratigraphic position of floodplain deposits attributed to both the Kuchchugui Suite (MIS6; Tumskoy (2012)) and the Zyryanian (MIS4) (Andreev et al., 2004; Andreev et al., 2009) is still under debate.

The main landscape elements, i.e. Yedoma Ice Complex uplands as well as thermokarst basins (alasses) may be cut by thermo-erosional gullies and river valleys and are subject to rapid coastal erosion processes (Günther et al., 2013) that form steep coastal bluffs. Depending on the prevailing type of coastal erosion, thaw slumps may form fromaffect Yedoma Ice Complex deposits, shaping a thermo-terrace with thermokarst mounds (remaining sedimentary polygon-centre fillings after melting of ice wedges surrounding an ice-wedge polygon; baydzherakhs) in front of a steep wall dominated bywith exposed ice wedges (Figure 3).

3 Material and Methods

The work presented here is based on material and observations of a one-day reconnaissance trip in 2002 (Schirrmeister et al., 2003a) and a follow-up four-week expedition to the Oyogos Yar coast in 2007 (Schirrmeister et al., 2008b) during which about 6 km of the Oyogos Yar coastline were studied between 72.683°N, 143.475°E and 72.672°N, 143.635°E.

3.1 Fieldwork

After overview surveys along the coastal bluffs ice wedges and sediment profiles from all exposed stratigraphic units were selected for extensive investigations and firstly described, photographed and sketched.

After cleaning the exposures from thawed material and debris, horizons were cryolithologically described (Murton and French, 1994; French and Shur, 2010; Murton, 2013) and samples were taken by axe and hammer in sub-profiles. The weight of the frozen sample compared to the weight of the sample after oven-drying was used to calculate the gravimetric ice content of the sediments, expressed as weight percentage (wt%) (Van Everdingen, 1998). Values higher than 100 wt% indicate ice over-saturation. Supernatant water fFrom thawed sediment samples with supernatant water we took samples was sampled for analysing the stable water isotope composition of pore and segregated texture ice.

A handheld drilling machine (HILTI TE 5 A) equipped with a core bit was used to obtain frozen sediment cores (150-290 cm^3) from profiles Oy7-07 (at 1.5 m asl) and Oy7-08 (at 4.0 m asl) for luminescence dating. Samples were protected from sunlight by using opaque plastic cylinders and sample bags. The sediment of the immediate surroundings of core positions was taken for high-purity Germanium (HPGe) low-level gamma spectrometry of radionuclide concentrations. Subsequent material processing and analyses were performed at the Luminescence Laboratory of the Technical University Bergakademie Freiberg (Germany).

In total, we sampled 44 ice wedges from all exposed stratigraphic units, seven in 2002 and 37 in 2007 (Figure 2). Stable isotope samples from ice wedges were taken by chain saw, by axe or by ice screws (in horizontal profiles covering the entire width of the studies ice wedges) along the ice wedge's growth direction (i.e. the profiles perpendicularly cut ~~perpendicular to the~~ frost cracking direction and near-vertical individual ice veins). The sampling resolution varied from about 1 and about 30 cm between different ice wedges (but remained constant within individual ice wedges), depending on fieldwork logistics, sampling tools and specific research questions. The samples were either melted on site with melt water stored in tightly closed 30-ml PE bottles or transported as blocks in frozen state to the cold laboratory of the Alfred Wegener Institute (AWI) in Potsdam for sub-sampling. The melted samples were stored cool (~5°C) before analysing the stable ~~water~~ isotope composition. Organic material enclosed in ice wedge was picked either in the field or in the AWI cold laboratory for radiocarbon dating.

3.2 Radiocarbon dating

Organic remains enclosed in ice-wedge samples (unidentified plant remains and lemming droppings) as well as plant remains from sediment samples were radiocarbon dated using the accelerator mass spectrometry (AMS) facilities at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research (Kiel University, Germany) (Grootes et al., 2004), CologneAMS (University of Cologne, Germany) (Dewald et al., 2013; Rethemeyer et al., 2013) and Poznań Radiocarbon Laboratory (Adam Mickiewicz University, Poznań, Poland) (Goslar et al., 2004). Conventional ^{14}C ages were calculated according to (Stuiver and Polach, 1977). Calibrated ages were determined as yr b2k (before CE2000) using Oxcal 4.2 (Bronk Ramsey, 2009) based on the IntCal13 dataset (Reimer et al., 2013).

3.3 IRSL dating

The cores were processed for quartz and feldspar at target grain size fractions of 20-40 µm, 40-63 µm, 63-100 µm, and 90-160 µm. Lacking coarse-grained material (>100 µm) and quartz optically stimulated luminescence (OSL) signals close to saturation required focusing on feldspar infrared stimulated luminescence (IRSL) of the grain size fraction 63-100 µm. Carbonates and organics were removed using 10% HCl and 30% H_2O_2, respectively. Feldspar flotation (0.2% HF, pH 2.4-2.7, dodecylamine) removed the quartz from sample extracts and subsequent density separation enriched K-feldspars (2.53-2.58 g cm^{-3}). Etching (10% HF, 5 min) removed the outer 10-µm layer of individual grains.

Aliquots of 2 and 1 mm diameter reflect the trade-off between low grain number per aliquot (reduced averaging of inter-grain variations) and sufficient luminescence signal intensities. The IRSL signals of feldspars were measured using a TL/OSL DA-20 Reader (Bøtter-Jensen et al., 2003) equipped with a ^{90}Sr beta irradiation source (4.95 Gy min^{-1}).

Signals were stimulated at 870 nm (IR diodes, 125 °C for 100 s) and detected through a 410 nm optical interference filter (Krbetschek et al., 1997). The measurement sequence followed the single-aliquot regenerative-dose (SAR) protocol according to Murray and Wintle (2000), including cycles to record recycling ratios, recuperation, and correct for sensitivity changes. Appropriate measurement conditions were evaluated and adjusted based on preheat tests and dose-recovery tests (Murray and Wintle, 2003). Processing of measured data and statistical analyses were performed using the software Analyst v4.31.7 (Duller, 2015) and the R package 'Luminescence' (Kreutzer et al., 2012), version 0.6.4. The small data set (n = 5) restricted age modelling to a simple measure of central tendency, i.e. arithmetic mean. The large data set (n = 49) showed no evidence for insufficient bleaching due to low scatter (standard deviation below 10%) and low skewness (<0.5) of equivalent doses and hence, suggested paleodose calculation based on the central age model (CAM) (Galbraith et al., 1999). Final IRSL ages, including dose rate modelling, were estimated using the software ADELE (Kulig, 2005). For the determination of the mineral-internal dose rate of the K-feldspars, a potassium content of 12.5 ± 0.5% was assumed (Huntley and Baril, 1997).

3.4 Stable-isotope analysis

The equilibrium technique was used to prepare ice-wedge as well as pore and segregated-ice samples for stable-isotope analysis. Stable oxygen ($\delta^{18}O$) and hydrogen (δD) isotope ratios were measured on a Finnigan 215 MAT Delta-S at AWI PotsdamUsing a mass spectrometer (Finnigan 215 MAT Delta-S) equilibrium technique was applied to analyse the oxygen ($\delta^{18}O$) and hydrogen (δD) stable-isotope ratios of all ice-wedge and texture-ice samples in the stable isotope laboratory of AWI Potsdam. The values are given in delta per mil notation (δ, ‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) Standard. Based on long-term standard measurements, the reproducibility of 1σ is better than ±0.1‰ for $\delta^{18}O$ and ±0.8‰ for δD, respectively (Meyer et al., 2000). The deuterium excess *d* (Dansgaard, 1964) was calculated by $d = \delta D - 8\delta^{18}O$.

For this study, we considered only ice wedges with a clear stratigraphic relation to one of the studied units and at least three samples. Exceptions were made only for a small Holocene ice wedge at the top of the Yedoma Ice Complex (two samples) as well as for narrow modern ice wedges, i.e. single veins or groups of ice veins representing the youngest ice-wedge growth stage (one to two samples). Following this, from the 44 sampled ice wedges, we considered in the following only 28. Partly, ice-wedge data were only interpreted as groups (i.e. recent ice wedge parts and modern ice veins).

In several cases, stable-isotope data, preferentially those from samples at the edge of ice wedges showed clear signs of post-genetic fractionation processes owing to exchange processes between wedge ice and surrounding sediments. The respective data are characterized by distinctly elevated $\delta^{18}O$ and δD values and decreased *d* excess values and were excluded from further analysis and interpretation.

Similar to ice wedges, we considered only pore and segregated texture-ice stable-isotope data with a clear attribution to one of the studied units and only units with at least three data points.

4 Results

Within this paper, we focus on our extensive studies of cryostratigraphy and, in particular, ground-ice stable isotopes. For more detailed results and discussion of distinct sediment profiles we refer to Wetterich et al. (2009), Schirrmeister et al. (2011b) and Wetterich et al. (2016). From these papers we also adopted most radiocarbon ages derived from sediment samples.

4.1 CryosStratigraphy~~, cryolithology~~ and geochronology

Eight ~~cryolithological~~ cryostratigraphic units were distinguished during fieldwork at the Oyogos Yar coast (Table 1, Figure 2). The studied ice wedges were attributed to five of the units based on field observations.

4.1.1 Unit I

The oldest unit studied at the Oyogos Yar coast is represented by floodplain deposits related to the **Kuchchugui Suite**~~, which typically shows a subdivision into two horizons~~. ~~The lower one~~The deposits consist~~s~~ of brownish-grey laminated silty sands and contain peat inclusions and in-situ grass roots. Unit 1 varies in ice content (31-108 wt%, mean 52 wt%, Table 2). Cryostructures include structureless cryostructure (no ice inclusions visible by naked eye) as well as horizontal ice layers (10-20 mm thick, 50-100 mm apart) with wavy lenticular and irregular reticulated ice lenses (1 mm thick).~~is characterized by a relatively low ice content (31-53 wt%) with massive cryostructure and peat inclusions as well as thin in-situ grass roots. The upper horizon is built from more ice-rich (up to 140 wt%) silty sands with bended, belt-like and lens-like reticulate cryostructures. It also contains grass roots and peat inclusions and is covered by a~~ A dark-brown peat soil layer covers the sequence with included coarse (>1 mm thick) irregular reticulated ice lenses between ice layers (10-20 mm thick and 50 mm apart).

Syngenetic ice wedges in ~~these deposits~~Unit I are rather small and can be ~~found in two ways~~divided into two types. The first type occurs in the lower horizon and consists of 0.3 to 0.75 m wide composite wedges (sand-ice wedges) composed of alternating ice and sand veins (1 to 10 mm wide). They exhibit rounded truncated heads and are buried by the upper sediment horizon of U~~u~~nit I. The second type within the upper horizon is represented by intersecting multistage ice wedges, i.e. composite wedges that transform upwards ~~pass over~~ into regular syngenetic ice wedges ~~of~~ 0.5 to 1 m wid~~eth~~. Their clean, transparent wedge ice ~~shows~~ contains many vertically oriented air bubbles (1-5 mm in diameter) and pronounced ice veins of 3-6 mm thickness. Additionally, epigenetic ice wedges from the overlying ~~unit~~ Unit II penetrate into the Kuchchugui deposits.

IRSL analyses of feldspars (63-100 µm, n = 49, CAM) yielded a deposition age of 112.5±9.6 kyr for sample Oy7-07-01. Suitable IRSL signal properties are indicated by high signal intensity, good reproducibility and low recuperation. This is confirmed by a low coefficient of variation in doses recovery tests (6.7%). The low standard deviation and low skewness value indicate no bleaching issues (Table ~~2~~3) and suggest a reliable IRSL age estimation.

Radiocarbon dating of moss peat from the upper horizon sampled directly above composite wedge Oya IW1 revealed a non-finite age of >44.5 cal kyr b2k for the leached residue and a mean age of 45.2 cal kyr b2k for humic acid, respectively (Table ~~3~~4).

4.1.2 Unit II

Unit II represents the **Buchchagy Ice Complex**. It is ~~characterized~~ represented by 6 to 8 m thick brown to grey silty sands with peat inclusions and two distinct peaty horizons up to 1 m thick about 3 m apart (Wetterich et al., 2016).~~ The corresponding sediments are~~ .

The lower peaty horizon consists of brownish blue grey silty sand with numerous peat inclusions up to 300 mm in diameter. Ice layers (30 mm thick) and wavy lenticular cryostructures (1-2 mm thick, 10-15 mm apart) in between are typical. The ice content varies between 25 and 112 wt% (Table 2) in the mineral part while the peaty deposits are ice oversaturated (113-793 wt%). Brownish grey silty sand covers the lower peaty horizon and contains fewer peaty remains and some twigs. Horizontal ice layers (5-20 mm thick, 50-100 mm apart) and curved lenticular and layered cryostructures (up to 2 mm thick) are observed. The upper peaty horizon is similar to the lower one as described above.

~~relatively ice-rich (gravimetric ice content 61-112 wt%, except for the peat horizons with even higher values), brown to grey silty sands with peat inclusions as well as lens-like and layered cryostructures.~~

Unit II contains syngenetic ice wedges 2 to 4 m wide and several m deep that penetrate into ~~unit~~ Unit I. Partly they are truncated and buried below grey loam with many peat inclusions, likely representing the lower peat horizon. The wedge ice of rather dirty yellowish-grey colour ~~exhibits~~ contains numerous ~~numeral~~ mineral inclusions and air bubbles of 1-5 mm in diameter. Ice-vein thickness is about 3-5 mm.

The only dating results available are infinite radiocarbon ages (>51 kyr BP and >49 kyr BP; Table ~~3~~4) for the two distinctive peaty layers (Wetterich et al., 2016). At the southern coast of Bol'shoy Lyakhovsky Island, opposite to the Oyogos Yar coast, the respective peaty horizons of the Buchchagy Ice Complex show infinite radiocarbon ages as well, whereas radioisotope (^{230}Th/U) disequilibria dating of peat revealed ages of 126+16/-13 kyr and 118+19-14 kyr for the lower, and 93±5 kyr and 89±5 kyr for the upper peat horizon (Wetterich et al., 2016). This geochronological information can be transferred to the Oyogos Yar coast. The chronostratigraphic link is supported by ice-wedge stable isotope data (see chapter 5.2).

4.1.3 Unit III

Unit III refers to deposits of the **Krest Yuryakh Suite** that is commonly related to the Last Interglacial. ~~This u~~Unit III comprises two ~~different kinds~~ types of deposits, both associated ~~to~~ with ~~thermokarst~~ thermokarst-lake development. The first type ~~likely~~ represents a succession of an ancient lake margin. It consists of bedded dark grey to greyish brown ~~dark grey to grey brown~~ silts, partly rippled. ~~with m~~Mollusc shells as well as plant detritus layers and plant inclusions (~~,~~ partly ~~accompanied by~~ wood fragments) are common. The upper part shows decreasing plant detritus content and numerous mollusc shells. The cryostructure is ~~lens-like~~irregular reticulated (1-2 mm thick)~~in the upper part and coarse lens-like reticulated in the lower part~~. ~~The gravimetric ice content is low (20 to 40 wt%).~~ The second type represents lacustrine sediments filling ice-wedge casts above ~~grey~~ taberal deposits~~ with massive cryostructure~~. The lacustrine deposits ~~They~~

consist of bedded grey clayey~~ish~~ sandy silts with brown peat lenses and alternating plant detritus layers. The cryostructures are~~, characterized by a lens-like reticulated to~~ layered (1 mm thick) and oriented parallel to the sedimentary bedding. For both kinds of deposits the ice content varies from 15 to 66 wt% (mean 36 wt%, Table 2). The underlying taberal deposits of grey silts exhibit a structureless cryostructure. ~~cryostructure and single ice lenses~~. ~~The upper part shows decreasing plant detritus content and numerous mollusc shells.~~

No syngenetic ice wedges were found, but partly toes of younger epigenetic ice wedges, presumably related to Unit IV were present.

IRSL analyses of sample Oy7-08-25 could only be based on few aliquots (n = 5) due to the limited material in the suitable grain size fraction (63-100 µm). Nevertheless, the low coefficient of variation (6.3%) in dose recovery tests (n = 5) indicates appropriate luminescence properties and measurement conditions. Reliable feldspar properties are further supported by high signal intensity, good reproducibility, low standard deviation and low skewness (Table ~~2~~3). The IRSL results date ~~unit~~ Unit III to 102.4±9.7 kyr.

A mean radiocarbon age of 48.3 cal kyr b2k was obtained from leached residue of wood in sample Oya-3-11 from an ice-wedge cast (Table ~~3~~4).

4.1.4 Unit IV

Unit IV represents the **Yedoma Ice Complex** that constitutes of grey-brown sandy silts with small (20x20 mm) ~~peat lenses~~ and larger (up to 200x400 mm) peat inclusions, which originate from buried cryosols, as well as twig fragments, grass roots and fine distributed plant detritus. The cryostructures are horizontally layered (1-2 mm thick, 30-100 mm apart) and irregular reticulated (2-3 mm thick, 10-30 mm long) between the ice layers~~is determined layered and lens-like reticulated between ice bands~~. The gravimetric ice content ranges from ~~50~~ 25 to more than ~~200~~ 240 wt% (mean 119 wt%, Table 2). Huge syngenetic ice wedges up to 8-10 m wide in the higher sections (2-5 m in the lower sections) ~~reach heights~~have vertical extents of more than 20 m. The wedge ice is mostly dirty grey as typical for Yedoma Ice Complex ice wedges with varying sediment contents but partly also milky white, indicating a much higher number of small air bubbles. Vertically oriented ice veins are mostly between 1 and 5 mm wide.

According to mean radiocarbon ages the **Yedoma Ice Complex** was deposited in the time period between about 49.4 and 36.3 cal kyr b2k (Table ~~3~~4). Several age reversals have been found; hence no clear age-depth relationship could be established.

4.1.5 Unit V

In the vast thermokarst basin, ~~unit~~ Unit V consists of **taberal Yedoma Ice Complex deposits**, which thawed ~~during~~ below a thermokarst ~~formation below a~~ lake and refroze after lake drainage or desiccation. Unit V is represented by light-grey silts with very little plant detritus. The top of Unit V consists of a paleosol layer with twigs and peat inclusions. The ~~lens-like layered~~ cryostructure is wavy layered (1 mm thick, 50-150 mm long, 10-20 mm apart) and ~~very little plant detritus.~~ ~~t~~The gravimetric ice content is around 40 wt% (Table 2). ~~Unit V is completed by a paleosol layer with twigs and peat inclusions.~~ ~~No~~ Whereas no syngenetic ice wedges were found, partly the epigenetic toes of ice wedges (related to Unit VII) were observed.

Radiocarbon ages of taberal Yedoma Ice Complex deposits revealed mean ages of about 46.0 and 40.1 cal kyr b2k (Table ~~3~~4) which correspond to ~~and confirm~~ the period of Yedoma Ice Complex deposition, not the time of thermokarst-lake development.

4.1.6 Unit VI

The Late Glacial to Holocene sequence starts with about 2 m **lacustrine deposits** of ~~unit~~ Unit VI ~~with lens-like layered cryostructure~~, partly filling ice-wedge casts. The cryostructure is layered and t~~T~~he gravimetric ice content is ~~4~~30 ~~to~~ -70 wt% (Table 2). Unit VI is characterised by alternating ~~layers~~ bedding of silty fine sand and plant detritus and contains also wood fragments and mollusc shells. The lake deposits are covered by a 20 to 30 cm thick peat horizon. No syngenetic ice wedges were found, but the lower parts of ice wedges of Unit VII.

Radiocarbon dating revealed a Late Glacial age (means about 18.1 to 12.7 cal kyr b2k) of the thermokarst-lake deposits (Table ~~3~~4).

4.1.7 Unit VII

The **palustrine deposits** of ~~unit~~ Unit VII consist of about 3 m of ice-rich greyish sandy silts, partly containing peat lenses~~.~~ and a pronounced brown peat horizon of 30 cm thickness and wood remains (20-30 cm in diameter). The cryostructure is layered (1 mm thick, 20-30 mm long, 50-100 mm apart)~~and coarse lens-like reticulated~~. The gravimetric ice content is ~~13~~50 ~~to~~ -180 wt% (mean 119 wt%, Table 2). The recent polygonal surface of the thermokarst basin is mirrored by widely distributed and actively growing syngenetic ice wedges. They are up to 3.5 m wide and up to about 8 m high with toes that reach ~~down until~~ the taberal deposits of ~~unit~~ Unit V. Their ice is mostly transparent to milky white but sometimes also dirty grey due to higher density of sediments and organic matter. Single ice veins are 1 to 10 mm wide. The ice of the most recent ice wedge parts as well as of the ~~up to 8 cm wide and up to 20 cm high~~ modern rejuvenation stages (up to 8 cm wide and up to 20 cm high) is more milky white due to a higher number of small air bubbles.

The palustrine deposits in the thermokarst basin accumulated over the Holocene (about 11.5 to 3.6 cal kyr b2k) with the pronounced peat horizon dated to about 9.3 cal kyr b2k (Table ~~3~~4). Organic remains in ice-wedge samples indicate syngenetic ice-wedge growth over the Late Holocene, i.e. since about 2.0 cal kyr b2k (Table ~~4~~5).

4.1.8 Unit VIII

Unit VIII depicts the up to 1-2 m thick **Holocene cover** on top of the Yedoma Ice Complex. Unit VIII was only found in places representing the fillings of small initial thermokarst ponds (bylary)~~and associated with initial thermokarst~~. The deposits ~~are characterised by~~consist of brownish grey loam with numerous peat inclusions. The cryostructures are ~~and a~~

layered (10-20 mm thick, 20-50 mm apart) and irregular reticulated (1 mm thick)~~cryostructure~~. The gravimetric ice content is 54 to 118 wt% (mean 92 wt%, Table 2). The transition to the unfrozen uppermost active layer contains a 20-30 mm thick ice layer built of vertical ice needles. Unit VIII contains s~~S~~mall, milky white syngenetic ice wedges less than 1 m wide whose toes penetrate into the Yedoma Ice Complex ice wedges (Figure 3a).~~ Moreover, Holocene cracking activity characterised by m~~Milky white ice veins likely of Holocene origin ~~was~~ were ~~also~~ observed in the upper parts of ~~the~~ two huge ice wedges of the Yedoma Ice Complex.

The Holocene cover deposits were radiocarbon dated to the early Holocene with mean ages of about 11.0 to 8.9 cal kyr b2k (Table ~~4~~5).

4.1.9 Generalised stratigraphic sequences

The described cryolithological units and the respective ice wedges have been studied in three **generalised stratigraphic sequences** A to C (Figure 2).

The first sequence A represents the stratigraph~~yic situation~~ of the eastern part of the study area (A in Figure 2). It consists of Kuchchugui floodplain deposits of ~~unit~~ Unit I, Buchchagy Ice Complex (~~unit~~ Unit II), and Krest Yuryakh ~~thermokarst~~ thermokarst-lake deposits (~~unit~~ Unit III), discordantly overlain by Yedoma Ice Complex (~~unit~~ Unit IV) and Holocene cover (~~unit~~ Unit VIII).

The second sequence B in the central part of the study area (B in Figure 2) comprises ~~in the lower part~~ Kuchchugui floodplain deposits (~~unit~~ Unit I) covered by Buchchagy Ice Complex (Unit ~~unit~~ II) and Krest Yuryakh ~~thermokarst~~ thermokarst-lake deposits (Unit~~unit~~ III). The main part consists of Yedoma Ice Complex deposits (Unit~~unit~~ IV) overlain by the Holocene cover (Unit~~unit~~ VIII).

Sequence C in the western part of the study area (C in Figure 2) ~~are~~ is represented by about 10 m high thermokarst basin outcrops and comprise Krest Yuryakh ~~thermokarst~~ thermokarst-lake deposits (Unit~~unit~~ III), covered by taberal Yedoma Ice Complex (Unit ~~unit~~ V) as well as Late Glacial to Holocene ~~thermokarst~~ thermokarst-lake (Unit ~~unit~~ VI) and thermokarst-basin palustrine deposits (Unit ~~unit~~ VII).

4.2 Stable isotope composition of ground ice

The basic parameters of the studied ice wedges of different units as well as their ~~basic parameters and~~ stable-isotope data are presented in Table ~~5~~6. The attribution of ice wedges to certain stratigraphic units is based on field observations and stable~~-water~~ isotope data. Additionally, pore and segregated ~~texture~~-ice stable isotope data are also summarised in Table ~~5~~6. Overall, both ice-wedge ~~and~~ as well as pore and segregated ~~texture~~-ice stable-isotope data show a high variability over time.

4.2.1 Unit I Kuchchugui floodplain deposits

The composite wedges exhibit mean $\delta^{18}O$ values of -30.7‰ for Oya IW1 (δD: -240.5‰) and -28.2‰ for Oy7-03 IW4 (δD: -225.6‰), respectively, with low internal variability (Figure 4, Table ~~5~~6). Their respective mean *d* excess values were low

(4.8‰ and 0‰). The corresponding slopes (intercepts) in a δ^{18}O-δD bi-plot are 7.41 and 6.7 (-13.23 and -36.78), respectively.

The intersected multi-stage ice wedges showed in the composite-wedge parts (Oy7-03 IW1+5) mean values of -29.7‰ for δ^{18}O, -235.0‰ for δD, and 2.3‰ for *d* excess with a regression line of $\delta D=8.68*\delta^{18}O+22.46$ ($r^2=0.98$). The upper regular part showed the lowest δ^{18}O and δD mean values (-34.1‰ and -268.0‰, respectively) observed in all units at the Oyogos Yar Coast (Figure 4, Table ~~5~~6). The mean *d* excess value is 4.9‰ and the co-isotopic regression line $\delta D = 8.74*\delta^{18}O +29.99$ ($r^2 = 0.93$).

Pore and segregated ~~Texture~~-ice stable-isotope values scatter between -29.8‰ and -23.1‰ for δ^{18}O, -231.8‰ and -191.4‰ for δD, as well as -8.0‰ and 6.2‰ for *d* excess (Figure 4, Table ~~5~~6). The regression line in a co-isotopic δ^{18}O-δD plot is $\delta D=6.24*\delta^{18}O-48.31$ ($r^2=0.99$), quite similar to that of composite wedge Oy7-03 IW4.

4.2.2 Unit II Buchchagy Ice Complex deposits

One syngenetic ice wedge was attributed to the Buchchagy Ice Complex (Oy7-07 IW1). The mean stable~~- water~~ isotope values (n=7) are -33.1‰ for δ^{18}O, -258.3‰ for δD, and 6.7‰ or *d* excess with very little variability (Figure 4, Table ~~5~~6). The regression line in a δ^{18}O-δD bi-plot is $\delta D=6.96*\delta^{18}O-27.89$ ($r^2=0.98$).

Pore and segregated ~~Texture~~-ice stable-isotope values scatter between -29.8‰ and -23.3‰ for δ^{18}O, -233.8‰ and -184.9‰ for δD, and -1.9‰ and 9.9‰ for *d* excess (Figure 4, Table ~~5~~6). The regression line in a co-isotopic δ^{18}O-δD plot with $\delta D=6.89*\delta^{18}O-26.83$ ($r^2=0.98$) is similar to the ice-wedge data.

4.2.3 Unit IV Yedoma Ice Complex deposits

In total, ten ice wedges of the Yedoma Ice Complex were studied in different altitude levels from 1.5 to about 35 m a.s.l. ~~In places, in particular c~~Close to the ground surface at the top of the Yedoma Ice Complex as well as at the slope to the thermokarst basin, ~~the~~ two ice wedges (Oy7-06 IW2 and Oy7-08 IW3) showed evidence of Holocene frost-cracking activity, i.e. Holocene ice veins. The respective samples, i.e. those with δ^{18}O values higher than -28.0‰ (maximum value of unaffected ice wedges of Unit ~~unit~~ IV and slightly lower than the minimum value (-27.1‰) of Holocene ice wedges in Unit ~~unit~~ VII), were accordingly attributed to Unit~~unit~~ VIII (Holocene cover deposits) instead of Unit IV.

The overall mean stable isotope values of the Yedoma Ice Complex ice wedges are -30.8‰ for δ^{18}O, -240.2‰ for δD, and 5.9‰ for *d* excess with a regression line of $\delta D=8.33*\delta^{18}O+15.92$ ($r^2=0.98$). The mean values for single ice-wedge profiles vary between -32.8‰ and -29.2‰ for δ^{18}O, -258.3‰ and -227.6‰ for δD, and 3.7‰ and 8.1‰ for *d* excess (Table ~~5~~6, Figure 4) without any clear altitudinal trend (Figure 5).

The pore and segregated ~~texture~~-ice stable-isotope values exhibit an enormous scatter and vary between -34.5‰ and -18.5‰ for δ^{18}O, -253.9‰ and -150.5‰ for δD, and -10.9‰ and 21.7‰ for *d* excess (Table ~~5~~6, Figure 4). The co-isotopic regression line is $\delta D=6.51*\delta^{18}O-36.00$ ($r^2=0.97$). A substantial altitudinal variability shows a generally decreasing (increasing) trend in

$\delta^{18}O$ and δD (*d* excess) values from about 6 m a.s.l. to a pronounced minimum (maximum) around 20 m a.s.l. and again higher (lower) values above (Figure 5).

4.2.4 Unit VII Palustrine deposits

The ice-wedge stable-isotope samples from Unit~~unit~~ VII can be attributed to four groups: (1) older lower sections, (2) high-resolution vertical profiles in the younger upper section, (3) recent, i.e. central parts of upper sections and (4) modern ice veins, i.e. rejuvenation stages. The first two groups show quite similar isotopic compositions with mean values between -25.4‰ and -25.0 ‰ for $\delta^{18}O$, -194.6‰ and -192.0‰ for δD, and 7.5‰ and 8.8‰ for *d* excess with co-isotopic slopes between 7.53 and 7.67 and intercepts between -3.76 and -0.75 (Table ~~5~~6, Figure 4). The recent ice wedge parts exhibit more enriched isotopic compositions with mean values of -22.7‰ for $\delta^{18}O$, -173.9‰ for δD, as well as 7.6‰ for *d* excess, whereas the modern ice veins show the most enriched mean values of all samples: -20.7 ‰ for $\delta^{18}O$, -158.3‰ for δD, and 7.7‰ for *d* excess. The co-isotopic regression lines are with $\delta D=8.03*\delta^{18}O+8.33$ ($r^2=0.99$) and $\delta D=7.79*\delta^{18}O+3.23$ ($r^2=0.99$), respectively, close to the Global Meteoric Water Line (GMWL: $\delta D=8*\delta^{18}O+10$).

The pore and segregated ~~texture~~-ice stable-isotope values group between -21.9‰ and -16.0‰ for $\delta^{18}O$, -171.4‰ and -124.2‰ for δD, and -3.7‰ and 10.7‰ for *d* excess (Table ~~5~~6) $\delta^{18}O$ and δD build two clusters in the co-isotope plot (Figure 4). The regression line is close to that of the ice wedges ($\delta D=7.57*\delta^{18}O-6.35$) but with a weaker correlation ($r^2=0.88$).

4.2.5 Unit VIII Holocene cover on top of the Ice Complex

The Holocene-influenced ice-wedge parts of the Yedoma Ice Complex show relatively little isotope variations. Mean values vary between -26.7‰ and -25.9 ‰ for $\delta^{18}O$, -205.1‰ and -200.2‰ for δD, ~~as well as~~and 6.7‰ and 8.4‰ for *d* excess. The co-isotopic regression slopes vary between 8.47 and 9.22 with intercepts between 18.81 and 40.26 (Table ~~5~~6, Figure 4). The two samples from a small ice wedge in the initial thermokarst depression show~~s~~ slightly more enriched values (mean $\delta^{18}O$: -24.9‰, mean δD: -195.6‰, mean *d* excess: 10.1‰).

The pore and segregated ~~texture~~-ice stable-isotope data are more enriched and spread between -20.7‰ and -17.6‰ for $\delta^{18}O$, -157.1‰ and -134.2‰ for δD, ~~as well as~~and 6.6‰ and 10.4‰ for *d* excess. The regression line accounts for $\delta D=7.23*\delta^{18}O-7.02$ ($r^2=0.99$).

5 Discussion

5.1 Chronostratigraphy and landscape development of the Oyogos Yar mainland

We identified eight cryostratigraphic units at the Oyogos Yar coast, ~~four less than~~whereas 12 were found at the opposite southern coast of Bol'shoy Lyakhovsky Island (Table 1). They represent basically three main landscape types which have undergone different permafrost aggradation and degradation patterns that varied over time and in space: Ice Complex deposits, flood plain deposits and ~~thermokarst~~ thermokarst-lake and thermokarst basin palustrine deposits. Hence, often a clear attribution of deposits and ice wedges to distinct units and their relation to each other is challenging, in particular for pre-Yedoma Ice Complex units which cannot be dated by the radiocarbon method.

At the Oyogos Yar coast we did not find deposits of the Yukagir Ice Complex (^{230}Th/U dated to 200.9±3.4 kyr) and the Zimov'e layer (IRSL-dated to 134±22 kyr) both known from Bol'shoy Lyakhovsky Island (Table 1). Hence, at our study site Kuchchugui floodplain deposits represent the oldest unit (Unit~~unit~~ I). The obtained IRSL age of 112.5±9.6 kyr of Unit~~unit~~ I in sequence B (Figure 2) is older by about 10 kyr than the respective ages of Kuchchugui deposits from Bol'shoy Lyakhovsky Island, but falls within the error range of the previous age determinations (Table 1). The latter were obtained from Kuchchugui taberal deposits below an ice-wedge cast attributed to the Last Interglacial. Hence, they may be influenced by thaw and refreeze during subsequent ~~thermokarst~~ thermokarst-lake development and may therefore represent rather minimum ages (Andreev et al., 2004).

The radiocarbon ages of >44.5 and 45.2 cal kyr b2k (Table 4) point to a much younger age of Unit~~unit~~ I in the eastern sequence A (Figure 2) but are close to the limit of the radiocarbon method. The stratigraphic position of Unit~~unit~~ I below deposits of the Buchchagy Ice Complex of Unit~~unit~~ II supports the age information obtained from IRSL dating which is why we discard the radiocarbon age. ~~However, to~~ To exclude a possible attribution of Unit~~unit~~ I in the eastern part of the study region (sequcence A) to the Zyryanian Stadial known from Bol'shoy Lyakhovsky Island (Table 1) additional age control is highly needed, if possible also using other approaches, e.g. uranium decay series in ground ice (Ewing et al., 2015). The Zyryanian at Bol'shoy Lyakhovsky Island shows similar sedimentary characteristics pointing to floodplain deposits (Andreev et al., 2004), but contains toes of Yedoma Ice Complex ice wedges instead of small truncated composite wedges found for Unit~~unit~~ I at Oyogos Yar. Kuchchugui ice wedges of Unit~~unit~~ I at Oyogos Yar are smaller and and have isotopic values that are less depleted compared to ice wedges on~~do not exhibit so depleted isotope values as compared to~~ Bol'shoy Lyakhovsky Island (see section 5.2). The ^{36}Cl/Cl^{-} ages of 98±31 and 68±31 kyr (Blinov et al., 2009) for ice wedges Oy7-03 IW1 and IW2 cannot finally resolve the attribution to a ~~genetic~~ stratigraphic unit but rather confirm the IRSL age for Unit~~unit~~ I in section A. We therefore, interpret Unit~~unit~~ I in section A as floodplain deposits of the early MIS5 with subsequent Ice Complex formation.

The Buchchagy Ice Complex (Unit~~unit~~ II) is known from both sides of the Dmitry Laptev Strait and represents Ice Complex formation of MIS5 age. It developed above the Kuchchugui floodplain deposits from 126+16/-13 kyr and 117+19/-14 kyr to 93±5 kyr and 89±5 kyr as deduced by ^{230}Th/U dating of two enclosing peat horizons on Bol'shoy Lyakhovsky Island (Wetterich et al., 2016). Its syngenetic ice wedges penetrate into the underlying Kuchchugui floodplain deposits. Given the age of the Kuchchugui deposits and the rather large uncertainty range of the ^{230}Th/U dating (in particular for the lower peat), the Buchchagy Ice Complex development likely took place in MIS5d-5b between about 110 and 90 kyr. The cryostratigraphic relation of Unit~~unit~~ II of Oyogos Yar to Bol'shoy Lyakhovsky Island is additionally confirmed by the very similar stable-isotope composition of ice-wedge samples from both locations (see section 5.2).

The Krest Yuryakh thermokarst-lake ~~lacustrine~~ and thermokarst basin palustrine ~~thermokarst~~ deposits (Unit ~~unit~~ III) indicate warm temperatures, at least in the summer season. These deposits filled~~y have been formed in~~ ice-wedge casts in taberal deposits; they were encountered within ~~and~~ wide thermokarst basins ~~within~~ which had developed in degraded ice-rich Buchchagy Ice Complex of Unit~~unit~~ II and are therefore younger. In this paper we present the first direct age determination for the Krest Yuryakh Suite at the Dmitry Laptev Strait derived from deposits within an ice-wedge cast. The IRSL for Unit III (~~age of~~ 102.4±9.7 kyr) points to a MIS5c~~n~~ origin ~~of unit III~~ rather ~~during the MIS5e~~ than ~~during~~ MIS5e (Eemian) as suggested previously ~~associated~~ (Wetterich et al., 2009; Kienast et al., 2011). ~~This~~The warm summer climate conditions inferred from the presence of extensive thermokarst lakes, however, fit~~s~~ good to a maximum in modeled summer temperatures around 105 kyr b2k (Andreev et al., 2011; Ganopolski and Calov, 2011) (Figure 7). It further narrows the duration of Buchchagy Ice Complex development. The radiocarbon age of about 48 cal kyr b2k again obtained at the very limit of the radiocarbon method might point to a distinctly younger formation of Unit~~unit~~ III. However, as it clearly contradicts the IRSL age, we assume relocation of the dated material and therefore, discard this age. Given the dating uncertainties and temporal overlaps for Units ~~units~~ I to III an absolute chronology is still challenging. Moreover, a temporal coexistence of Ice Complex accumulation plains, thermokarst basins and floodplains in the same region during MIS5 ~~seems to be possible~~cannot be excluded but is considered to be unlikely.

In contrast to Bol'shoy Lyakhovsky Island, there is neither dating nor sedimentary evidence for floodplains of the Zyryanian stadial (MIS4) at Oyogos Yar (Table 1), even though a presence of such Zyryanian stadial deposits in the eastern section A cannot be ruled out and asks for age control as part of future studies.

~~Starting from at least 50 kyrs b2k~~ Yedoma Ice Complex (Unit~~unit~~ IV) ~~formed~~ started forming at Oyogos Yar from at least 50 kyrs b2k, confirming earlier findings (Gravis, 1978; Kaplina and Lozhkin, 1984; Tomirdiaro, 1984; Nagaoka et al., 1995). Radiocarbon ages from Bol'shoy Lyakhovsky Island indicate even earlier Ice Complex formation since about 60 cal kyr b2k (Table 1) (Wetterich et al., 2014). Even though the youngest age from Unit~~unit~~ IV at Oyogos Yar is dated to 36.3 cal kyr b2k (Table ~~3~~4) a longer ~~development~~ Yedoma Ice Complex formation can be assumed as indicated from Bol'shoy Lyakhovsky Island where ages of 33.5 to 32.5 cal kyr 2bk have been found for the Molotkov interstadial stratum of the Yedoma Ice Complex (Andreev et al., 2009; Wetterich et al., 2014) (Table 1). It remains unclear whether the ~~development of the~~ Yedoma Ice Complex formation at Oyogos Yar has further continued until the Sartan stadial (or even until the end of the Pleistocene as known from Cape Mamontov Klyk (Schirrmeister et al., 2008a) and Bykovsky Peninsula (Schirrmeister et al., 2002b)) or the accumulation regime has changed. On Bol'shoy Lyakhovsky Island the prevailing Yedoma Ice Complex formation moved from plain to erosional landforms such as river valleys where the Sartan stadial stratum of the Yedoma Ice Complex has been formed at least between about 30 and 26.7 cal kyr b2k (Wetterich et al., 2011). At Oyogos Yar potential equivalent Ice Complex deposits in river valleys have not been found along the studied coastline section but may exist further east in the ~~vicinity~~ valley of the Kondrat'eva River.

Consequently it is not possible to estimate whether there has been substantial permafrost degradation on the top of the Oyogos Yar Yedoma Ice Complex during the postglacial warming as well as the duration of the potential erosional gap. The

Holocene cover (Unit~~unit~~ VIII) has been developed since 11 cal kyr b2k according to our data that mirror Bol'shoy Lyakhovsky Island conditions (Andreev et al., 2009; Wetterich et al., 2014).

Dated ~~taberal Ice Complex deposits of unit V and the overlying lacustrine~~ thermokarst-lake deposits of Unit ~~units~~ VI ~~and VII~~ prove widespread permafrost degradation, i.e. ~~related to~~ the development of vast thermokarst basins during the last deglaciation. Thermokarst started at Oyogos Yar around 18 cal kyr b2k; about 3 kyr earlier than reported from Bol'shoy Lyakhovsky Island (Andreev et al., 2009; Wetterich et al., 2009). The lacustrine phase (Unit~~unit~~ VI) of the studied Oyogos Yar thermokarst basin development ended around 13 cal kyr b2k ~~and was followed by the palustrine phase (unit VIII) continuing until today~~. This confirms results of earlier studies (Gravis, 1978; Kaplina and Lozhkin, 1984; Tomirdiaro, 1984; Nagaoka et al., 1995). In contrast, on Bol'shoy Lyakhovsky Island the lacustrine phase of the studied thermokarst basins ended only around 8 cal kyr b2k (Andreev et al., 2009; Wetterich et al., 2009). However, thermokarst development depends on manifold factors ~~as~~ such as (micro-)climate, relief, substrate, ice content, and drainage. Hence, these deviations are regarded as minor given the fact that they fit into the general temporal pattern of thermokarst formation during the last deglaciation (Walter et al., 2007).

The palustrine phase (Unit VII) covers the entire Holocene, includes the distinctive peat horizon (about 9.3 kyr b2k) and continues until today. The youngest radiocarbon age of the palustrine deposits (3.6 kyr b2k) and the series of radiocarbon ages of actively growing covering the last two millennia (Table 5) (Opel et al., 2017) as well as the shape of the ice wedges point to a predominantly lateral ice-wedge growth in the ~~last two millennia~~ Late Holocene. ~~can be concluded from radiocarbon ages of actively growing ice wedges of unit VII (Table 4)~~ This indicates ~~indicating~~ rather stable surfaces in the thermokarst basin~~s~~ with low accumulation rates.

5.2 Regional palaeoclimate deduced from ground ice and its stable-isotope compositions

For all Oyogos Yar units the mean stable-~~water~~ isotope compositions of ice wedges are more depleted than those of pore and segregated ~~texture~~ ice. Mean $\delta^{18}O$ values of ice wedges are between about 2‰ and 8‰ and mean δD values between about 15‰ and 58‰ lower than the corresponding mean values of pore and segregated ~~texture~~ ice (Figure 4). Except for two ice wedges of Unit~~unit~~ VIII mean ice-wedge *d* excess values are higher by about 1‰ to 7‰ than the respective values of pore and segregated ~~texture~~ ice. The slopes in a $\delta^{18}O$-δD diagram are in most cases lower for pore and segregated ~~texture~~ ice than for ice wedges (Table ~~5~~6). This reflects the differences in ice genesis involving different water sources and fractionation processes. Whereas ice-wedge stable isotopes reflect a direct winter climate signal, ~~in particular~~ the contribution of summer precipitation as well as evaporation effects may be responsible for the more enriched mean stable isotope values of pore and segregated ~~texture~~ ice (Meyer et al., 2002a; Schwamborn et al., 2006). On the other hand, freezing processes within the seasonally thawed active layer would both enrich and deplete stable-isotope values as discussed below. Hence, the climatic interpretation of stable isotopes in particular pore and segregated ice samples is challenging due to the partial overprinting of the original meteoric signal by secondary fractionation processes associated with consecutive freeze-thaw cycles within the active layer. The degree of overprinting may depend heavily on the specific environmental conditions during final ice formation (e.g. composition of soil moisture in terms of different water sources, climate conditions, freezing direction and velocity). ~~Hence, it can be concluded that texture-ice stable isotopes rather reflect secondary fractionation processes than climate information.~~ However, mean ~~texture-ice~~ stable-isotope data of pore and segregated may indicate generally colder climate conditions for the formation of Units~~units~~ I, II and IV during distinct periods of the last Interglacial and Glacial and significantly warmer conditions for the formation of Units~~units~~ VII and VIII during the Holocene (Figure 4, Table 6).

The enormous scatter of ~~texture-ice~~ stable isotopes of pore and segregated ice within the Yedoma Ice Complex (Unit~~unit~~ IV) (Figure 5) leads to the interpretation that it does reflect mainly secondary fractionation processes rather than climate conditions. In particular the $\delta^{18}O$ and δD minimum with corresponding *d* excess maximum around 20 m a.s.l., where pore and segregated ~~texture~~ ice $\delta^{18}O$ and δD values drop even below ice wedge $\delta^{18}O$ and δD values, indicates ~~massive~~ substantial contribution of not climate-related secondary fractionation processes (Figure 5). Besides changing proportions of different moisture sources (summer and winter precipitation, melt water) and evaporation from active layer and polygonal ponds (leading to a heavier isotopic composition of the remaining water), in particular numerous freeze-thaw cycles with moisture segregation are assumed to control the soil moisture's stable-isotope composition before it enters a perennially frozen state. During freezing, soil moisture migrates to the freezing front. This process is accompanied by kinetic isotope fractionation, where ~~During freezing of soil moisture~~ the first ice lenses exhibit~~s~~ a heavier isotopic composition than the remaining and in particular the last moisture and ice. Hence, the $\delta^{18}O$ and δD decrease from 15 to 21 m a.s.l. is most likely related to persistent sediment freezing ~~from below~~ leading to very low $\delta^{18}O$ and δD as well as high *d* excess ~~isotope~~ values in the last freezing stage.

In contrast, more detailed and constrained climate variability is traceable from ice-wedge stable-isotope values, in particular when a reliable age control is available. This is indicated by ice-wedge co-isotopic slopes closer to the GMWL (Table ~~5~~6) and recent precipitation (Meyer et al., 2002b; Opel et al., 2011). Ice-wedge stable isotopes allow to detect winter temperature variability on different time scales from Glacial-Interglacial scale over intra-unit scale (such as within Unit~~unit~~ IV Yedoma Ice Complex) up to centennial scale (such as within an ice wedge). ~~However, on the long-term scale ice wedges provide rather snapshots of past climate conditions whereas they may provide centennial-scales time series on according millennial time-scales~~ (Opel et al., 2017)~~.~~

In the following we discuss the ice-wedge stable-isotope data from Oyogos Yar obtained within this study. In a first step we relate our data to those from Bol'shoy Lyakhovsky Island published earlier (Meyer et al., 2002b; Wetterich et al., 2009; Wetterich et al., 2011; Wetterich et al., 2014; Wetterich et al., 2016) to enhance the palaeoclimatic understanding for the entire Dmitry Laptev Strait region (Figure 6). However, one has to keep in mind that apart from few ice wedges in ~~units~~ Units IV (only Bol'shoy Lyakhovsky) and VII (Oyogos Yar and Bol'shoy Lyakhovsky) all ice wedges are dated only indirectly by age determinations of host sediments. Due to the downward transfer of snowmelt and corresponding stable isotope signatures into the several meters deep frost cracks, ice wedges are always younger than host sediments at the exactly same altitude. It is so far not possible to determine the corresponding age offsets between host sediments and studied syngenetic ice wedges for different units. but dDepending on deposition rates estimated age offsets of a few hundreds to few thousands years seem to be most reasonable to us.

For our climate interpretation we use a tentative classification of mean ice wedge $\delta^{18}O$ values with six classes (extremely cold: -38‰ to -35‰, very cold: -35‰ to -32‰, cold: -32‰ to -29‰, moderate -29‰ to -26‰, warm: -26‰ to -23‰, very warm: -23‰ to -20‰). This classification uses roughly the Last Glacial Maximum and modern climate conditions as end-members.

The oldest ice wedges at the Dmitry Laptev Strait are from the Yukagir Ice Complex on Bol'shoy Lyakhovsky Island, dated to 200.9±3.4 kyr (Table 1). The formation of Ice Complex ice wedges point most likely occurred into stable climate and accumulation conditions. (Meyer et al., 2002b) reported according mean stable-isotope values of around -32‰ for $\delta^{18}O$ and around -250‰ for δD (Figure 6). The inferred cold to very cold winter climate conditions indicate strong seasonal differences for the late MIS7 with warm and wet summers as reconstructed from biological proxies in host sediments (Andreev et al., 2004).

The occurrence of composite wedges in Kuchchugui floodplain deposits (Unitunit I) at Oyogos Yar points to rather dry winter conditions that provided not enough snow to fill the frost cracks by snowmelt and/or a high accumulation regime that delivers sufficient material (e.g. wind-blown sand) to cause the high sediment fraction in these composite wedges. The latter is supported by the fact that the studied composite wedges (Oy7-03 IW4 and Oya IW1) are buried and truncated (Figure_3f). Their rounded convex thaw surfaces indicate a deepening of the active layer or a local water body that leads to a melting of the composite wedges surface before deposition of new sediments. Their mean $\delta^{18}O$ (-28.2‰ and -30.7‰) and δD (-227‰ and -244‰) values point to moderate to cold winter temperatures during formation. However, given the little widths of the composite wedges and their high sediment content, the low internal variability, low *d* excess values and low slopes may indicate different levels of isotopic exchanges between ice veins, sediment veins and host sediments (Meyer et al., 2002a; Meyer et al., 2010a). This is in particular likely for Oy7-03 IW4, which additionally shows a co-isotopic regression similar to that of corresponding pore and segregated texture ice (Table 56). Hence, we exclude the composite-wedge data from our palaeoclimatic interpretation. Interestingly, composite wedges Oy7-03 IW1+5 show similar regression lines as the intersected ice wedges Oy7-03 IW1+2 they pass into, but with distinctly enriched mean isotope values ($\delta^{18}O$: -29.7‰, δD: -235‰ compared to $\delta^{18}O$: -34.1‰, δD: -268‰, respectively). Whereas the first fits well into the described composite-wedge pattern the latter represent the minimum isotope values found at Oyogos Yar and indicate very cold winter climate for the initiation during the early stage of ice-wedge genesis formation in the Kuchchugui Unitunit I.

Even more severe climate conditions can be inferred from two Kuchchugui ice wedges on Bol'shoy Lyakhovsky Island. Mean stable isotope values of about -35.5‰ for $\delta^{18}O$ and -280‰ for δD -235‰ (Figure 6) indicate extremely cold winter temperatures (Meyer et al., 2002b). As pollen-based reconstructions point to relatively cold summer temperatures (Andreev et al., 2011) generally cold climate conditions can be concluded for this period, attributed to the MIS5 stadial.

The presence existence of the Buchchagy Ice Complex (Unitunit II) indicates cold-stage climate conditions during its formation on both sides of the Dmitry Laptev Strait. Very cold and stable winter climate conditions during ice-wedge formation are confirmed by ice-wedge $\delta^{18}O$ and δD values (means -33‰ and -258‰, respectively), which are slightly lower than those of ~~-~~the Yukagir ice wedges. The isotopic composition is nearly identical on both sides of the Dmitry Laptev Strait (Figure 6) and underlines the stratigraphic correlation. Pollen-based reconstructions from host sediments indicate cool summer temperatures (Wetterich et al., 2016) and clearly point to stadial conditions with a generally colder climate in MIS5d.

The thick deposits of the Yedoma Ice Complex (Unit~~unit~~ IV) with their huge ice wedges ~~mirror~~ formed under long-term cold stage conditions during the MIS3 (Molotkov interstadial stratum) from about 60 cal kyr b2k to about 32 cal kyr b2k. Mean $\delta^{18}O$ and δD values of -31‰ and -240‰, respectively, generally confirm cold winter temperatures during ice-wedge formation, but indicate slightly warmer temperatures than those of Yukagir and Buchchagy ~~ice wedges~~time (Figure 6). The variability of stable-isotope values with ~~respect to~~ altitude in this unit indicates changing conditions from very cold to moderate winter temperatures (Figure 5). Similar variations have been observed in corresponding Yedoma Ice Complex ice wedges from Bol'shoy Lyakhovsky Island (Meyer et al., 2002b; Wetterich et al., 2014). However, due to age reversals in the dated sediment profiles (Figure 5) (Schirrmeister et al., 2011b) it is not possible to attribute single ice-wedge profiles to distinct time periods. It is noteworthy that the ice-wedge profiles close to the top of Unit~~unit~~ IV exhibit more depleted isotope compositions likely pointing to climate ~~deterioration~~ cooling towards the transitions to MIS2.

The Sartan stadial stratum of the Yedoma Ice Complex on Bol'shoy Lyakhovsky Island formed at least between about 30 and 26.7 cal kyr b2k (Table 1) and exhibits the lowest stable-isotope values (mean $\delta^{18}O$ of -37‰, mean δD of -290‰) (Figure 6) found in ice wedges of the Dmitry Laptev Strait. They indicate extremely cold winter temperatures during the Last Glacial Maximum. A generally cold climate is furthermore confirmed by pollen-based temperature reconstruction from the host sediments (Wetterich et al., 2011).

Significantly enriched stable-isotope values were found in Holocene Oyogos Yar ice wedges in both cover deposits of the Yedoma Ice Complex (Unit~~unit~~ VIII) and palustrine sediments of thermokarst basins (Unit~~unit~~ VII) (Figure 6). Mean $\delta^{18}O$ (δD) values of about -26‰ (-200‰) and -25‰ (-190‰), respectively, point to warm interglacial winter temperatures during ice-wedge formation. Similar mean values ($\delta^{18}O$: -24.5‰, δD: -187‰) ~~could be~~were obtained from corresponding Holocene ice wedges on Bol'shoy Lyakhovsky Island (Meyer et al., 2002b; Wetterich et al., 2009). Distinctly warmer summer temperatures were also derived from pollen-based reconstructions that, however, indicate a gradual cooling since the Early Holocene (Andreev et al., 2009).

The warming from the Last Glacial to the Holocene is also accompanied by a slight increase (about 2‰ for Oyogos Yar, about 1‰ for Bol'shoy Lyakhovsky Island) in mean *d* excess values (Table ~~5~~6). This likely indicates only minor changes in the moisture generation and transport patterns and/or seasonality of precipitation between Pleistocene and Holocene.

Whereas there exist no dating results for ice wedges from the cover deposits, radiocarbon ages from ice wedges of ~~palustrine~~ thermokarst basin palustrine deposits on both sides of the Dmitry Laptev Strait indicate that the derived temperature information can be attributed mainly to the last two millennia. It is even possible to go more into detail. The recent parts of actively growing ice wedges at Oyogos Yar exhibit more enriched mean $\delta^{18}O$ (δD) values of about -23‰ (-175‰). The highest $\delta^{18}O$ (δD) values of about -20.5‰ (-160‰) on Oyogos Yar (Opel et al., 2017) and Bol'shoy Lyakhovsky Island (Meyer et al., 2002b) were determined for modern ice veins, i.e. the youngest, actively growing ice -wedges (rejuvenation stages). They represent the warmest winter temperatures at all mirrored in ice-wedge stable isotopes from the Dmitry Laptev Strait (Figure 6).

5.3 Relation of ice-wedge palaeoclimate information to large-scale climate dynamics

The present ice-wedge stable-isotope record of the Dmitry Laptev Strait is based on new data from Oyogos Yar and earlier data from Bol'shoy Lyakhovsky Island. It contains ice-wedge isotopes from seven stratigraphic units and covers roughly 200 kyr (Table 1, Figure 6). Other regional ice-wedge based reconstructions such as those from Cape Mamontov Klyk (Boereboom et al., 2013), the Lena River Delta (Wetterich et al., 2008), Bykovsky Peninsula (Meyer et al., 2002a) or Duvanny Yar at the Kolyma River (Vasil'chuk et al., 2001) date only back to MIS3 or MIS4 and/or contain only single stratigraphic units (Streletskaya et al., 2015). Therefore, we additionally compare our data to the continuous NGRIP ice-core $\delta^{18}O$ record from Greenland (North Greenland Ice Core Project members et al., 2004) with age scale GICC05modelext (Wolff et al., 2010) as well asand climate-model output (Figure 7). For the latter we use mean summer (JJA) and (extended) winter (DJFMAM, the cold period of the year, likely covered by ice wedge stable isotopess) temperatures for the Laptev Sea region (centred at about 70°N, 120°E) from the Earth System model of intermediate complexity CLIMBER-2 (Petoukhov et al., 2000) driven by orbital forcing and greenhouse gas concentrations (Ganopolski and Calov, 2011). When comparing these different datasets, we are aware that the stable-isotope datasets, i.e. our ice-wedge record and the Greenland ice-core record, are constrained by different seasonalities and different climate regimes and exhibit a different temporal resolution. Therefore, linking of distinct high-amplitude events may be questionable. Furthermore, the age uncertainties of our record are comparably large and may be sufficient in several cased to bring the data in accord with the modelled temperatures.

The inferred cold to very cold temperatures of Yukagir Ice Complex ice wedges inferred from stable-isotope values (age about 200 kyrs b2k) do not fit to the modelled warm winter temperatures of this period. In , in contrast, to warm summer temperatures climate conditions inferred from pollen (Andreev et al., 2004) confirm modelled summer temperatures. Considering an age offset between ice wedges and the dated peat horizon it is likely that the ice wedges are younger and correspond to decreasing modelled winter temperatures between 200 and 180 kyrs b2k (Figure 7).

The very cold to extremely cold temperatures reflected in stable isotopes of Kuchchugui ice wedges (Unit 1, dated to about 110 to 100 kyr b2k) do not fit the modelled winter temperatures, but correspond to a minimum in winter (i.e. NDJFAM insolation (Meyer et al., 2015)) insolation around 100 kyr b2k (Laskar et al., 2004) (Figure 7not shown). Modelled cold winter periods were either earlier (around 130 kyr b2k) or later (around 90 kyr b2k) both accompanied by cold summer temperatures (Figure 7) as also inferred from Kuchchugui pollen (Andreev et al., 2011). In contrast, the NGRIP ice-core record shows a colder period around 110 kyr b2k that might correspond to the very low ice-wedge $\delta^{18}O$ and δD values of the Kuchchugui ice wedges in Unitunit I. Considering a potential Zyranian age interpretation for the according floodplain deposits in sequence A (see section 5.1), even the very cold MIS4 stadial (around 65 kyr b2k) seems to be possible interpretation.

The inferred very cold winter temperatures of the Buchchagy Ice Complex ice wedges do not correspond to an according cold period in modelled winter temperatures as well but may fit to the cold period around 110 kyr b2k seen in the NGRIP ice core. A younger age can be ruled out as the Krest Yuryakh warm period with enhanced thermokarst processes including melting of ice wedges attributed to the Buchagy Ice Complex is centred about 102 kyr b2k (MIS5c).

All in all, our data show a rather unexpected climate variability during the MIS5. Surprisingly cold winter conditions during MIS5d were succeeded by the peak interglacial warming during MIS5c leading to widespread thermokarst formation with vast thermokarst lakes.

Both, the NGRIP ice core record and the modelled temperatures (summer and winter) show high-frequency climate fluctuations during the MIS3. Even though not temporally resolvable, the altitudinal variability in ice-wedge isotopes at Oyogos Yar (Figure 5) and Bol'shoy Lyakhovsky indicates that similar climate variations likely have affected the Dmitry Laptev Strait region as well. Similar fluctuations within the same range of $\delta^{18}O$ and δD values have also been reported for Cape Mamontov Klyk (Boereboom et al., 2013), the Bykovsky Peninsula (Meyer et al., 2002a), and Duvanny Yar (Vasil'chuk et al., 2001). A more stable MIS3 summer climate, even though with a distinct interstadial optimum around 40 cal kyr b2k was inferred from pollen data onfrom Bol'shoy Lyakhovsky and other study sites in the Laptev Sea region (Wetterich et al., 2014).

The extremely cold winter temperatures reflected by ice-wedges stable isotopes of the Sartan stadial Yedoma Ice Complex on Bol'shoy Lyakhovsky correspond well to the Last Glacial Maximum cold period in the NGRIP ice core record and the modelled temperatures (Figure 7). Interestingly, such extremely depleted $\delta^{18}O$ and δD values have not been found at any other study site in the Laptev Sea region, even though corresponding Ice Complex strata have been studied extensively (Wetterich et al., 2011).

The substantial warming from the Last Glacial to the Holocene as captured by modelled temperatures and the NGRIP record is also found in our Dmitry Laptev Strait record as well as other regional ice-wedge stable-isotope records such as Cape Mamontov Klyk (Boereboom et al., 2013), Lena River Delta (Wetterich et al., 2008), and Bykovsky Peninsula (Meyer et al., 2002a). The detected $\delta^{18}O$ difference of about 6‰ between the studied Yedoma Ice Complex (MIS3) and Holocene ice wedges corresponds well to the regional pattern. However, if when compared comparing to the Last Glacial Maximum and Holocene ice wedges, $\delta^{18}O$values increased about twice as much (11-12‰). This underlines the winter warming at the Dmitry Laptev Strait was about twice as much, underlining the peculiarity of this cold event at the Dmitry Laptev Strait.

The slightly increasing mean *d* excess values (about 2‰ for Oyogos Yar, about 1‰ for Bol'shoy Lyakhovsky Island) which go along with the Last Glacial to Holocene transition are in line with observations at Cape Mamontov Klyk (Boereboom et al., 2013) and in the Lena River Delta (Wetterich et al., 2008) and indicate rather constant moisture generation and transport pathways over this transition. In contrast, mean *d* excess values at the Bykovsky Peninsula show an increase of about 10‰ (Meyer et al., 2002a) pointing to substantial changes in the local to regional moisture regime.

The NGRIP record as well as the modelled summer temperatures show a cooling after the Northern Hemisphere Early Holocene insolation maximum. In contrast, our ice-wedge data and the modelled winter temperatures verify a general Holocene winter warming trend with the highest temperatures today (Figure 7) which is likely related to seasonal insolation and greenhouse gas forcing (Meyer et al., 2015; Opel et al., 2017).

6 Conclusions and outlook

The present study summarises comprehensive stable- isotope data from ice wedges interpreted as winter climate proxy from the Oyogos Yar mainland coast in addition to and in comparison to pre-existing data from Bol'shoy Lyakhovsky Island in the Northeast Siberian Arctic covering the last about 200 kyr. Seven distinct generations of ice -wedgew development are distinguished, confirming coldest winter climate conditions during MIS5 and MIS2, warmest conditions during MIS1 and winter climate instability during MIS3. Since dating ice wedges directly is challenging and chronostratigraphic correlation to surrounding frozen deposits holds difficulties, which are even more complicated by different dating approaches beyond the radiocarbon limit (such as luminescence dating and radioisotope disequilibria dating), further method development is needed in ice-wedge dating and in understanding of the chronological relation between ice wedges and host sediments (i.e. age offsets). However, in course of the present study valuable geochronological data was were obtained by IRSL dating of deposits of the Kuchchugui stratum to MIS5d (112.5±9.6 kyr) and of deposits of the Krest Yuryakh stratum to MIS5c (102.4±9.7 kyr), formerly assigned with the MIS5e. If comparing Comparing ice-wedge stable isotope data to with climate model output (CLIMBER-2) and Greenland ice core records (NGRIP) revealed high correspondence was found for MIS2 and MIS1. For older periods it is more difficult due to dating issues and rather low temporal resolution. In particular, high and rapid climate variability during MIS5 present in three units in the Oyogos Yar record holds controversial potential and asks for further research to improve the application of ice wedge stable isotopes as winter climate proxy.

Author contributions

TO initiated and designed the present study, and wrote the paper with contributions of the other co-authors. TO, AD, HM, SW, and LS sampled and described ground ice and sediments. HM carried out stable-isotope analyses and helped withsupported interpretation. MF conducted IRSL dating and provided interpretation. SW and LS provided stratigraphic information and interpretation. All co-authors contributed to the final discussion of obtained results and interpretations, and have approved the final version of the manuscript.

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Data availability.

The data presented in this paper are available at PANGAEA (doi will be provided as soon as possible).

Table 1. **Synopsis of the stratigraphic units exposed on the Dmitry Laptev Strait according to the latest compilation by Tumskoy (2012) and updates from this study. Grey shaded strata were not found at the Oyogos Yar coast (OY), but are described from Bol'shoy Lyakhovsky Island (BL). MIS refers to Marine Isotope Stage and SIW to syngenetic ice wedges. Radicarbon ages are given as mean calibrated ages b2k. Further information is given in the following studies from both sides of the Dmitry Laptev Strait:**

(a) this study, (b) (Schirrmeister et al., 2011b), (c) (Andreev et al., 2009), (d) (Wetterich et al., 2009), (e) (Opel et al., 2011) (f) (Wetterich et al., 2011), (g) (Wetterich et al., 2014), (h) (Andreev et al., 2004), (i) (Wetterich et al., 2016), (j) (Schirrmeister et al., 2002a)

Stratigraphic unit [a]	**Local stratigraphy**	**Period**	**Description**	**BL age (kyr b2k)**	**OY age (kyr b2k)**	**Dating method**	**MIS**	**SIW presence**	**Reference**
VIII	Cover deposits	Holocene	Holocene cover on top of Yedoma IC	10.9 to 0	11.0 to 0	^{14}C-AMS	1	Yes	a, b, c
VII	Alas (Laptev Suite)	Holocene	Thermokarst basin palustrine deposits	8.4 to 0	13.0 to 0	^{14}C-AMS	1	Yes	a, b, c, d, e
VI	Alas (Laptev Suite)	Late Glacial to Holocene	Thermokarst-lake ~~lacustrine~~ deposits	14.7 to 8.0	18.1 to 12.7	^{14}C-AMS	2-1	No	a, b, c, d
--	Sartan (Yana Suite)	Stadial (LGM	Yedoma IC deposits	30.0 to 26.7	--	^{14}C-AMS	2	Yes	f
V	Molotkov (Oyogos Suite)	Interstadial	Taberal Yedoma IC deposits	>54 to 37.3	46.0 to 40.1	^{14}C-AMS	3	No	a, b, c, d
IV	Molotkov (Oyogos Suite)	Interstadial	Yedoma IC deposits	>59 to 32.5	49.4 to 36.3	^{14}C-AMS	3	Yes	a, b, c, g
--	Zyryanian (U~~u~~nit IV in Andreev et al. (2004))	Stadial	Floodplain deposits	57±10, 68±14, 77±12, 77±14	--	IRSL	4	Yes	h
III	Kazantsevo (Krest Yuryakh Suite)	Interstadial	Thermokarst-lake ~~lacustrine~~ and thermokarst basin palustrine deposits	--	102.4±9.7	IRSL	5	No	a, d, h~~i~~
II	Kazantsevo (Bychchagy Suite)	Stadial	Buchchagy IC deposits	89±5, 93±5, 117+19/-14, 126+16/-13	--	^{230}Th/U	5	Yes	a, i
I	Keremesitsko (Kuchchugui Suite)	Stadial	Floodplain deposits	99±15 102±16	112.5±9.6	IRSL	5	Yes	a, h
--	Keremesitsko (Zimov'e layer)	Stadial	Palaeo active layer	134±22	--	IRSL	6-5	No	h
--	Keremesitsko (Yukagir Suite)	Interstadial	Yukagir IC deposits	200.9±3.4	--	^{230}Th/U	7	Yes	j

Table 2. Gravimetric ice content (minimum, mean and maximum values, standard deviations) of the sediments, expressed as weight percentage (wt%) (Van Everdingen, 1998).

Stratigraphic unit	Samples (n)	Ice content min (wt‰)	Ice content mean (wt‰)	Ice content max (wt‰)	Ice content sd (wt‰)
VIII	3	54.4	92.4	118.0	33.6
VII	6	52.4	119.3	183.3	43.5
VI	3	29.4	46.3	70.8	21.7
V	3	32.7	39.0	42.3	5.4
IV	24	24.6	118.7	241.7	58.8
III	31	15.0	36.2	66.4	10.2
II	12	25.6	163.7	793.8	224.2
I	6	30.9	52.3	108.5	28.9

Table ~~2~~3. IRSL samples Oy7-07-01 (Unit~~unit~~ I) and Oy7-08-25 (Unit ~~unit~~ III) with all paleodose and dose rate parameters used for final age calculation (n = number of aliquots, CAM = Central Age Model according to (Galbraith et al., 1999) m asl = meter above sea level, m bs = meter below surface).

ID		**Oy7-07-01**	**Oy7-08-25**
Paleodose parameters:			
n		49	5
mean	(Gy)	288.4 ± 4.0	270.8 ± 8.0
Standard deviation	(%)	9.6	6.6
skewness		0.4	0.2
Coefficient of variation	(%)	6.7	6.3
CAM	(Gy)	286.9 ± 3.9	-
Dose rate parameters:			
^{238}U	(Bq kg^{-1})	24.77 ± 2.55	33.43 ± 0.88
^{232}Th	(Bq kg^{-1})	31.75 ± 1.12	38.14 ± 1.88
^{40}K	(Bq kg^{-1})	572.95 ± 7.99	528.11 ± 3.05
Water content	(%)	30.5	27.5
Height / cover thickness	(m asl / m bs)	1.5 / 24	4 / 22
Total dose rate	(Gy kyr^{-1})	2.6	2.6
Age	**(kyr)**	**112.5 ± 9.6**	**102.4 ± 9.7**

Table ~~3~~4. Radiocarbon ages and calibrated ages (95.4% probability) of sediment samples from Oyogos Yar coast. NaN indicates that the calibration failed and no calibrated age is available.

Sample ID	Unit	Height (m asl)	Lab ID	Conventional age (yr BP)	Calibrated age (mean) (yr b2k)	Remarks
~~Field~~ Reconnaissance trip~~campaign~~ 2002 (this study)						
Oya-2-1	VIII	0.4 m bs	KIA 25724	7985±40	9052-8708 (8880)	Sequence B
Oya-2-5	VIII	1.9 m bs	KIA 25725	8345±40	9521-9321 (9421)	Sequence B
Oya-2-8	VIII	3.0 m bs	KIA 25726	9645±35	11,237-10,842 (11,040)	Sequence B
Oya-4-1	IV	17	KIA 25731	>36,690	> 40,921 (-)	Sequence B
Oya-6-1	I	2.5	KIA 25732	>43,350 41,520+1030/-910	> 44,506 (-) 47,139-43,297 (45,218)	leached residue humic acid Sequence A
Oya-3-11	III	2	KIA 25730	47,700+1380/-1180	50,906-45,666 (48,286)	IW cast below Unit~~unit~~ IV Sequence B
Field campaign 2007 – Sequence A: Buchchagy Ice Complex (Wetterich et al., 2016)						
Oy7-10-09	II	6.2	Poz-51638	>49,000	-	Upper peat
Oy7-10-04	II	3.3	Poz-51637	>51,000	-	Lower peat
Field campaign 2007 – Sequence B: Yedoma Ice Complex (Schirrmeister et al., 2011b)						
Oy7-08-63	IV	27.0	KIA37638	32,220+370/-350	37,199-35,324 (36,262)	
Oy7-08-62	IV	26.5	KIA37637	34,630+420/-400	40,208-38,435 (39,322)	
Oy7-08-57	IV	24.0	KIA37636	38,600+930/-830	44,365-41,551 (42,958)	
Oy7-08-53	IV	22.0	KIA37635	44,900+1230/-1060	NaN-46,593 (NaN)	
Oy7-08-47	IV	19.2	KIA37634	40,850+1750/-1440	48,313-42,357 (45,335)	
Oy7-08-42	IV	17.1	KIA37633	48,540+1750/-1440	53,128-45,594 (49,361)	
Oy7-08-38	IV	15.5	KIA37632	44,840+1270/-1100	NaN-46,238 (NaN)	
Oy7-08-37	IV	12.0	KIA37631	43,860+1270/-1090	49,686-45,380 (47,533)	
Oy7-08-32	IV	9.5	KIA37630	41,420+1040/-920	46,909-43,225 (45,067)	
Field campaign 2007 – Sequence C: Taberal Yedoma Ice Complex to Holocene (Wetterich et al., 2009))						
Oy7-11-14	VII	11.1	KIA35234	3325±35	3690-3513 (3602)	
Oy7-11-12	VII	10.1	KIA35233	8335±45	9524-9198 (9361)	
Oy7-11-10	VII	8.8	KIA35232	8260±40	9461-9144 (9303)	
Oy7-11-09	VII	8.6	KIA36687	9985±35	11,665-11,322 (11,494)	
Oy7-11-08	VII	8.3	KIA36686	11,145±40	13,155-12,942 (13,049)	
Oy7-11-07	VI	8.0	KIA35231	14,830+70/-60	18,299-17,899 (18,099)	
Oy7-11-06	VI	7.7	KIA36688	10,720+40/-35	12,781-12,651 (12,716)	
Oy7-11-04	VI	7.1	KIA35230	11,995±50	14,062-13,786 (13,924)	

Oy7-11-03	V	6.8	KIA35229	41,290+2370/-1830	49,458-42,469 (45,964)	
Oy7-11-01	V	6.0	KIA35228	36,580+1090/-960	40,863-39,333 (40,098)	

Table ~~4~~5. Radiocarbon ages and calibrated ages (95.4% probability, if not otherwise indicated) of organic remains in Holocene ice-wedge samples of Unit VII in sequence C. All samples were taken in a similar depth (about 1 to 1.5 m below durface).

Sample ID	Lab ID	Conventional age (yr BP)	Calibrated age (mean) (yr b2k)	Remarks
Ice wedge Oy7-04 IW2 (Oy7-04-…) (Opel et al., 2011; Opel et al., 2017)				
205	COL3997.1.1	1607 ±49	1659-1438 (1549)	
242	KIA 35630	523 ± 43	690-551 (621)	
247	KIA 35631	3518 ± 31	3927-3751 (3839)	Reworked
263	KIA 35632	412 ± 30	570-380 (475)	
267	KIA 35633	258 ± 51	519-193 (356)	(89.7% probability)
274	KIA 35634	488 ± 58	696-382 (539)	
290	KIA 35635	1479 ± 106	1659-1232 (1446)	
Ice wedge Oy7-11 ~~IW2~~ IW1 (Oy7-11-…) (Opel et al., 2011)				
138	KIA 35636	8959 ± 43	10,278-9970 (10,124)	Redistributed
162	KIA 35637	8300 ± 43	9486-9188 (9337)	Redistributed
189	KIA 35638	857 ± 43	956-737 (847)	
Ice wedge Oy7-11 IW7 (Oy7-11-…) (Opel et al., 2017)				
719	KIA 40385	1858 ± 60	1976-1674 (1825)	
723	KIA 40386	1868 ± 36	1931-1765 (1848)	
740	KIA 40387	1081 ± 22	1104-984 (1044)	
747	KIA 40388	1098 ± 24	1100-1005 (1053)	
796	KIA 40390	$F^{14}C$ 1.2661 ± 0.005	20-18(19)	Post-bomb
820	KIA 40391	225 ± 25	358-198 (278)	(84.5% probability)
Hy27	COL1925.1.1	1579 ± 43	1606-1429 (1518)	
Hy31	KIA 40393	14,200 ± 71	17,575-17,108 (17,342)	Redistributed
Hy40	KIA 40394	6640 ± 50	7637-7487 (7562)	Redistributed

Table ~~5~~6. Stable isotope ($\delta^{18}O$, δD and *d* excess) minimum, mean and maximum values, standard deviations as well as slopes and intercept in the $\delta^{18}O$-δD diagram for all considered ice wedges and for pore and segregated ice per unit. Ice wedges marked with an asterisk contain samples attributed to Unit IV and Unit VIII, respectively (see section 4.2.3).

Ice wedge (profiles/group of samples)	Altitude (m a.s.l.)	Width (m)	Samples (n)	$\delta^{18}O$ min (‰)	$\delta^{18}O$ mean (‰)	$\delta^{18}O$ max (‰)	$\delta^{18}O$ sd (‰)	δD min (‰)	δD mean (‰)	δD max (‰)	δD sd (‰)	*d* min (‰)	*d* mean (‰)	*d* max (‰)	*d* sd (‰)	Slope	Intercept	R^2
Unit VIII Holocene cover deposits																		
Oy7-08 IW5	36.0	0.5	2	-26.55	-25.71	-24.87	1.18	-201.1	-195.6	-190.1	7.8	8.9	10.1	11.3	1.7	6.57	-26.58	1.00
Oy7-08 IW4	35.0	10.2	26	-27.81	-25.86	-20.89	1.44	-216.9	-200.2	-158.8	12.3	2.6	6.7	9.0	1.5	8.47	18.81	0.99
Oy7-08 IW3*	30.0	5.0	11	-27.94	-26.43	-24.38	1.14	-216.8	-203.7	-183.9	10.2	5.9	7.7	11.1	1.7	9.22	40.26	0.99
Oy7-06 IW2*	20.0	2	8	-27.14	-26.69	-25.84	0.47	-209.3	-205.1	-197.1	4.1	7.6	8.4	9.6	0.7	8.60	24.51	0.98
~~Texture~~ Pore and segregated ice	Several	n/a	3	-20.65	-19.60	-17.59	1.74	-157.1	-148.7	-134.2	12.7	6.6	8.1	10.4	2.0	7.23	-7.02	0.99
Unit VII Holocene palustrine deposits																		
Modern ice veins	11	< 0.08	14	-24.38	-20.74	-18.24	1.61	-186.4	-158.3	-137.3	12.6	4.7	7.7	9.1	1.1	7.79	3.23	0.99
Recent IW parts	11	varying	24	-25.27	-22.68	-18.27	1.66	-193.5	-173.9	-137.5	13.4	4.8	7.6	9.5	1.1	8.03	8.33	0.99
Oy7-04 IW2	10.0	3.2	104	-27.09	-25.10	-21.59	1.26	-207.8	-192.0	-164.2	9.6	6.2	8.8	11.3	1.1	7.58	-1.83	0.99
Oy7-11 IW1	10.0	3.5	119	-26.64	-25.01	-21.62	1.03	-203.9	-192.1	-167.2	7.8	5.1	8.0	9.8	0.9	7.59	-2.19	0.99
Oy7-11 IW7	10.0	2.5	236	-26.53	-24.99	-20.73	0.90	-203.2	-192.4	-159.9	6.9	4.1	7.5	9.3	0.9	7.67	-0.75	0.99
Oy7-02 IW1	8.0	~1.5	14	-26.28	-25.36	-23.41	0.79	-201.3	-194.6	-179.5	6.0	6.5	8.2	9.2	0.9	7.53	-3.76	0.99
~~Texture~~ Pore and segregated ice	Several	n/a	23	-21.93	-17.61	-16.00	1.63	-171.4	-139.7	-124.2	13.2	-3.7	1.2	10.7	4.6	7.57	-6.35	0.88
Unit IV Yedoma Ice Complex deposits																		
Oya-IW3	Ca. 35.0	n/a	8	-32.51	-31.47	-28.27	1.60	-256.0	-246.8	-219.9	13.6	4.0	5.0	6.3	0.9	8.49	20.31	1.00
Oya-IW4	Ca. 35.0	n/a	6	-31.72	-31.41	-31.00	0.26	-249.4	-247.6	-243.5	2.1	2.2	3.7	4.5	0.8	7.55	-10.53	0.84
Oy7-08 IW3*	30.0	5.0	22	-31.68	-29.96	-28.01	1.13	-250.8	-234.8	-218.4	9.5	2.7	4.8	7.2	1.2	8.32	14.41	0.99
Oy7-08 IW1	25.0	5.7	34	-32.72	-31.48	-30.11	0.57	-255.1	-246.7	-236.7	4.1	3.1	5.2	7.1	1.0	7.07	-23.91	0.95
Oy7-06 IW2*	20.0	2.0	14	-30.49	-29.45	-28.05	0.80	-239.6	-228.6	-214.2	7.6	4.3	7.0	10.2	2.0	9.29	44.81	0.95
Oya-IW5	16.0	3.0	15	-33.29	-32.84	-31.90	0.41	-262.1	-258.3	-249.6	3.5	3.8	4.5	5.6	0.6	8.55	22.66	0.98
Oy7-06 IW1	9.0	3.5	34	-31.30	-30.13	-28.01	0.87	-241.8	-233.9	-218.2	6.1	5.2	7.2	9.0	1.0	7.01	-22.69	0.99
Oya-IW2	6.6-7.0	1.5	8	-31.32	-30.96	-30.45	0.36	-241.9	-239.5	-236.3	2.2	7.0	8.1	9.3	0.9	5.95	-55.37	0.94
Oya-IW6	5.0	1.5	6	-33.04	-31.65	-30.39	1.08	-256.0	-246.1	-236.8	7.9	4.7	7.1	8.3	1.4	7.26	-16.31	0.98
Oy7-01 IW4	1.5	0.5	3	-29.71	-29.23	-28.31	0.80	-231.7	-227.6	-220.2	6.4	6.0	6.3	6.5	0.3	8.00	6.45	1.00

~~Texture~~ Pore and segregated ice	Several	n/a	44	-34.45	-26.14	-18.48	4.84	-253.9	-206.2	-150.5	32.0	-10.9	2.9	21.7	9.0	6.51	-36.00	0.97
Unit II Buchchagy Ice Complex deposits																		
Oy7-07 IW1	4.0	1.7	7	-33.52	-33.13	-32.68	0.29	-261.1	-258.3	-255.1	2.1	6.1	6.7	7.2	0.4	6.96	-27.89	0.98
~~Texture~~ Pore and segregated ice	Several	n/a	8	-29.80	-26.71	-23.34	2.55	-233.8	-210.9	-184.9	17.8	-1.9	2.8	9.9	4.0	6.89	-26.83	0.98
Unit I Kuchchugui floodplain deposits																		
Oy7-03 IW1+2	3.5	0.4-1.0	5+1	-34.88	-34.11	-32.77	0.75	-273.6	-268.0	-255.1	6.8	1.8	4.9	7.1	1.9	8.74	29.99	0.93
Oy7-03 IW1+5	2.0	0.3-0.4	3+2	-30.15	-29.66	-29.29	0.37	-238.7	-235.0	-231.5	3.3	1.5	2.3	2.8	0.5	8.68	22.46	0.98
Oy7-03 IW4	2.0	0.4	4	-28.35	-28.19	-28.08	0.12	-226.7	-225.6	-224.7	0.9	-0.4	0.0	0.4	0.4	6.70	-36.78	0.82
Oya IW1	1.5	0.75	6	-31.12	-30.67	-30.42	0.26	-243.8	-240.5	-238.6	2.0	4.4	4.8	5.1	0.2	7.41	-13.23	0.99
~~Texture~~ Pore and segregated ice	Several	n/a	10	-29.75	-25.99	-23.09	2.52	-231.8	-210.5	-191.4	15.8	-8.0	-2.6	6.2	4.6	6.24	-48.31	0.99

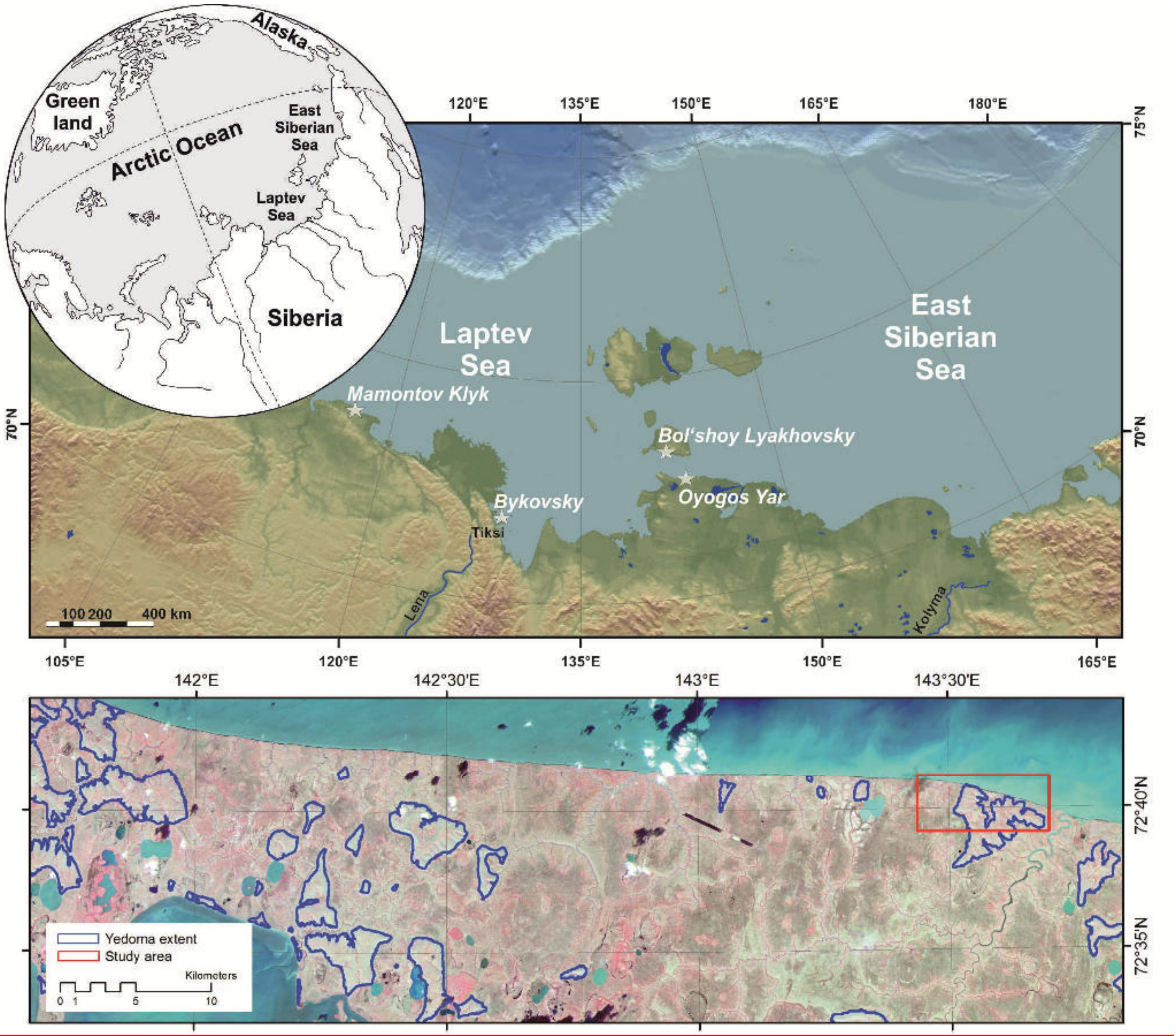

Figure 1. Overview ~~M~~map of the Laptev and East Siberian seas region ~~study region~~(top) and detailed map the Oyogos Yar coast with extent of Yedoma Ice Complex remnants and the position of the coastal exposure presented in Figure 2 (bottom, background image: false color infrared RapidEye mosaic August 2010, modified after Günther et al. (2013)).

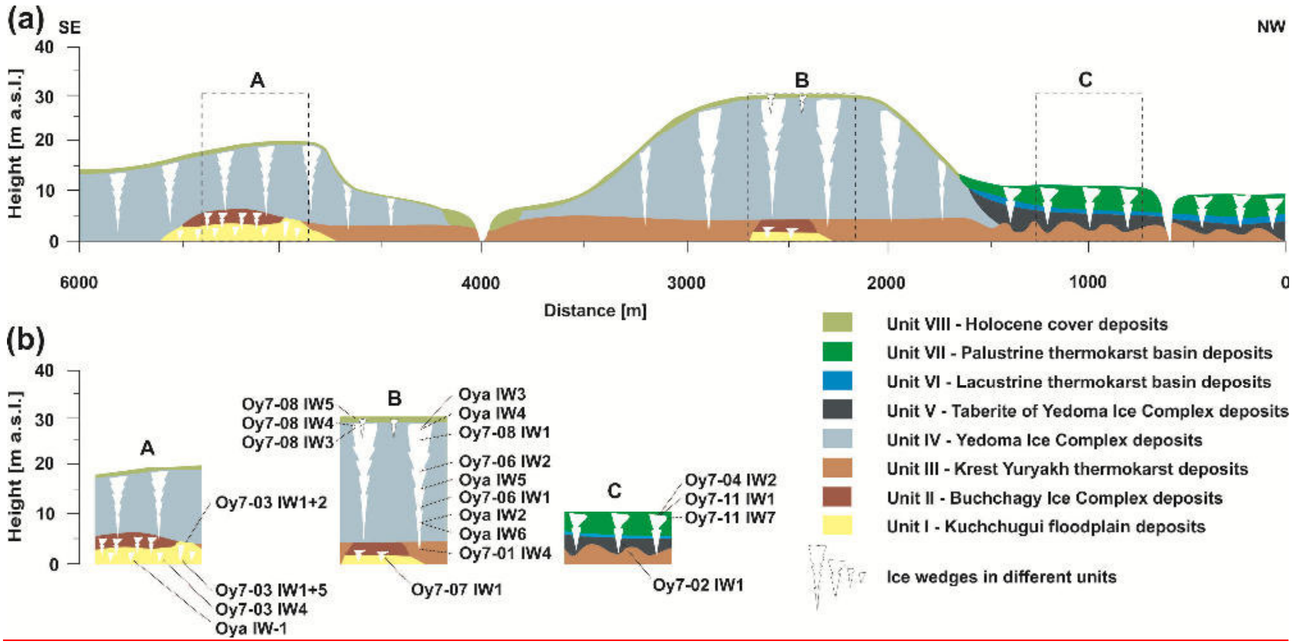

Figure 2. (a) ~~Overall~~ Generalised overall stratigraphic sketch of the Oyogos Yar mainland coast about 30 km west of the Kondrat'eva River mouth indicating the main stratigraphic units, and (b) the approximate positions of the studied ice wedges in three ~~outbreak schemes~~insets (sequences A to C). Updated and redrawn after (Blinov et al., 2009).

Figure 3: Photographs of selected outcrops and ice wedges of different units. CSIW means composite sand-ice wedge.

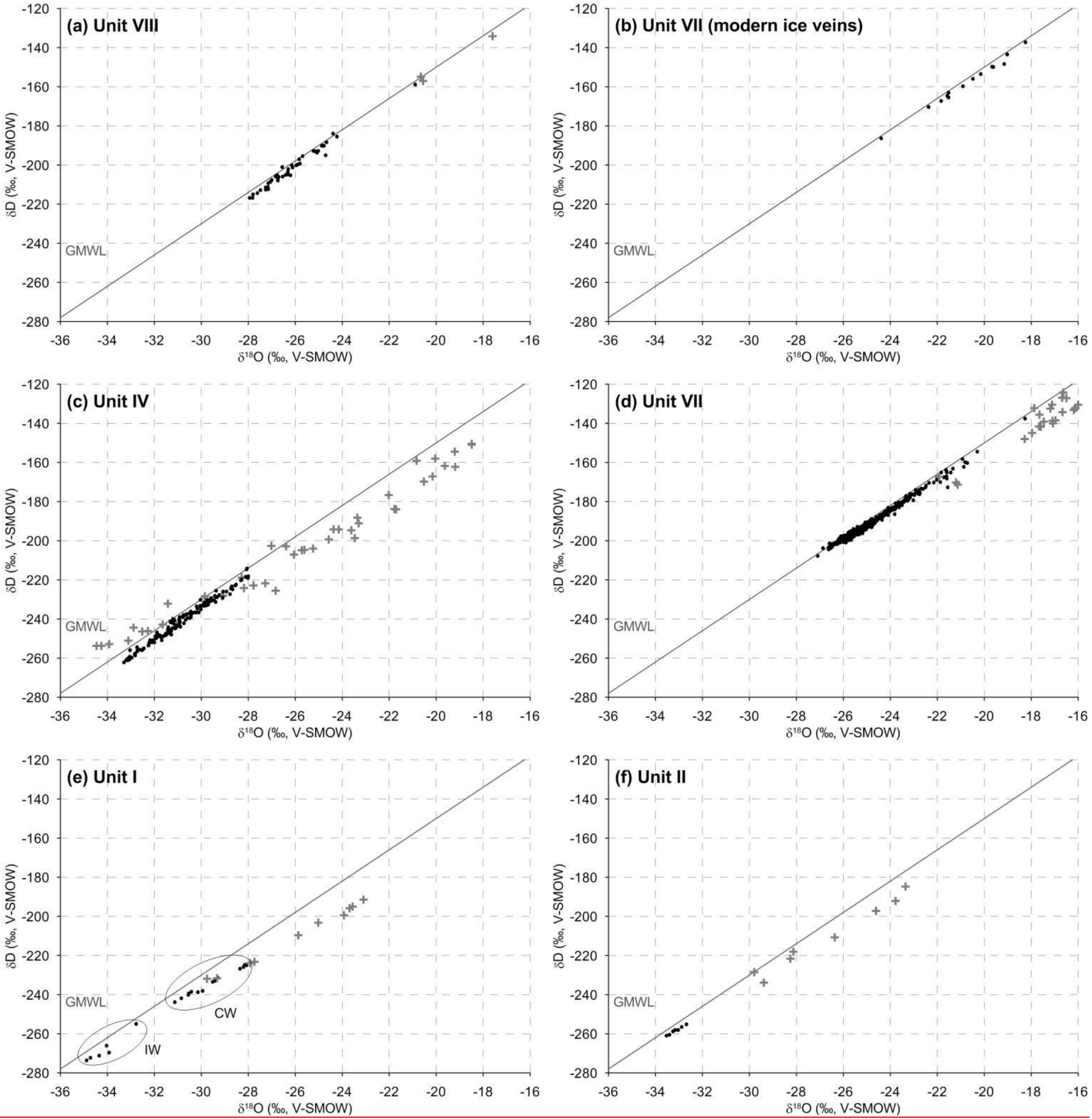

Figure 4. **δ^{18}O-δD diagrams for ice-wedge and pore and segregated ~~texture~~ ice data attributed to the studied units. Black dots refer to ice-wedge data and grey crosses to ~~texture ice~~ data of pore and segregated ice. In panel (e) IW indicates ice-wedge samples and CW composite-wedge samples.**

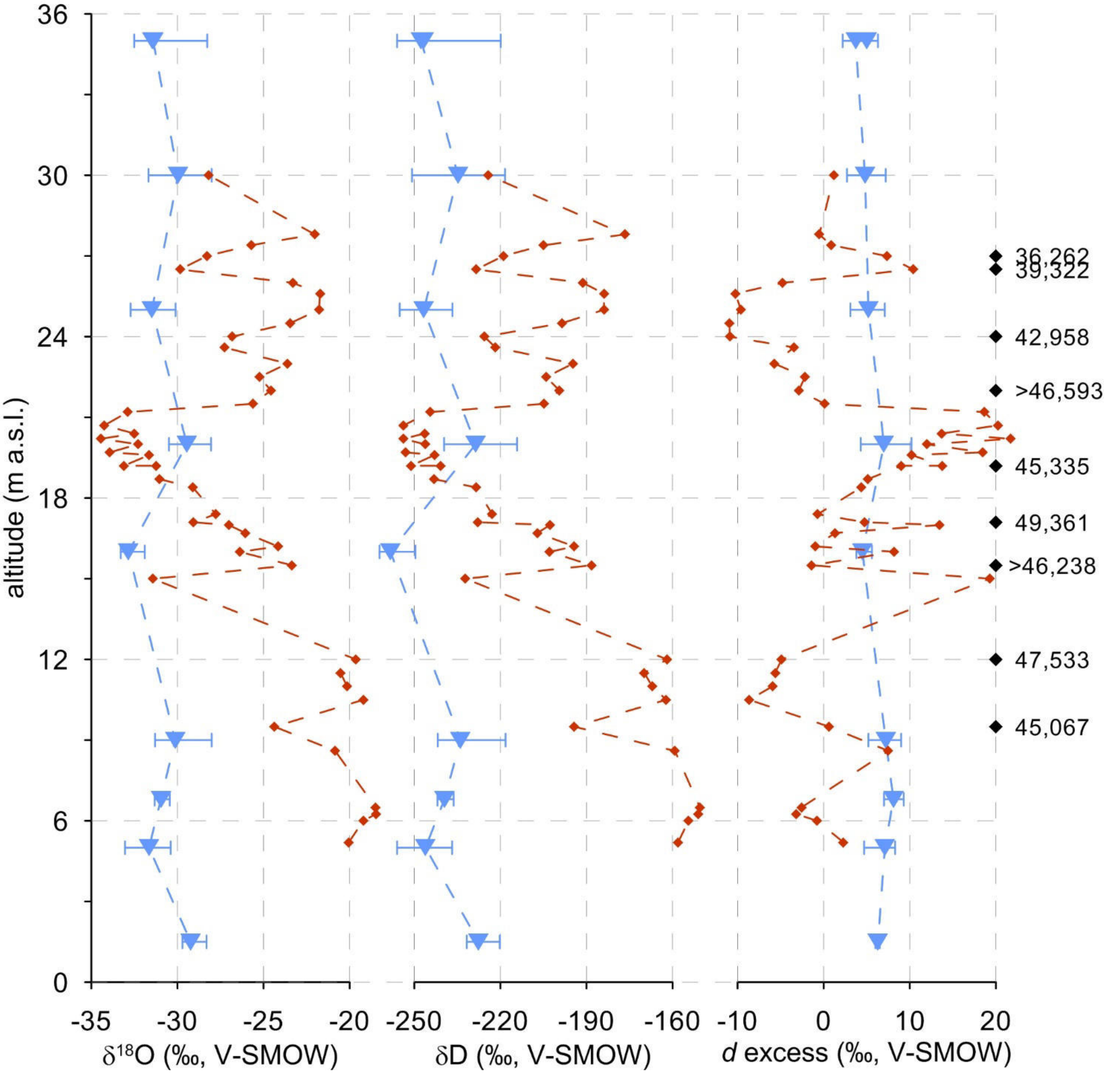

Figure 5. **Single $\delta^{18}O$, δD and *d* excess data of pore and segregated ~~texture~~ ice (red dots) and $\delta^{18}O$, δD and *d* excess data (min, mean, max) of horizontal ice wedges profiles (blue triangles) of the Yedoma Ice Complex (U~~u~~nit IV) plotted against altitude. Additionally given are radiocarbon ages (mean calibrated yr b2k, in two cases minimum ages) obtained from sediment samples. These ages do not necessarily reflect the age of the ice wedges which are assumed to be younger.**

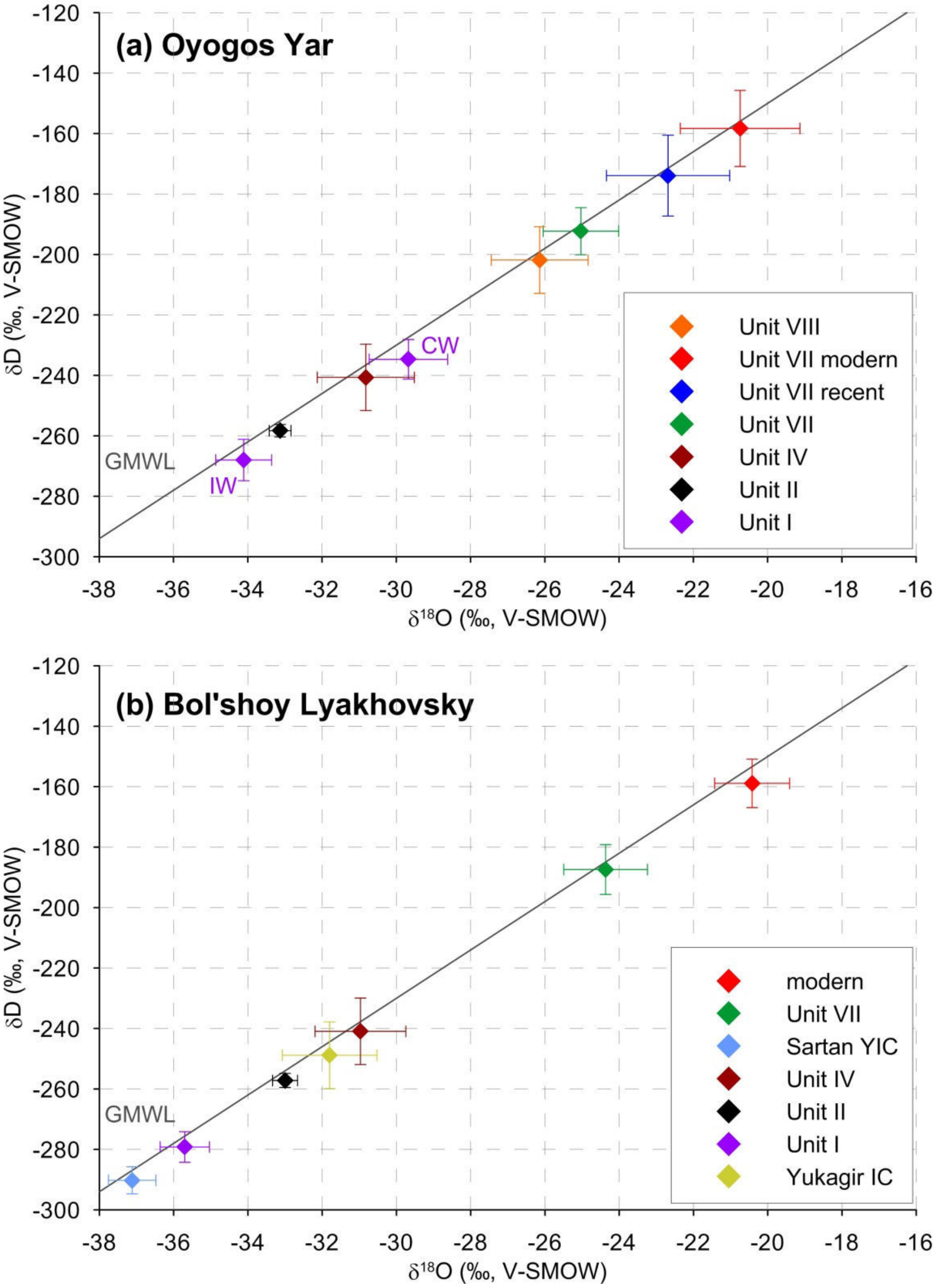

Figure 6. **$\delta^{18}O$-δD diagrams for ice-wedge data of the different units from Oyogos Yar (this study) compared to that from Bol'shoy Lyakhovsky Island (Meyer et al., 2002b; Wetterich et al., 2009; Wetterich et al., 2011; Wetterich et al., 2014; Wetterich et al., 2016). Shown are mean $\delta^{18}O$ and δD values and respective standard deviations. IW indicates ice-wedge samples and CW composite-wedge samples**

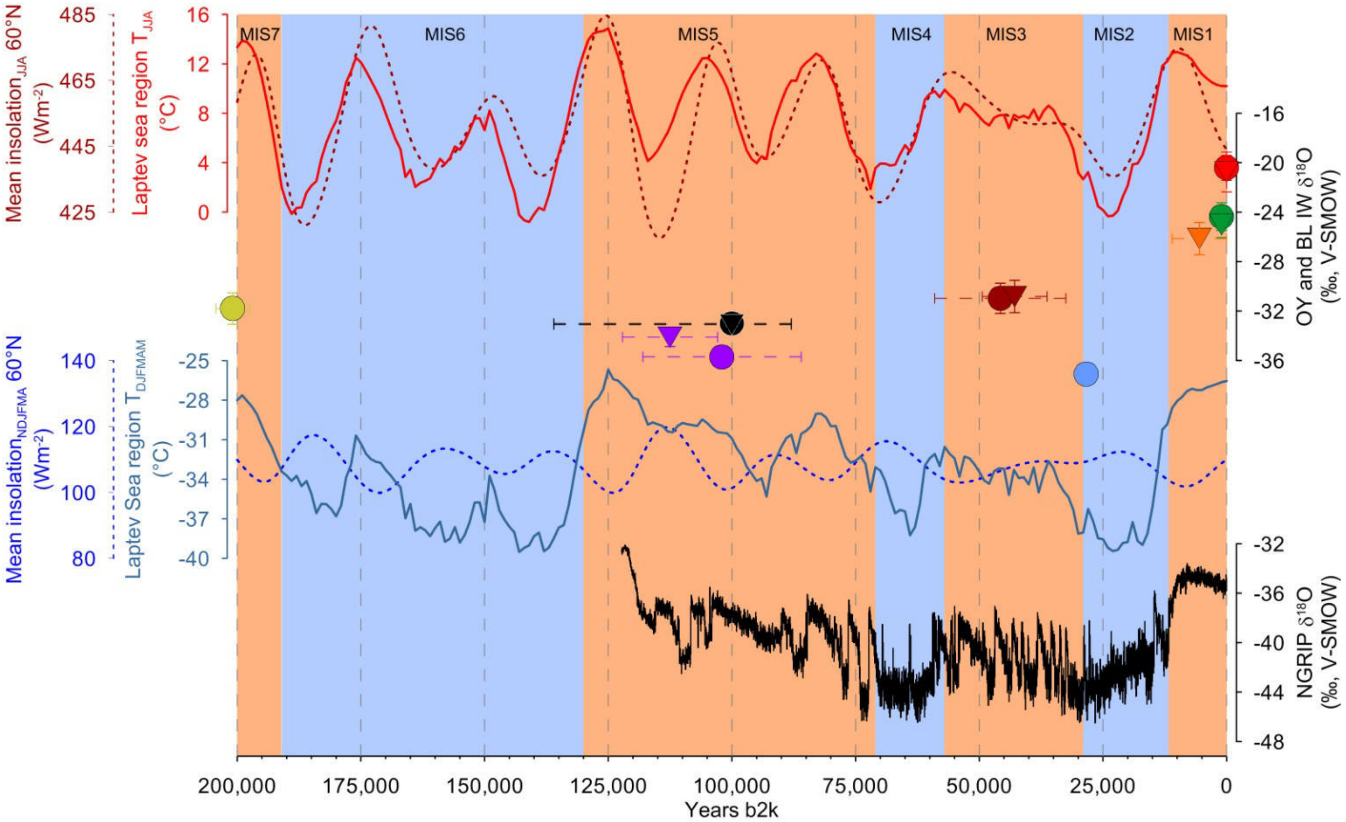

Figure 7. **Mean $\delta^{18}O$ data and standard deviations for the different units from Oyogos Yar (triangles) and Bol'shoy Lyakhovsky Island (~~open~~ circles) (interpreted age with ~~dating~~ maximum age ranges from Tables 1, 3, 4, 5 ~~uncertainties~~, colour coding corresponding to Figure 6) compared to modelled mean summer and winter temperatures for the Laptev Sea region (Ganopolski and Calov, 2011), mean summer (JJA) and extended winter (NDJFAM) insolation at 60°N (Laskar et al., 2004) ~~as well as~~and the NGRIP $\delta^{18}O$ ice core record from Greenland (North Greenland Ice Core Project members et al., 2004; Wolff et al., 2010).**

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