Reply to editor's comments

Dear Denis-Didier, we much appreciate your effort and your helpful comments. Our replies are given below in blue.
Please note: All page and line numbers refer to the revised manuscript with track changes after completing the revision based on comments of three referees.

P3, L6 What is the elevation of the site? You never indiacte such parameter to the study sites, please do so
Thank you for this suggestion! We added the elevation for both study sites.

P4, L14 give the coordinates of this site
Thank you for this suggestion! We added coordinates for our Adycha sampling site.

P4, L26 I guess these bags were prepared before to prevent any pollution. Can you precise this point please?
We used freshly opened standard Whirl-Pak bags to store and melt the samples without any additional preparation. We added some information to the text.

P5, L11 How was it extracted?
We picked organic remains from our ice-wedge as well as host sediment samples at the ice-wedge sampling sites. We added this to the manuscript.

P7, L22 add "bs" that you use later
Changed accordingly.

P7, L26 can you be more precise than unidentified plant? Were they leaves, piece of wood, roots? Same thing about the beetle remains.
We added more details to the text (Plants: bract fragments and roots, Beetle remains: complete pieces and fragments of elytron).

P7, L29 idem
We added more details to the text (twigs, roots and florets).

P8, L16 can you check as it seems to be rather Empetrum nigrum? add also the common name "crowberry"
Thank you for correcting our mistake! Changed accordingly.

P8, L19 I would rather first introduce the values and then how they plot on the diagram than the contrary which doesn't seem logical.
Changed accordingly.

P8, L26 are 1.4m above river level a height enough preventing any pollution by the river during flood periods during the melting season of the snow cover?
The sampling site was actively eroding and therefore freshly exposed. Hence, a lateral contamination with river water can be excluded. We cannot exclude flooding of this river bank during the spring snowmelt period but haven't observed any indications on recent flooding on the riverbank surface. We would furthermore expect that the frost crack would have been already filled with snowmelt generated above the crack rather than with potential river flood water. And even if spring flood might contribute to frost crack infill, we assume only minor contamination as the spring flood also originates from winter snow.
We haven't changed the text.

P9, L12 Thanks for adding this comment following reviewer 3's review. I second this review as in the European loess sequences we have studied, thermokarsts have been described corresponding to one of the long interstadials/Dansgaard-Oeschger events identified in Greenland ice-core (see Rousseau et al 2017 Quat. Sci. Rev. fig. 2).
It is indeed one of the major open research questions to elucidate whether these long interstadials/D-O events know from Greenland ice cores and European loess sequences can also be detected with similar characteristics in the remote and highly continental East Siberia. The likely windblown sediments exposed in the Batagay megaslump (in particular the Upper Sand unit) may help to solve this question.

P9, L23 in fact it depends for which purpose you use these dates: dating the ice wedge development or the dating of its infilling?
The timing of frost-crack infilling (i.e. formation of an ice vein within an ice wedge) and ice-wedge development is identical. Please note that we are not speaking about the filling of an ice-wedge pseudomorph by accumulation of new sediments.

P9, L31 but still could it be one of the extremely long younger last climate cycle interstadials than the last interglacial?
This could indeed be, even though it is rather unlikely given the new radiocarbon ages presented in this paper. The unit of wood and plant remains is located about 10 and 5 m below the studied ice wedges B17-IW5 and B17-IW6, respectively. Both, ice wedges and host sediments yielded mainly non-finite ages or ages close to the method limit. Also, the plant macro-fossil record points to interglacial not interstadial conditions. However, to better constrain the age of this unit systematic dating with independent approaches, e.g. luminescence, is needed.
We added a sentence on this to the end of section 5.1.

P11, L34 are you sure that warm=interglacial? interstadial warming in Greenland during the last climate cycle were estimated to be about 12°C in average (see Kindler et al 2013 Clim. Past)
Given the stratigraphic position of this erosional surface and the interpretation of the plant macro-fossil record (see above) we assume rather interglacial than interstadial warming to be the cause for this erosional event. We added an “e.g.” to make this clearer. However, additional dating is required for confirmation.

P12, L30 well, this is not clear at all as DO events are associated with high SST linked to variation in the sea ice surface which is not opposed to a changed in the source region of the transported moisture.
We agree and changed the sentence to relate the SST and moisture-source discussion to the Late Holocene (represented by the ice wedge A17-IW3 with much lower *d* values).

P13, L23 rather write "per mil"
Changed accordingly.

P14, L25 this is Greenland interstadial GI8, one of the long interstadial. See my previous comments.
We agree that there seems to be a temporal coincidence for this warm period. However, in the mentioned East Siberian studies (Wetterich et al., 2014 and Meyer et al., 2002a) the warmer period seems to be longer compared to GI8 (i.e. 48 to 32 kyr, centred around 40ky and regionally varying). No chances were made to the text. Temporally better constrained permafrost deposits from East Siberia are needed to investigate possible relations between the rapid changes in the North Atlantic realm and East Siberia.

P15, L1 Figure 1 doesn't give any indication about the elevation of these mountains. Can you tell?
Both mountain ranges reach elevations of more than 2,000 m. This was added to the text.

P15, L3 is there any modelling experiment available showing this or is this just a working hypothesis?
To our knowledge there is no modelling study available yet, so this is rather a working hypothesis and subject to future work. No changes made to the text.

P15, L16 Is there any modelling experiment supporting this?
To our knowledge there is no modelling study available yet. This is subject to future work.
No changes made to the text.

Reply to referee's comments
We much appreciate the efforts of all three referees reviewing our manuscript. All reviewers raised some points that will help us to improve our manuscript. Our replies are given below in blue. All page and line numbers refer to the original paper in CPD.

Please note that we have changed the stratigraphic interpretation of ice wedge B17-IW1. Based on new field observations of some of the authors we now attribute ice wedge B17-IW1 to the Lower Ice Complex instead of the Lower Sand as before. The erosional surface indicated in Figure 4 is now interpreted as the stratigraphic boundary between Lower Ice Complex and Lower Sand unit. We have accordingly changed the reply letter and the revised manuscript.

Anonymous Referee #1

The authors present a reconstruction of winter precipitation isotope ratios and inferred winter temperatures from relict ice wedges in Pleistocene strata in the Batagay megaslump headwall and late Holocene wedge ice near the Adycha River. These wedges span the last ~140 ka. The authors claim this study fills an important gap in knowledge of paleoclimate of the Yana Highlands. Temporal variations in the isotopic composition of the ice wedges, particularly the wedges that are well-dated and substantial in size (i.e., least prone to post-depositional overprinting), broadly support the conclusion that past stadial and interstadial winters in this region were cooler than today. Further, wedge ice from other areas across Siberia are more enriched than the Yana Highlands, both today and in the past, which suggests this region has always been the most continental area in northern Siberia.
Thank you for this accurate summary!

I read this paper with great interest. Relict ice wedges are an important paleo-meteoric water archive with a tightly constrained seasonality (winter only) and offer some of the oldest known ice in the Northern Hemisphere, extending beyond the temporal limits of the Greenland ice cores. As I see it, ice wedges have an important role to play in advancing our knowledge of Quaternary climate change in non-glaciated Arctic regions where ice cores are not possible.
The authors do a good job explaining their methods and summarising the most important features of this interesting dataset. There are several uncertainties about the integrity of the smaller ice wedge samples, and dating of the pre-MIS 3 wedges, but the authors are up-front about these uncertainties and to a large extent they do not confound the conclusions highlighted in this paper. This paper lays the groundwork for future studies to develop more detailed ice wedge records and paleoclimate inferences from this site. The topic and scope of this work are highly appropriate for Climate of the Past.
I am mostly satisfied with the paper in its current form, but I have a few concerns that I feel should be addressed before it is accepted in final form. Following these revisions I would recommend this paper is accepted.

Thank you for this assessment of our manuscript and for your suggestions and comments we used to improve the manuscript! Please see below for details.

Major comments:
To establish how much more continental the study area was in the past, the authors should consider that the global oceans were more enriched during past cold stages. For example, during MIS2 mean ocean water was ~1.2‰ enriched in 18O. In the discussion, please acknowledge this and provide some discussion – note that standardising for this effect would make some of the relict wedge ice (e.g., B17-IW4) similar in value to the late Holocene wedge ice. I do appreciate there are uncertainties about paleo-source region and possible heterogeneity in the isotope composition of marine source waters. However, some attention to this issue is needed.
Thank you for this suggestion. We agree that this is an important issue when interpreting relict ice isotopes. We, therefore, added this aspect to the discussion in section 5.3. However, we decided not to standardize and recalculate our isotope values. We think that this is not viable because we don't know the exact ages of the studied ice wedges, and so we don't know exactly what sea level was at that time and how isotopically enriched ocean water was exactly.

specific comments
P2, L31 – 'right side' is ambiguous, since it depends on which direction one is oriented.
We replaced "right bank" with "east bank" for clarification.

P3, L13 – 'MIS6 or MIS7'. Does cryostratigraphy provide any indication if this deposit (and the ice wedges) represent a glacial or interglacial period? Ideally say which is more likely.
The cryostratigraphy does not really arbitrate between glacial and interglacial conditions, though the narrow syngenetic wedges and abundance of windblown sand is more consistent with glacial conditions. Palaeoecological data rather indicate the MIS 6 cold stage (Ashastina et al., 2018). We therefore removed the reference to MIS 7 in the entire manuscript.

P4, L1 – you refer to this as the second study site, which is understandable but also confusing since there is a 'Site 2' in Figure 2.
We changed this sentence and omitted "second study site".

P4, L23-25 – if possible, please give a reference for pore ice-wedge ice exchange.
We added two references (Meyer et al, 2002a and Meyer et al., 2010).

P5, L21 – 'outlined below'
Changed accordingly.

P6, L23 – what is meant by redistribution?
We mean relocation of the hare dropping by erosion and deposition processes within the degrading slump which resulted in a contamination. We changed the sentences for clarification.

P11, L5-8 – The co-isotope linearity of this cluster is remarkable. Why not report the slope, intercept and r2 for a line drawn through all data within a cluster, as was done for the individual wedges?
Thank you for this suggestion, we added this information to Table 1 and the text.

P11, L8-9 – arguably, the MIS6 wedge is part of the first cluster. Only one of the datapoints is an outlier.
We assume you refer to ice wedge B17-IW6 from the Upper Ice Complex, not to ice wedge B17-IW1 formerly interpreted as MIS 6. We agree that 3 out of 4 samples of B17-IW6 plot below and close to the GMWL. Therefore, we added B17-IW6 to cluster 1.

P11, L12-15 – this could be explained more. If you are correct, then divergence from the Cluster 1 line could provide valuable information about aridity.
The observed relation between wedge d excess and cryostratigraphic interpretation (high d excess corresponding to wedges formed during drier conditions, lower d excess corresponding to wedges formed during moister conditions) might indeed point towards the divergence from cluster 1 (or GMWL) as indicator of aridity (or drier conditions). This, however, needs thorough evaluation as it might be a site or regional feature and has not been observed in today's coastal ice-wedge sites. We changed the wording in the manuscript for more clarity.

P11, L17 – please add a reference (e.g., Pfahl and Sodeman, 2014, Clim. Past.)
Thank you for this suggestion. We added this reference.

P11, L21 – this is an interesting line of discussion. Can you expand on this point, and comment on how different snowpack evolutions would be expected to influence the isotopic composition of the eventual meltwaters?
Little is known yet about the isotopic changes of the winter precipitation in the snowpack before its incorporation into wedge ice. A few studies suggest an isotopic enrichment in the snowpack and/or the snowmelt prior to filling of frost cracks (see Opel et al., 2018, Permafrost and Periglacial Processes; Grinter et al., 2018, Quaternary Research) due to several processes (e.g. sublimation and depth-hoar development). The effect on *d* excess hasn't been estimated yet. For intrasedimental ice it is even more unclear as several freeze-thaw cycles have to be taken into account. We, therefore, added only a few words and the references to the text.

P12, L2-5, the point of this sentence is not entirely clear.
We changed this sentence for clarity.

P12, L9, specify that you are talking about d18O. Also, I would advise against specifying a number (e.g., -40) … better to simply say even more depleted values compared to MIS3 wedge ice is expected.
Changed accordingly.

P12, L18-19, please clarify what is meant here.
We deleted this sentence.

P14, L1, clarify that mean dexcess of 6 permille is a Late Holocene value … same for the Yakutia example.
Changed accordingly.

P14, L18-20, this last sentence seems irrelevant to the study … further, it is not clear how this study area provides the ideal conditions are validating/advancing the Cl dating method. Suggest deleting this sentence.
The Batagay megaslump may be a very good site to validate/advance the $^{36}Cl/Cl^-$ dating approach, as it provides both, very old ice and a logical stratigraphy. The latter is missing at other study sites in the Siberian North that exhibit complex spatial stratigraphic patterns. However, as suggested by ref#2 we have moved this aspect to the discussion (section 5.1) and have expanded it slightly.

Figure 7. the #7 datapoint is missing x/y error bars.
We checked this figure again and found that there are error bars for datapoint #7. There are, however, no error bars for the second Batagay datapoint (#16) as these values haven't been reported by Vasil'chuk et al. (2017). We furthermore updated the dataset for several sites and therefore this figure as suggested by ref#2.

Anonymous Referee #2

The manuscript presents stratigraphy, geochronology, and ice-wedge stable isotope data from the Batagay megaslump- a remarkable bluff of late-Middle- and and Late-Pleistocene sediments in interior Yakutia exposed by a spectacularly-large thaw slump. They add some new radiocarbon dates to the emerging chronological framework for this site, and provide some new stable O and H isotope data for a small number of ice-wedges ranging in age from MIS 6(?) to the Holocene. Focusing on the broad MIS 3 interval, the authors conclude that winter temperatures during MIS 3 were colder at this site in interior Yakutia, relative to a compilation of purportedly MIS 3 ice wedges from mostly coastal sites.
Thank you for this summary.

In principle I think data and discussion from this kind of proxy archive are a good fit for the scope and audience for Climate of the Past. I also think this site is really a remarkable find, particularly because of the potential for preservation of pre-MIS 5 relict ground ice. The writing and figures are mostly clear. But several factors make me unable to recommend publication: 1 Relatively low number of analyses 2 Poor chronology that inhibits meaningful comparison between sites 3 Speculative nature of the paleoclimate discussion.
I elaborate on these points below, with more specific comments at the end.
Thank you for your assessment, we respond to your more detailed comments below.

Note: Though the title of the manuscript alludes to Middle and Late Pleistocene climate and continentality, my main points of concern are limited to the MIS 3 part of the story because the authors acknowledge that the data from younger and older parts of the sequence are equivocal (p14/line10).

1. The Batagay megaslump headwall exposure is over 1 km long, yet the conclusions re: MIS 3 rest on data collected from only two ice wedges at a single measured section. The discussion and conclusion around Holocene climate is similarly based on analyses of only a single ice wedge. I realize that field work on sites like this is difficult and potentially dangerous, but the chainsaw sampling is rapid and contemporary analytical techniques allow for hundreds of samples to be analyzed in relatively short order. Rather than limited and equivocal results from a reconnaissance visit to the field site, my sense is that this topic deserves “high-resolution systematic sampling and dating”, as the authors point out in their conclusion.
We acknowledge that a larger number of studied ice wedges and samples would have been better but unfortunately this could not be realized due to short time in the field and dangerous outcrop conditions, in particular close to the headwall. However, we are convinced that our results and conclusions presented in this study are not equivocal but worth to be published in Climate of the Past (as also stated by referee 1) for the following reasons:
1. The Yana Highlands as most continental region of the Northern Hemisphere are largely understudied in terms of palaeoclimate research.
2. We present stable isotope data of six ice and composite wedges from the Batagay megaslump and one ice wedge from the nearby Adycha River. When compared to previous ice-wedge studies this is not a low number of studied wedges.
3. We present this for the first time in an international peer-reviewed journal and the first data at all for the Lower Ice Complex and a nearby Holocene wedge. Our data for the MIS 3 is confirmed by independent data previously published in Russian by Vasil’chuk et al. (2017) but we provide additional cryostratigraphic context and new radiocarbon age information.
4. Our Batagay MIS3 stable isotope data show unprecedented low δ^{18}O values and remarkably high *d* values that are worth to be presented and discussed.
5. Our study is the first one that compares published and yet unpublished ice-wedge stable isotope data for the MIS 3 across Siberia and show that winter temperatures during the MIS 3 have been

lower in the Yana Highlands than in all other regions. A similar pattern is found for the late Holocene and can be deduced for modern winter precipitation.
6. We deduce that the extreme continentality known from modern meteorological observations persisted also during the MIS 3 and the late Holocene.
7. We present new ice-wedge observations and relate them together with the stable isotope composition of ice and composite wedges to the deposition regimes of the different units exposed in the Batagay megaslump.
8. We furthermore present the first pore-ice stable isotope data for the Yana Highlands.

2. Most critically, I question if the available data support a meaningful conclusion re: MIS 3. In other words, what does it actually mean to compare a single probably-MIS3 ice-wedge from one site to another single probably-MIS3 ice-wedge from another site (as is done in Fig 7 and Table S2), since this interval spans ~30,000 years and includes some pretty high-amplitude multi-millennial-scale climate oscillations in high-resolution proxy records?
We already acknowledged in the manuscript that there are some limitations in the dataset used for the spatial comparison:
"Additionally, all except two of the considered wedges or their host sediments have been directly dated by radiocarbon methods to between about 50 and 30 kyr ago. We appreciate that an ice wedge may not contain a full record of this time period and that the climate was not uniform throughout this period; in particular, a warmer period around 40 kyr BP is well known from several palaeoecological proxies for some of the study sites (Wetterich et al., 2014)."

However, we don't know yet if millennial-scale climate oscillations characterized MIS 3 in East Siberia (West Beringia), underlining the need for some high-resolution records covering this period to determine if they did exist. Thus, we are uncertain of their spatial extent and significance in the ice-age Northern Hemisphere. Following Murton et al. (2017), there are indeed hints that the MIS 3 in northern areas of Northeast Siberia was a time of general climate stability. Other records suggest that the interstadial climate was not monolithic, but that the early interstadial was characterized by dry but relatively warm conditions, and cooler and drier climates prevailed later in MIS 3 (e.g. Kienast et al. 2005, Quaternary Research; Sher et al. 2005, Quaternary Science Reviews; Lozhkin et al. 2007, Journal of Paleolimnology; Wetterich et al. 2014, Quaternary Science Reviews). This pattern differs from more southerly sites with evidence for numerous climate fluctuations (Lozhkin&Anderson. 2011, Quaternary Science Reviews).

We added some information on this to section 5.4.1.

To ensure the best possible quality of the dataset
1) we excluded the MIS2 period which shows lower temperatures in Northeast Siberia and limited the time period of interest to 50 to 30 kyr;
2) except for two ice wedges (one of these is also from the Batagay megaslump (Vasil'chuk et al., 2017) we considered only dated ice wedges (radiocarbon dating of host sediments or ice wedges);
3) we reported not only mean values for the respective ice wedges but also standard deviations to account for climate-dependent $\delta^{18}O$ variations captured by the ice wedges;
4) we used only ice wedge datasets that include both $\delta^{18}O$ and *d* (to be able to detect outliers due to post-depositional processes).

The time interval is also notoriously difficult to date accurately with 14C methods, and many purportedly finite ~35-45 14C ka BP dates in the literature ought to be viewed with a strong dose of skepticism (notably, for example, the purported MIS 3 chronology for Mamontova Gora - an important comparative site Fig 7/Table S2).
To our understanding, 14C dating has made substantial progress over the last years, making 14C dating even in the age range 35-45 k 14C years much more reliable. Calibration is possible back to

50ka cal BP (Reimer et al., 2013, Radiocarbon). All 14C ages used in the manuscript are from the last about 15 years and not from older literature. This is also true for the 14C age from Mamontova Gora (Popp et al., 2006, Permafrost and Periglacial Processes).
Furthermore, we are using 14C to identify the MIS 3 as a whole, not its substages, i.e. MIS 3 rather than Dansgaard-Oeschger events. So, the technique applied is adequate to do this.

Seven out of the 18 sites in the Fig 7/Table S2 ice-wedge compilation are unpublished, so readers can't assess the reliability of these chronologies for themselves.
All stable isotope data used for Figs. 7-9 including previously unpublished data will be made available in PANGAEA after acceptance of the manuscript, except the data from Vasil'chuk et al. (2017).

The authors mention the issue of dating and a long MIS 3 (p12/line26) but do not really address it in a way that justifies the approach. One example of the interpretive difficulties: Novaya Sibir, Belkovsky, and Kotel'ny are all above 74 degN in the New Siberian Islands, yet only Novaya Sibir has relatively depleted isotope composition. Is the between-site difference in isotope composition due to differing age or some sitespecific factor? Either way, the lack of good chronological control inhibits meaningful comparison.
The focus of our study is on the ice wedges from Batagay and we use the other data to illustrate the peculiarity of the Yana Highlands. To distinguish between age- and/or site-specific aspects in the New Siberian Islands is beyond the scope of this paper. By focusing on the broad MIS timescale, the isotope values from Batagay contrast significantly with those from other sites. Despite uncertainties in age the Batagay ice wedges are more depleted than those at any other North Siberian site.

One last point of criticism on the comparison of different sites: why was the compilation/comparison limited to just one "MIS 3" ice-wedge from each site? In the context of this analysis, would it not be more useful to compare the average isotope composition of multiple ice-wedges from a particular stratigraphic interval (e.g. the 10 ice wedges with dD and d18O data attributed to the yedoma ice complex in Opel et al 2017)?
Thank you for this comment. Unfortunately for several sites we rely on only one studied ice wedge. However, we followed the referee's suggestion and reviewed again stable isotope data related to the MIS 3 ice wedges. We added all available data to the following study sites: Lena Delta/Kurungnakh (4), Bykovsky (6), Muostakh (7), Buor Khaya (8), Belkovsky (9), Stolbovoy (10), Bol'shoy Lyakhovsky (12), and Oyogos Yar (13) and updated Figures 7 to 9 and Table S3 accordingly.

3. I acknowledge that quantitative paleoclimate reconstruction from this type of archive is highly uncertain, but the climate implications presented here are vague. Differences in isotope composition between areas are quantified, but then unsupported paleotemperature interpreations are made (e.g. "significantly lower [temperatures]" p14/line7; "extremely low winter temperatures" p11/line23 vs "very low winter temperatures" p11/line26). These distinctions need to be defined.
The paleotemperature interpretation has followed a tentative classification also used in Opel et al. 2017 (Climate of the Past) and is not based on quantitative temperature calibration. We, therefore, decided to omit the use of this paleotemperature interpretation. We have changed the text and Table 4 accordingly.

The authors have not really addressed the issue of paleogeography, nor potential differences in moisture source both through time and for different sites. For example (assuming for a moment that it's possible to meaningfully compare MIS 3 IWs at the Batagay site to those compiled in Fig 7), there's an interesting spatial pattern whereby the Novaya Sibir Island site also has highly depleted IW isotope composition during MIS 3. What are the paleogeographic implications of Late Pleistocene sea level change, with respect to continentality? What are current and modelled MIS 3 moisture sources for that site and the Batagay site? Is there paleoceanographic proxy evidence (e.g. from planktic

forams) for changes in surface water isotopic composition at likely moisture sources? All of these points would likely provide useful context for evaluating the data presented in the manuscript.
During MIS 3 the sea level was lower by 60 to 80 m, the wide Arctic shelves were exposed, leading to an increased continentality of entire Northeast Siberia. However, Novaya Sibir' Island would still have the lowest continentality of all considered sites. To analyze current and modelled MIS3 moisture sources for Batagay and Novaya Sibir' is beyond the scope of the manuscript which is not an MIS 3 stable isotope review but focusing on the cryostratigraphy and new ground ice isotope data from Batagay.
The issue of a changed surface water isotope composition at the moisture sources was also raised by referee #1 (see above). We added some thoughts on this to the discussion.

Other points: This manuscript, which includes many co-authors on earlier papers that document the chronostratigraphic framework for the site, introduces yet another unit-stratigraphic nomenclature for the Batagay megaslump headwall exposure. For example, at least by my interpretation, "upper Ice Complex" (this ms) = Unit III (Ashastina et al. 2017) = Unit 4 (Murton et al. 2017). Given the potential importance of this site, and since all the key players are co-authors on this manuscript, it would be very useful to the community if the authors could reconcile these different frameworks here in this manuscript.
You are right, the different stratigraphies which originate from different studied sections of the outcrop (see Figure 2) can be confusing. But observations of main units are more or less similar.
To relate the stratigraphies used in Ashastina et al. (2017) and Murton et al. (2017) and to establish a reconciled stratigraphy for future studies of the Batagay megaslump we added a new table (Table 1) containing this information.

This group is highly experienced in stable isotope studies of ground ice. Nevertheless, it would be useful to provide some additional methods data. Is the quoted lab precision for dD and d18O 1sigma or 2sigma? What are the summary statistics for the internal quality control secondary standard?
The lab precision at AWI Potsdam isotope lab is given as better than ±0.1‰ for $\delta^{18}O$ and ±0.8‰ for δD, respectively. For this purpose, we use a three-point calibration for each measurement sequence and one standard for internal quality control. When one of the three standards is outside the ranges given above, the measurement is repeated.
All single measurements have a 1 sigma error, which usually is <0.05‰ for $\delta^{18}O$ and <0.5‰ for δD. When the single measurement 1 sigma is larger than ±0.1‰ for $\delta^{18}O$ and ±0.8‰ for δD, the measurement is repeated.
When testing for internal quality control using an independent standard, these tests usually yield a statistical error of <0.05‰ for $\delta^{18}O$ and <0.5‰ for δD for long-term measurements (N>20). This is, however, not done for each individual sample series, but tested on a regular base (every few months).

And most importantly (p4/line24), how exactly did the authors decide which samples to exclude from further analyses? The description in the manuscript is very vague (please clarify, with a citation or two, what exchange processes are being invoked between IW and pore ice), and I would strongly prefer that the authors present ALL the ice-wedge stable isotope data first and then justify to readers why some data should be excluded from further consideration.
We first plotted the stable isotope profiles and compared them with our observations of sediment content in the wedge-ice samples. In total, five samples out of the studied seven wedges had to be excluded due to high sediment content and/or distinctly changed isotope values (similar to those of intrasedimental ice of host sediments). For transparency, we decided to present all ice-wedge stable isotope data in the supplement (Table S2) and indicate the excluded samples.
As far as we know these processes haven't been studied in detail. We therefore added two references to the manuscript (Meyer et al. 2002a, 2010) that present similar cases of exchange

processes between wedge ice and host sediments (detectable in stable isotopes and electrical conductivity).

Specific comments:
Referencing: There are points in the introduction and discussion where it would be useful and appropriate to include some citations to relevant work in North America, where there is a long tradition of stable isotope work on ice wedges (e.g. Fraser and Burn; Michel) and the stratigraphic complexities of Middle/Late Pleistocene permafrost exposures (e.g. Péwé, Westgate; Fraser & Burn; Froese, Reyes).
Thank you for this suggestion. We, added some references to the introduction and discussion of chronostratigraphy.

Title: Given the substantial interpretive and chronological uncertainty re: the lower sand and upper unit ice wedge data, I suggest removing "Middle and Late Pleistocene" from the title and replacing it with something more specific
We replaced "Middle and Late Pleistocene" by "Past" to take into account the chronological uncertainty regarding the Lower Ice Complex (was Lower Sand unit before) and consider the Holocene ice-wedge data.

Section 1 in the slump floor: Why is the one sampled wedge from the lower sand collected away from the exposed headwall, as indicated in Fig 3?
Due to the dangerous working conditions at the foot of a 55 m high and partly inclined headwall with thawed material falling down constantly, we decided to sample this wedge in another position close to the headwall.

Can authors reject the possibility that the sampled section is actually younger material displaced into an apparently lower stratigraphic position by slumping?
Yes, we can do this. Several ice wedges were found in the Lower Ice Complex (was lower part of the Lower Sand unit before) in the badlands-like not degraded remains of the slump floor. The material sampled fits well with observations made at the headwall. Also, there was no evidence of slip surfaces observed in or near section 1. The ice-wedge itself was an intact, freshly exposed ice-wedge.

And I'm troubled by the rejection of the 14C age on hare droppings from the ice-wedge. If this was a pristine, freshly exposed ice-wedge, how would younger material be incorporated into the wedge itself? Surely the outermost surface of the wedge ice is removed prior to sampling? And if material "entered into or later froze onto the surface" (p8/line24), doesn't this also imply possible reliability issues with the isotope data from that wedge?
Given the IRSL age reported in Ashastina et al. (2017) and the erosional surface in Section 1 we can exclude a younger age than MIS 6 for this sample. Therefore, the young age has to be caused by contamination. We see only one possible way: contamination of a non-finite age of the hare dropping by modern carbon during the handling of the ice-wedge sample (i.e. modern tiny and/or dissolved carbon from e.g. mud attached to the hare dropping in the sample bag.
As the ice wedge itself is melting constantly it is somehow "cleaning itself" and the only possible contamination would be with own meltwater.

p8/line18: Do you mean ". . ..different stratigraphic contexts"? This would make more sense. Also, the next few sentences of this paragraph are pretty vague and not particularly useful. I think it's pretty obvious now that adequate dating of these sediments is going to be a major challenge. There's some mention of alternative approaches in the conclusion section, which really should be moved into the discussion and properly addressed.
We added some discussion on dating old permafrost and ice wedges to section 5.1.

wood layer and the thaw unconformity (p. 8/9 transition): I assume you mean “. . .situated above the lower sand unit and BELOW the upper Ice Complex. . ...” on p8/line29, since you reasonably attribute the wood layer to the last interglacial?
You are right, changed accordingly.

14C dating (Table 2 and p5): I appreciate the details on pre-treatement and analysis. Please clarify if smaller blanks were measured for background correction of the many samples with low mass of organic C (Table 2).
Size-matched standards and blanks were analysed along with the samples and were used for normalization and blank correction. We added this information to the text.

Fig. 5: The changing vertical scale is confusing. Since the ice-wedge morphology is important in this context, I recommend a stratigraphic diagram to scale, with additional panels showing the photographs that are currently relegated to the Supplemental file.
We considered this suggestion. As a stratigraphic diagram to scale would look spartan, we decided to keep the original diagram but to add indications for the broken vertical scale. We feel, that the ice-wedge photographs are well placed in the supplement.

Fig 6. The blue inverted triangles for upper sand ice wedges are very hard to distinguish.
We changed the colors to improve visible distinguishability.

References: Ashastina et al. 2017 Climate of the Past 13: 795-818. Murton et al. 2017 Quat Res 87: 314-330. Opel et al. 2017 Climate of the Past 13: 587-611.

Anonymous Referee #3

The aim of the paper submitted by T. Opel and co-authors to CP is to provide new reconstructions of winter temperatures from Pleistocene relict ice-wedges exposed in the huge Batagay mega-slump structure in Central Yakutia, completed by a close Holocene outcrop from the Adycha River. This contribution provides new data for the reconstruction and discussion of the palaeoclimate of the Yana highlands on a long time span (< 140 ka or older). The study is based on a short field investigation focusing on the sampling of ice from ice-wedges for isotopic analyse and organic remains from encasing sediments for 14C dating (the oldest part of the sequence being already dated by OSL). The reconstruction of winter palaeotemperatures is achieved using co-isotopic composition (δD-δ18O) of ice from the ice-wedges preserved in the various Batagay sections and from intra-sedimentary ice.
It is a very interesting contribution based on a methodology that has already been developed and published by the first author in PPP (Opel et al., PPP, 2018).
The manuscript is well organised and the topic is fully in agreement with the publication goals of Climate of the Past.
Thank you for this summary!

Observations and questions:
1) My main concern is that the author never consider that the climate of the Last glacial was subject to extremely rapid climatic changes between stadial and interstadial conditions that would probably have affected winter temperatures.
This point should be discussed.

As pointed out already in response to Referee #2 it is not clear yet whether the rapid climate changes known from the North Atlantic region (e.g. the Greenland ice cores) and Europe have also affected East Siberia (West Beringia) due to the lack of high-resolution records covering this period. Thus, we are uncertain of their spatial extent and significance in the ice-age Northern Hemisphere. Following

Murton et al. (2017), there are indeed hints that the MIS 3 in northern areas of Northeast Siberia was a time of general climate stability. Other records suggest that the interstadial climate was not monolithic, but that the early interstadial was characterized by dry but relatively warm conditions, and cooler and drier climates prevailed later in MIS 3 (e.g. Kienast et al. 2005, Quaternary Research; Sher et al. 2005, Quaternary Science Reviews; Lozhkin et al. 2007, Journal of Paleolimnology; Wetterich et al. 2014, Quaternary Science Reviews). This pattern differs from more southerly sites with evidence for numerous climate fluctuations (Lozhkin&Anderson. 2011, Quaternary Science Reviews).
We added some information on this to section 5.4.1.

In addition, in the discussion the various episodes of thawing of the ice complex and associated erosional surfaces are only allocated to interglacial conditions (P. 8/L.16) whereas it is likely that they could also occur during MIS 3 during the warming phases characterising the beginning of the stronger interstadials as GI 14 or 12 for example…
This has been apparently observed by the authors (P.10/L15): « The upward transition of wedges from the upper ice complex to upper sand unit, however, was interrupted episodically by thaw, producing a number of thaw unconformities at different depths ».
Thank you, we added the exceptionally warm interstadials as another possible cause for the observed thaw unconformities.

2) Please explain the difference between Ice complexes and Sand units including intrasedimentary ice / % of ice?
Unfortunately, there are no data on gravimetric ice content available yet. This will be a subject of future studies. The major difference is the amount of wedge ice: huge and wide ice wedges in the Ice Complexes and narrow composite wedges in the sand units.

3) General concern: even if it is not the main topic of the paper, palaeoenvironmental and palaeoclimatic information derived from vegetal macro-remains should be exposed with more details (only short mentions as in P.9/L.1).
We added some information here as this unit of wood and plant remains does not contain ice wedges and is therefore not considered in later parts of the manuscript. However, the main palaeoecological results from Ashastina et al. (2018, Quaternary Science Reviews) are summarized per unit and presented in Table 4 (was Table 3 before) and also mentioned in section 5.3. We prefer not to include more palaeoecological information to the manuscript which focuses on ground ice isotopes and cryostratigraphy.

4) According to the various radiocarbon dating results, exposed in part 4.1, no ages corresponding to MIS 2 are found in the upper Ice and upper Sand Complexes presented as dating from MIS3-2 (P.8/L.13) ?.
You are right, most of the new radiocarbon ages presented in this study belong to MIS 3 (except for B17-IW5-02 which is placed at the boundary of MIS 3 and MIS 2). However, in the earlier study by Ashastina et al. (2017, Climate of the Past) radiocarbon ages for their Section C (equivalent to our Section 2) range from > 51 to 12.66 kyr BP. This supports a deposition of the Upper Ice Complex and the Upper Sand during MIS 3 and MIS 2.

In addition, most of the 14C ages are even older (37 - 38 000 BP or infinite MIS 4?).
+ P8/L.28-30: “radiocarbon dating of a wood layer (up to 1.5 thick) ABOVE the Lower sand unit and the upper Ice Complex reveal an infinite radiocarbon age …”
According to this statement the upper Ice Complex should not be allocated to MIS3 and even more to MIS 2.
There was a mistake. It should read as follows “…above the Lower Sand unit and BELOW the Upper Ice Complex.” Hence, we stick to our chronostratigraphic interpretation of the Upper Ice Complex

and Upper Sand being formed during MIS 3 and MIS2. However, we don't really have a firm maximum age for it the Upper Ice Complex at present. A formation beginning in MIS 4 may be possible but has to be the subject of future studies.

5) As pointed by R2 I also think that the change in isotopic composition of ocean water between glacial periods and the Holocene should be taken in account …
The issue of a changed surface water isotope composition at the moisture sources was also raised by referee #1 (see above). We added some thoughts on this to the discussion.

6) Finally: in the whole paper the water supply, necessary to the development of individual ice veins forming ice wedges, is supposed to result only from precipitations (snow). What about the proportion of water originating from the melting of markedly older ice-rich permafrost sediments or ice wedges that could be trapped in permafrost cracks and mixed in various proportion with snow melt water during ice wedge forming process?
The substantial contribution of meltwater of relict ground ice seems to be a very unlikely explanation and has to our knowledge not been described in ice-wedge literature. When ice-wedge cracks are open in winter and spring the active layer is either frozen or just starting to melt, so it seems difficult to envisage how meltwater from old ice-rich permafrost could infill cracks. If the melting occurred in mid to late summer when the active layer was thawed more deeply, then it would be easier to envisage melt of older ground ice, e.g. by underground thermal erosion. But by that time of year the cracks would probably have infilled or closed by thermal expansion.

Figures
I have presently great difficulties to connect the very large-scale Figure 3, based on a panoramic photograph, and the schematic but detailed cryo-stratigraphic illustrations of figures 4 & 5.
In addition in Figure 3 the author should at least include a vertical scale! and the location of the various studied profiles is not very clear.
To resolve this problem we need an additional medium scale Figure (a kind of stratigraphic log) based on a summary of the various formations, including their stratigraphic relations, respective thickness and the position of the various studied sections.
Thank you for this suggestion. We added a stratigraphic scheme to Figure 3 that shows the different units their respective thicknesses and indicated the positions of the sections.

Conclusion
This is a new and interesting contribution, well suited for Climate of the Past, and I think that it can be published after a moderate revision taking in account the various questions and observations exposed above.
Thank you for this assessment!

~~Middle and Late Pleistocene~~ Past climate and continentality inferred from ice wedges at Batagay megaslump in the Northern Hemisphere’s most continental region, Yana Highlands, interior Yakutia

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Abstract

Ice wedges in the Yana Highlands of interior Yakutia—the most continental region of the Northern Hemisphere—were investigated to elucidate changes in ~~the~~ winter climate and continentality ~~during~~ since the Middle ~~to Late~~ Pleistocene. The Batagay megaslump exposes ice wedges and composite wedges that were sampled from three cryostratigraphic units: the L~~l~~ower ~~sand unit~~Ice Complex of likely pre-Marine Isotope Stage (MIS) 6 age, the ~~upper~~ Upper Ice Complex (Yedoma) and the ~~upper~~ Upper ~~sand~~ Sand unit (both MIS 3 to ~~MIS~~2). A terrace of the nearby Adycha River provides a Late Holocene (MIS 1) ice wedge that serves as a modern ~~endmember~~ reference for ~~analysis~~interpretation. The s~~S~~table-isotope ~~values~~ composition of ice wedges in the MIS 3 ~~upper~~ Upper ~~Yedoma~~ Ice Complex at Batagay ~~are~~ is more depleted (mean δ^{18}O about –35‰) than ~~those~~ that from 17 other ice-wedge study sites across coastal and central Yakutia. This observation points to lower winter temperatures and, therefore, higher continentality in the Yana Highlands during MIS 3. Likewise, more depleted isotope values ~~compared to other sites in Yakutia~~ are found in Holocene wedge ice (mean δ^{18}O about –29‰) compared to other sites in Yakutia. Ice-wedge isotopic signatures of the ~~MIS6 lower~~ Lower ~~sand unit~~ Ice Complex (mean δ^{18}O about –33‰) and of the MIS 3–~~-~~2 ~~upper~~ Upper ~~sand~~ Sand unit (mean δ^{18}O from about –~~-~~33 to –~~-~~30‰) are less distinctive regionally. ~~and~~ The latter unit preserves traces of fast formation in rapidly accumulating sand sheets and of post-depositional isotopic fractionation.

1 Introduction

Interior Yakutia is currently the most continental region of the Northern Hemisphere. At Verkhoyansk, the pole of cold of the Northern Hemisphere, mean monthly air temperature ranges exceed 60°C and absolute temperatures ranges can ~~exceed~~ reach 100°C (Lydolph, 1985). Mean annual precipitation is only 155 mm (Lydolph, 1985). Scarce ~~stable~~ stable-isotope data indicate that modern winter precipitation in this region has the most depleted isotopic composition in Siberia (Kurita et al., 2004; Kurita et al., 2005) according to the "continental effect" in stable isotope fractionation, i.e. the farthest distance from the source region (Dansgaard, 1964). However, warm summers enrich stable isotopes in summer precipitation at interior sites compared to coastal sites in the North, which also reflects the strong continentality of interior Yakutia. During Late Pleistocene cold stages, when lower sea level exposed larger areas of continental shelves, interior Yakutia probably experienced even stronger continentality, with further decreased annual precipitation and ~~larger~~ increased annual temperature amplitudes. Such increased amplitudes must have resulted from either lower winter temperatures or higher summer temperatures or a combination of both. ~~Although~~ While biological proxies such as pollen or plant macrofossil remains can be used to reconstruct summer climate, winter conditions in ~~this region~~interior Yakutia may be inferred only from ice wedges, which ~~are widespread~~can be found in Middle and Late Pleistocene as well as Holocene permafrost deposits. Ice wedges provide winter temperature information due to their specific seasonality, with frost cracking in winter and crack infilling by snowmelt in spring (Opel et al., 2018). They integrate the ~~stable~~ stable-isotope composition of ~~cold~~ cold-season precipitation (Meyer et al., 2015), which in high northern latitudes is mainly a function of temperature (Dansgaard, 1964). However, a knowledge gap exists about the winter palaeoclimate of interior Yakutia, because ice-wedge studies in the Yana Highlands—between the Verkhoyansky and Chersky ranges—began only recently (Vasil'chuk et al., 2017). In contrast, other sites in east ~~Siberian~~ Siberia (west Beringia) ~~sites~~ have been extensively studied over recent decades, including the coastal lowlands to the north (e.g. Meyer et al., 2002a; Meyer et al., 2002b; Opel et al., 2017b), the Kolyma region to the east (e.g. Vasil'chuk et al., 2001; Vasil'chuk, 2013; Vasil'chuk and Vasil'chuk, 2014) as well as central Yakutia to the south (e.g. Popp et al., 2006) (Figure 1). Ice-wedge studies have been carried out also in east Beringia, e.g. in Alaska, Yukon, and Northwest Territories (Kotler and Burn, 2000; Meyer et al., 2010b; Fritz et al., 2012; Lachniet et al., 2012; Porter et al., 2016).

Here we report cryostratigraphic field observations of ice wedges and composite wedges made during a reconnaissance expedition from 27 July to 5 August 2017 together with stable-isotope data from the Batagay megaslump and Adycha River floodplain (Figure 1). New radiocarbon ages from organic remains in ice wedges and host sediments ~~from the former~~ help constrain the late Quaternary chronology. The observations and ages elucidate the history of wedge development, past winter temperatures and continentality since ~~MIS 6~~the Middle Pleistocene.

2 Study site characteristics, stratigraphy and chronology

Neither study site has been glaciated during at least the last 50,000 years, and the Batagay megaslump provides access to permafrost formations since the Middle Pleistocene (Ashastina et al., 2017; Murton et al., 2017). The present mean annual air temperature at Batagay is –~~-~~15.4°C (mean of the coldest month: –~~-~~47.7°C, mean of the warmest month: 15.4°C) and the mean annual precipitation is 170 to 200 mm (Ivanova, 2003). Prevailing wind directions are southwest in winter (January) and north or northeast in summer (July) (Murton et al., 2017). The mean annual temperature of the permafrost is ~~-5.5 to~~ –~~-~~8.0 to –5.5°C and the active-layer depth between 0.2–~~-~~0.4 m beneath forest and moss covers and 0.4–~~ to~~ 1.2 m beneath open sites (Ivanova, 2003).

The **Batagay megaslump** (67.58°N, 134.77°E), close to the city of Batagay on the ~~right~~ east bank of the Yana River, is the world's largest known thaw slump (Figure 2) (Ashastina et al., 2017; Murton et al., 2017). It is located on a hillslope in the taiga landscape (328 m above sea level for the highest part of the headwall) and exposes a sequence of permafrost deposits at least 60 m thick, with underlying bedrock cropping out in places (Kunitsky et al., 2013). The slump has formed during recent decades (Savvinov et al., 2018), with increasing headwall retreat rates of up to 30 m per year. In 2016 it reached a width of 840 m and a total area of >70 ha (Günther et al., 2016).

The slump exposes ~~Holocene and~~ Pleistocene and Holocene permafrost formations ranging in age from MIS 6 (or older) to MIS 1 (Ashastina et al., 2017; Murton et al., 2017; Ashastina et al., 2018). Above slate bedrock and a basal diamicton, four major cryostratigraphic units contain ice wedges and/or composite wedges (Figure 3, Table 1).

~~-~~The lowest unit is a pebbly dark sand 3–~~-~~7 m thick, with ice wedges at least 2–~~-~~3 m high and 1 m wide truncated by a thaw unconformity. This **L~~l~~ower Ice Complex** has neither been dated nor sampled previously for wedge ice.

~~Above it is t~~The **L~~l~~ower ~~sand~~ Sand** unit above ~~,~~ reaches~~ing~~ about 20 ~~to 30~~ m in thickness and is composed of yellowish pore-ice cemented (fine) sand with grey horizontal bands. It contains tall, narrow syngenetic ice wedges up to 0.5 m wide. The middle part of the unit was dated to 142.8±25.3 and >123.2 ~~ka~~ kyr by optically-stimulated luminescence (OSL) and to 210.0±23.0 ~~ka~~ kyr by ~~infrared~~ infrared-stimulated luminescence (IRSL) (Ashastina et al., 2017), pointing to its deposition during MIS 6~~ or even MIS7~~. This age is supported by palaeoecological data (Ashastina et al., 2018). An ~~thin~~ organic-rich ~~layer~~ unit of silty sand with abundant wood~~y~~ and plant remains~~ debris~~ (in lenses up to 3 m thick) overlies a distinct erosional surface near the top of the ~~lower~~ Lower ~~sand~~ Sand unit. A wood fragment yielded a conventional radiocarbon age of 49.32±3.15 ^{14}C ~~ka~~ kyr BP, outside of the range of calibration (Murton et al., 2017), though palaeoecological analysis points to a Last Interglacial age for the organic material (Ashastina et al., 2018).

The overlying **~~upper~~ Upper Ice Complex** is 20–~~40~~25 m thick and dominated by huge syngenetic ice wedges up to few metres wide and at least several metres high within silty and sandy deposits. Finite radiocarbon ages from 49.0±2.0 ~~^{14}C ka BP~~ to 12.66±0.05 ^{14}C ~~ka~~ kyr BP (Ashastina et al., 2017) indicate sedimentation gaps or erosive events and reveal a MIS 3 to ~~late~~ MIS 2 age for the upper part of the ~~upper~~ Upper Ice Complex. This unit has numerous chronostratigraphic analogies in the coastal lowlands of northern Yakutia, i.e. the Yedoma Ice Complex (Schirrmeister et al., 2011b; Murton et al., 2015). The ~~upper~~ Upper Ice Complex forms the highest Pleistocene stratigraphic unit in the upper central part (upslope) of the slump headwall, whereas downslope towards the slump mouth it is overlain and partially grades into the **~~upper~~ Upper ~~sand~~ Sand unit** (Figure 3).

The ~~upper~~ Upper ~~sand~~ Sand is up to about 20 m thick and consists of pore-ice cemented brown to grey sand with narrow (≤ 0.5 m wide) syngenetic ice wedges and composite wedges. Radiocarbon ages between 36.30±0.70 ^{14}C ~~ka~~ kyr BP and 26.18±0.22 ^{14}C ~~ka~~ kyr BP (Ashastina et al., 2017; Murton et al., 2017) indicate deposition during MIS 3 and MIS 2, similar to the ~~upper~~ Upper Ice Complex, but in a more complex spatio-temporal pattern, likely due to varying palaeotopography~~ and~~, sediment supply, and accumulation rates.

A near-surface layer 1–~~-~~1.5 m thick of brown sand and modern soil covers the sequence. This layer was dated to ~~0.~~295±~~0.0~~30 ~~ka~~ ^{14}C yr BP (Ashastina et al., 2017). Distinct (thermo-)erosional contacts can be found between the L~~l~~ower Ice Complex and the ~~lower~~ Lower ~~sand~~Sand, the L~~l~~ower ~~sand~~ Sand and the ~~upper~~ Upper Ice Complex and below the near-surface layer.

According to Murton et al. (2017) exposed floodplains of proximal rivers such as the Batagay~~y~~ and Yana, within 2 and 10 km, respectively, of the slump are the assumed major source of the sediments exposed in the headwall, which implies upslope directed transport by wind. Periglacial~~, proluvial, or~~ and nival processes on nearby hillslopes may also have contributed to sediment supply (Ashastina et al., 2017).

~~The second study site, chosen as a~~For a ~~Late~~ late Holocene reference, we studied an ice wedge at ~~is~~ the actively eroding Holocene to recent bank of a small cut-off channel of the **Adycha River** (67.66°N, 135.69°E, 138 m above sea level), about 40 km east of the Batagay megaslump (Figure 1). The Adycha site is located about 3 km upstream of the 60–~~-~~65 m high and 1.2 km long ~~river~~ river-bluff stratigraphic section at Ulakhan Sullar (Kaplina et al., 1983; Sher et al., 2011; Germonpre et al., 2017). Organic-rich silty sands of alluvial origin are exposed in the Adycha riverbank section.

3 Material and Methods

3.1 Fieldwork

Cryostratigraphic observations of ice wedges, composite wedges, unit contacts and sediments at the Batagay megaslump and a terrace of the Adycha River provided a framework ~~with which we selected samples~~for sample selection. A total of six ice wedges and composite wedges from the L~~l~~ower ~~sand~~Ice Complex, the ~~upper~~ Upper Ice Complex and the ~~upper~~ Upper ~~sand~~ Sand were described in detail and sampled at two sections of the slump (Figures 2, 3). Section 1 was studied in a gully in the icy badlands of the slump~~,~~ (Figure 4), and Section 2 was studied in a headwall slope segment (Figure 5). Composite wedges ~~The~~ of the L~~l~~ower ~~Ice Complex was~~ Sand unit were inaccessible due to dangerous outcrop conditions, and no wedges were observed in the near-surface layer. At the Adycha River, we sampled a single ice wedge.

~~-~~Ice samples about 4 cm wide, mostly in horizontal profiles, were obtained by chain saw. Details about the studied ice and composite wedges are given in Table S1. The ice samples were melted on site in freshly opened standard Whirl-Pak sample bags, and the meltwater filled up 30 ml PE bottles that were then ~~then~~ tightly closed and stored cool until stable-isotope analysis.

In addition, water from small streams draining the slump was sampled in several parts of the slump floor and the main outflow stream (n=7) as well as from summer precipitation (n=4). Supernatant water from selected Batagay megaslump host sediment samples (n=9) was taken for stable-isotope analysis of intrasedimental pore and segregated ice.

3.2 Stable-isotope analysis

The stable oxygen ($\delta^{18}O$) and hydrogen (δD) isotope ratios of all samples were determined at the Stable Isotope Laboratory of the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research in Potsdam, using a Finnigan MAT Delta S mass spectrometer with an analytical precision of better than ±0.1‰ for $\delta^{18}O$ and ±0.8‰ for δD (Meyer et al., 2000). The isotopic composition is expressed in δ per mille values (‰) relative to the V-SMOW standard. The deuterium excess *d* was calculated as $d = \delta D - 8 \times \delta^{18}O$ (Dansgaard, 1964). ~~In some cases~~For three of seven studied wedges, samples were excluded from further analysis (five in total, Table S2) on the basis that they were lateral ~~ice-wedge~~ samples with high sediment content and/or had isotopic values distinctly different from the wedge centres and similar to host sediments, probably due to exchange processes between wedge ice and host sediments (Meyer et al., 2002a; Meyer et al., 2010a)~~were excluded from further analysis~~.

3.3 Radiocarbon dating

We picked ~~O~~organic material from our ~~ice-~~ice-wedge~~s~~ and host sediment samples for ~~s was~~ radiocarbon dating~~ed~~ at the MICADAS ^{14}C dating facility of the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research in Bremerhaven. The organic material was subjected to chemical leaching and cleaning following the ABA (acid–~~-~~base–~~-~~acid) procedure. Material was first submerged in 1 M HCl (for 30 min at 60 °C) to remove carbonate contamination. Following rinsing with Milli-Q water, samples were submerged in 1 M NaOH (for 30 min at 60 °C) to leach out humic acids. The base leaching was repeated for a minimum of 7 times or until no coloring of the solution was evident. Afterwards the material was subjected to a final acid treatment (1 M HCl; 30 min at 60 °C), rinsed to neutral with Milli-Q and dried for a minimum of 12 h at 60 °C. Milli-Q used for cleaning and acid/base solutions was pre-cleaned by liquid–~~-~~liquid extraction with dichloromethane to remove remaining organic contamination.

Samples were packed in tin capsules and combusted individually using an Elementar vario ISOTOPE EA (Elemental Analyzer). If samples were smaller than approximately 200 µgC, the CO_2 produced by combustion with the EA was directly injected into the hybrid ion source of the Ionplus MICADAS using the gas interface system GIS (Fahrni et al., 2013). For larger samples, the CO_2 produced was graphitized using the Ionplus AGE3 system (Automated Graphitization System; (Wacker et al., 2010c). The radiocarbon content of the samples was determined alongside size-matched reference standards (oxalic acid; NIST 4990c) and blanks (phthalic anhydride; Sigma-Aldrich 320065) using the Ionplus MICADAS dating system (Synal et al., 2007; Wacker et al., 2010a), and blank correction and standard normalization were performed using the BATS software (Wacker et al., 2010b). Results are reported as F^{14}C (Reimer et al., 2004) and conventional radiocarbon (^{14}C) ages in years BP. Several analyses yielded lower ^{14}C intensities than the blanks included in the respective sequence. In these cases, results are reported as $F^{14}C_{\text{sample}} < F^{14}C_{\text{blanks}}$. Conventional ^{14}C ages were calibrated using Oxcal 4.3 (Bronk Ramsey, 2009) based on the IntCAL13 dataset (Reimer et al., 2013).

4 Results

4.1 Batagay megaslump

4.1.1 Field observations of ice wedges

The present study confirms cryostratigraphic observations about ice wedges and composite wedges from earlier studies (Ashastina et al., 2017; Murton et al., 2017) and provides new observations about ice-wedge ~~ice ~~relationships across contacts between the cryostratigraphic units, ~~which are~~as ~~outlines ~~outlined below.

In the L~~l~~ower Ice Complex, ice wedges are truncated by a thaw unconformity, though the toes of some narrow syngenetic composite wedges in the overlying L~~l~~ower ~~sand ~~Sand unit extend down across the contact (Figure S1). A single example of clear ice sharply overlying the shoulder of an ~~composite~~ice wedge in the L~~l~~ower ~~sand unit~~Ice Complex (B17-IW1, Figure 4) contained brown plant remains and round, few-mm diameter organic bodies identified as hare droppings. This ice lacked the foliation characteristic of wedge ice and is interpreted as pool ice.

The basal contact of the L~~l~~ower Ice Complex was not observed.

In the L~~l~~ower and ~~upper ~~Upper ~~sand ~~Sand units, narrow syngenetic wedges vary in apparent width from a few centimetres to about 0.5 m. Width commonly varies irregularly with height along individual wedges, sometimes gradually, sometimes abruptly. Wedge height varies from a few metres to at least 12 m. Wedges tend to be oriented approximately at right angle to colour bands in the sand, such that wedges in the ~~upper ~~Upper ~~sand ~~Sand unit—whose bands dip downslope, parallel to the ground surface—are characteristically subvertical, with their tops inclined downslope (Figure S2). The wedge infills grade between end members of ice-wedge ice and icy sand wedges, with slightly sandy ice-wedge ice (i.e. composite wedges) the most common type. ~~A single example of clear ice sharply overlying the shoulder of a composite wedge in the lower sand unit (B17-IW1, Figure 4) contained brown plant remains and round, few-mm diameter organic bodies identified as hare droppings. This ice lacked the foliation characteristic of wedge ice and is interpreted as pool ice.~~

Near the base of the ~~upper ~~Upper Ice Complex, syngenetic ice wedges, a few metres wide tend to narrow downwards in the lower several metres of the unit and terminate with irregular or flattish or U- to V-shaped toes over a vertical distance of about 1–3 m (Figure S2). At the northeast part of the slump headwall, however, the base of the ~~upper ~~Upper Ice Complex is a sharp contact that cuts down into and truncates bands in the underlying L~~l~~ower ~~sand ~~Sand unit over a vertical distance of up to at least several metres (Figure 3). As a result, the ~~upper ~~Upper ~~ice ~~Ice ~~complex ~~Complex thickens substantially downslope.

The top of the ~~upper ~~Upper ~~ice ~~Ice ~~complex ~~Complex displays a variety of wedge relationships with the overlying ~~upper ~~Upper ~~sand ~~Sand unit (Figure S3). Some wide syngenetic wedges terminate along planar to gently undulating contacts that are horizontal to gently dipping and have apparent widths of about 1–3 m; some taper upward into narrow wedges characteristic of the ~~upper~~ Upper ~~sand~~ Sand unit; some taper irregularly upward, marked by shoulders up to about 0.5 m wide; and some end upwards with a narrow offshoot. These changes occur over a vertical distance of about 1–3 m.

4.1.2 Lower ~~sand unit~~Ice Complex (pre-MIS ~~7-~~6)

A small truncated ice wedge B17-IW1 (0.5 m wide, 1.1 m high) from the L~~l~~ower ~~sand unit~~Ice Complex was sampled in section 1 (Figure 4) near the slump bottom, about 50 m below the ground surface ~~(~~and about 5 m below the altitude level in the Lower Sand unit dated by luminescence to 142.8±25.3 and >123.2 ~~ka~~ kyr (~~by~~ OSL) and to 210.0±23.0 ~~ka~~ kyr ~~by~~ (IRSL) (Ashastina et al., 2017). It shows a mean stable-isotope composition of –33.1‰ for δ^{18}O, –256.7‰ for δD, and 8.0‰ for *d* ~~excess~~ (n=6), with very little variability (Table ~~1~~2, Figure 6). The regression line in a δ^{18}O–δD bi-plot is $\delta D = 12.78\ \delta^{18}O + 166.23$ ($R^2 = 0.80$).

The isotopic composition of the intrasedimental ice (n=~~4~~2) shows similar mean δ values (–32.~~6~~5‰ for δ^{18}O, –~~244~~247.~~3~~1‰ for δD), but higher *d* ~~excess~~ values (~~14.7~~12.8‰). The co-isotopic regression line is δD = ~~20.06~~4.09 δ^{18}O ~~+~~ – ~~405.23~~114.27 ~~(R^2 = 0.77)~~.

Radiocarbon dating of twigs, Cyperaceae stems and roots from a sediment sample 0.5 m above the truncated ice wedge yielded nonfinite ages of >53,400 and >37,500 ^{14}C yr BP (Table ~~2~~3). A hare dropping from the ice wedge was dated to 15,792±358 ^{14}C yr BP, which can be only explained by ~~redistribution or~~ contamination with relocated material.

4.1.3 Lower Sand unit (MIS 6)

The isotopic composition of intrasedimental ice (n=2) from the Lower Sand unit shows very little variability (mean –32.3‰ for δ^{18}O, –241.6‰ for δD, 16.6‰ for *d* (Table 2, Figure 6). The co-isotopic regression line is $\delta D = 1.33\ \delta^{18}O - 198.54$.

4.1.~~3~~ 4 Upper Ice Complex (MIS 3–~~-~~2)

Two large syngenetic ice wedges from the overlying ice-rich ~~upper~~ Upper Ice Complex in section 2 (Figure 5) in the southern part of the slump show more depleted isotope values as compared to the ~~lower sand unit~~Lower Ice Complex (Table ~~1~~2, Figure 6). Ice wedge B17-IW6 (about 0.5 m wide, sampled about 26 m below surface, bs) shows a mean isotopic composition of –35.1‰ for δ^{18}O, –269.4‰ for δD, and 11.0‰ for *d* ~~excess~~ (n=4). The co-isotopic regression is $\delta D = 12.25\ \delta^{18}O + 159.79$ ($R^2 = 0.99$). The mean ~~stable-~~ stable-isotope values of ice wedge B17-IW5 (about 1.6 m wide and sampled about 20 m ~~below surface~~bs) are –34.9‰ for δ^{18}O, –271.0‰ for δD, and 8.1‰ for *d* ~~excess~~ (n=12). The regression line in a δ^{18}O–δD bi-plot is $\delta D = 7.41\ \delta^{18}O - 12.36$ ($R^2 = 0.99$). The intrasedimental ice data (n=2) show distinctly enriched mean values (–26.2‰ for δ^{18}O, –195.0‰ for δD, 14.5‰ for *d* ~~excess~~).

Unidentified plant (bract fragments and roots) and insect (complete pieces and fragments of elytron) remains from ice wedge B17-IW6 as well as Cyperaceae remains and roots from host sediment at the lowest studied level in section 2, about 26 m ~~below surface~~bs, both revealed nonfinite ages (>37,500 ^{14}C yr BP; Table ~~2~~3). At the level of about 20 m bs rootlets from the host sediment yielded ages of >37,500 and 47,550±677 ^{14}C yr BP, whereas unidentified plant remains (twigs, roots and florets) from within ice wedge B17-IW5 were dated to 24,858±536 ^{14}C yr BP.

4.1.~~4~~ 5 Upper ~~sand~~ Sand unit (MIS 3-2)

Two narrow sand ~~-~~ice wedges (composite wedges) and one ice wedge were sampled from the rather ice-poor ~~upper~~ Upper ~~sand~~ Sand unit in section 2 (Figure 5) at the southern part of the slump. Composite wedge B17-IW2 (0.25 m wide) was sampled 2.6 and 2.8 m bs, and composite wedge B17-IW3 (0.2 m wide) was sampled 2.0 m bs. The stable-isotope composition of the composite wedges from the ~~upper~~ Upper ~~sand~~ Sand unit differs from those of ~~both underlying units, i.e.~~ the ~~lower sand unit~~Lower Ice Complex and the ~~upper~~ Upper Ice Complex (Table ~~1~~2, Figure 6). The mean values are –32.8‰ and –31.9‰ for δ^{18}O, –247.5‰ and –240.5‰ for δD, and 15.1‰ and 14.7‰ for *d* ~~excess~~ (n=4 and n=2), respectively, and plot well above the Global Meteoric Water Line (GMWL, $\delta D = 8\ \delta^{18}O + 10$) (Craig, 1961)~~)~~. The corresponding regressions are $\delta D = 12.51\ \delta^{18}O + 163.29$ ($R^2 = 0.92$) and $\delta D = 14.47\ \delta^{18}O + 220.91$, respectively.

Ice wedge B17-IW4 (about 0.4 m wide and containing a few thin sand veins) was sampled in the ~~upper~~ Upper ~~sand~~ Sand 2.0 m bs and exhibits a more enriched stable-isotope composition (mean values –29.9‰ for δ^{18}O, –227.8‰ for δD, and 11.6‰ for *d* ~~excess~~ (n=6). The co-isotopic regression is $\delta D = 15.03\ \delta^{18}O + 222.01$ ($R^2 = 0.91$) (Table ~~1~~2, Figure 6).

The intrasedimental ice (n=3) shows similar mean δ values (–30.6‰ for δ^{18}O, –220.0‰ for δD) but higher *d* ~~excess~~ (24.4‰) values compared to the composite wedges and the ice wedges of the ~~upper~~ Upper ~~sand~~Sand. The regression line in a δ^{18}O–δD bi-plot is $\delta D = 10.61\ \delta^{18}O + 104.19$ ($R^2 = 0.99$).

Two radiocarbon ages (analysed as gas) of small samples of *Empetrum nigrum*~~*a*~~ (crowberry) leaf, twigs, and Cyperaceae remains from host sediment about 11 m bs are nonfinite, whereas a graphite target yielded an age of 38,348±236 ^{14}C yr BP.

4.1.~~5~~ 6 Slump outflow

The samples from the outflow stream draining the slump show ~~plot well above the GMWL (Table 1, Figure 6). Their~~ average stable-isotope values ~~are~~ of –31.7‰ for δ^{18}O, –238.6‰ for δD, and 15.2‰ for *d*. ~~excess~~. They plot on a co-isotopic regression line of $\delta D = 8.84\ \delta^{18}O + 41.83$ ($R^2 = 0.97$, n=7), well above the GMWL (Table 2, Figure 6) ~~($\delta D = 8.84\ \delta^{18}O + 41.83$ ($R^2 = 0.97$, n=7)~~.

4.1.~~6~~ 7 Summer precipitation

The samples of summer precipitation at the Batagay megaslump ~~from both sites~~ show much more enriched stable-isotope compositions than the wedges, as expected (Table ~~1~~2). Mean values are –14.3‰ for δ^{18}O, –112.0‰ for δD, and 2.6‰ for *d* (n=4). The samples ~~taken at the Batagay megaslump~~ plot on a co-isotopic regression line of $\delta D = 7.93\ \delta^{18}O + 1.65$ ($R^2 = 1$). ~~Mean values are –14.3‰ for δ^{18}O, –112.0‰ for δD, and 2.6‰ for *d* excess (n=4).~~

4.2 Adycha River

Ice wedge A17-IW3 was about 0.3 m wide and sampled about 1.4 m above river level and about 2 m below the ground surface. Its mean stable isotope values are –29.0‰ for $\delta^{18}O$, –226.3‰ for δD, and 5.5‰ for *d* ~~excess~~ (n=10, Table ~~1~~2, Figure 6). The regression line in a $\delta^{18}O$–δD bi-plot is $\delta D = 7.01\ \delta^{18}O$ –~~-~~ 23.25 ($R^2 = 0.99$).
Rootlets and larch needles from the host sediment were dated to 213±109 ^{14}C yr BP and confirm the Late Holocene age of the alluvial sediments and the ice wedge.

5 Discussion

5.1 Chronostratigraphy of the Batagay megaslump

To date, the exceptionally long record of permafrost history under highly continental climate conditions as ~~preserved~~ exposed in the Batagay megaslump is still not entirely established in terms of its geochronology. Previous studies by Ashastina et al. (2017) and Murton et al. (2017) provide the general differentiation into four main units with ice and/or composite wedges overlain by Late Holocene cover deposits, which are the L~~l~~ower Ice Complex (pre-MIS 6), the L~~l~~ower ~~sand~~ Sand unit (MIS ~~7-~~6), the ~~upper~~ Upper Ice Complex (MIS 3–~~-~~2) and the ~~upper~~ Upper ~~sand~~ Sand unit (MIS 3–~~-~~2). Thaw unconformities as observed in sampled sections of this study (Figure 4, Figure 5), but also in previous studies (Ashastina et al., 2017; Murton et al., 2017) question the ~~completeness~~ chronological continuity of the archive. Such (thermo-)erosional features are often observed in late Quaternary permafrost chronologies (e.g. Wetterich et al., 2009) and most likely caused by intense permafrost degradation during warm stages such as the Last Interglacial with widespread thermokarst (Reyes et al., 2010; e.g. Kienast et al., 2011) or exceptionally warm interstadials, but might also relate to palaeotopography and respective accumulation and erosion areas. The Batagay megaslump, on account of its huge dimensions and rapid erosion, holds potential ~~The Batagay megaslump exposes the single stratigraphic units in different contacts. Its complex structure, the rapid erosion and the huge dimensions, however, hold potential~~ to identify additional records and units in future studies. With the present study and additional radiocarbon dating, further confidence of the existing stratigraphy is reached, although the wedge-ice derived age information ~~asks for~~requires careful interpretation. Due to the formation mechanism and downward directed growth of wedge ice, organic remains from inside the ice are commonly younger than those of the host deposits at the same altitude (i.e. sampling depth). The risk ~~to date~~of dating redeposited organic material, that entered into or later froze onto the surface of ice recently exposed in a slump, is ~~always given~~common, in particular in erosional features such as ~~a~~ slump-floor ~~with~~ gullies. It can be seen in the truncated **L~~l~~ower ~~sand unit~~Ice Complex** (Figure 4) where an age of about 16 ^{14}C ~~ka~~ kyr BP was obtained from the ice wedge, while radiocarbon dates of the host deposit are infinite and luminescence ages of the overlying Lower Sand unit reach 142.8±25.3 ~~ka~~ kyr and >123.2 ~~ka~~ kyr by OSL as well as 210.0±23.0 ~~ka~~ kyr by IRSL (Ashastina et al., 2017). We therefore excluded this anomalously young radiocarbon age from further interpretation.

A distinct ~~layer~~ unit of wood and ~~other~~ plant remains up to ~~1.5~~3 m thick and traceable along the exposure is situated ~~above~~ near the top of the L~~l~~ower ~~sand~~ Sand unit and below the ~~upper~~ Upper Ice Complex. Radiocarbon dating of this layer revealed an infinite radiocarbon age of >44 ^{14}C ~~ka~~ kyr BP (Ashastina et al., 2017) as well as an ~~out~~ out-~~of~~ of-calibration age of 49.32±3.15 ^{14}C ~~ka~~ kyr BP (Murton et al., 2017). The palaeobotanic proxy data indicate a warm climate. The plant macro-fossil record is characterized by considerable species richness (34 species), mainly representing northern Taiga forests, including larch and birch trees, shrub alder and raspberry and further representatives of the taiga's understorey. Hence the unit is aligned to the Last Interglacial (Ashastina et al., 2018), ~~that~~ which caused particular thaw of the underlying L~~l~~ower ~~sand~~ Sand unit and formed a disconformity~~rdance in the sequences~~.

The expected difference between ice-hosted and sediment-hosted ages of the same sample depth is clearly seen in the **~~upper~~ Upper Ice Complex**, where organic remains from the ice wedge are dated to about 25 ^{14}C ~~ka~~ kyr BP and the host deposits yield nonfinite to about 48 ^{14}C ~~ka~~ kyr BP ages (Figure 5). However, even though the age offset is very large and a contamination of the dated sample in the field cannot be fully excluded, such information may be reliable and lies within the previously dated overall accumulation period of the ~~upper~~ Upper Ice Complex between about 49 and 13 ^{14}C ~~ka~~ kyr BP (Ashastina et al., 2017; Murton et al., 2017).

The new radiocarbon ages from the **~~upper~~ Upper ~~sand~~ Sand unit** largely confirm the assumed accumulation period of this unit from about 36 to 26 ^{14}C ~~ka~~ kyr BP (Ashastina et al., 2017; Murton et al., 2017), but predate it by about 2000 years, at least with a date of about 38 ^{14}C ~~ka~~ kyr BP and nonfinite ages of >37.5 ^{14}C ~~ka~~ kyr BP from the host deposits. We note that the ~~upper~~ Upper ~~sand~~ Sand unit has been studied at two different sites of the slump in different altitude levels (north-northeast of the central headwall (Ashastina et al., 2017; Murton et al., 2017) and together with the ~~upper~~ Upper Ice Complex more downslope in the southern part of the slump~~,~~ (Figure 2), which complicates the correlation of dating results from different sampling sites. Furthermore, close to our section 2, the ~~upper~~ Upper ~~sand~~ Sand could not clearly be differentiated from the ~~upper~~ Upper Ice Complex during fieldwork in 2014 (Ashastina et al., 2017). Hence, the more or less simultaneous accumulation of both the ~~upper~~ Upper Ice Complex and the ~~upper~~ Upper ~~sand~~ Sand unit during MIS 3–~~-~~2 but their differing spatial distribution in the slump highlights the importance of palaeo-topography in a hillslope setting and varying sediment sources and velocities of deposition and require future sampling and analysis at higher vertical resolution.

Interestingly, no indications for an ~~upper~~ Upper ~~sand~~ Sand ~~layer~~ unit have been found in the top~~most part~~ of the modern headwall on the upslope part of the slump. Additionally, there are no significant Holocene deposits exposed at all in the upper part of the slump. However, carcasses of *Equus lenensis* and ~~baby~~ juvenile *Bison priscus* (dated to 4.45±0.35 ~~ka ^{14}C BP~~ and 8.22~~15~~ +0.45/-0.40 ~~ka~~ kyr ^{14}C BP, respectively) were found at the exit of the slump (Murton et al., 2017). These observations may be related to (a) the palaeo-topographic situation and transport and deposition regimes of windblown ~~dust~~ material during MIS 3–~~-~~1, likely decreasing upslope, (b) widespread permafrost degradation since the Late Glacial~~-~~–Early Holocene transition, and/or (c) changed hydrological and vegetation patterns in the Holocene preventing transport and/or deposition of windblown ~~dust~~sediment.

The **L~~l~~ower Ice Complex** is not dated so far. Given the dating results of the overlying L~~l~~ower ~~sand~~ Sand unit it ~~may~~ might correspond to the Yukagir Ice Complex from Bol'shoy Lyakhovsky Island, which has been dated by radioisotope disequilibria (^{230}Th/U) in peat to 178±14 kyr, 221±27 ~~ka~~ kyr (Wetterich et al., 2019) and ~~to~~ 201±3 ~~ka~~ kyr (Schirrmeister et al., 2002). Hence this unit most likely has survived ~~two~~ both the last and current interglacials. Dating such an old Ice Complex is challenging as the dating approaches are limited and partly still in development. Independently dated tephra layers have been proven useful to date old permafrost in east Beringia, i.e. in Alaska (Schirrmeister et al., 2016) and in Yukon (Froese et al., 2008). However, no tephra layers have been identified yet in the study region due to the long distance from active volcanos. But with its clearly defined stratigraphy and the access to very old permafrost and ice wedges, the Batagay megaslump may be a suitable site to evaluate and further develop the ice-wedge dating approaches using ^{36}Cl/Cl$^-$ (Blinov et al., 2009) as well as uranium isotope methods (Ewing et al., 2015). To better constrain the chronostratigraphy of the exposed units a systematic dating approach is needed, which should additionally include independent dating of host sediments, e.g. by luminescence.

5.2 Cryostratigraphy at the Batagay megaslump – implications for ice-wedge growth regime

The shape and composition of the wedges in the Batagay megaslump correspond to the assumed genesis of the respective units and may also provide palaeoclimate information (Table ~~3~~4). Both the L~~l~~ower and ~~upper~~ Upper Ice Complex units are characterized by ice wedges up to several m wide, whereas both the L~~l~~ower and ~~upper~~ Upper ~~sand~~ Sand units contain tall narrow wedges. The former indicates more stable surface conditions with lower ~~accumulation~~ rates of sand aggradation and sufficient melt water supply during the formation of both Ice Complexes that allowed more horizontal growth of ice wedges. The tall narrow wedges of both sand units, in contrast, point to rapid ~~upslope~~ upslope-directed aeolian deposition of ~~sediments~~ sand and, therefore, a predominant vertical ice-wedge growth in persistent polygonal patterns. The downslope inclination of narrow syngenetic wedges in the ~~upper~~ Upper ~~sand~~ Sand unit indicates upward growth subvertically at right angle to the aggrading depositional (hillslope) surface~~, a hillslope~~. The tall and narrow wedges in the sand units are similar in size and shape to chimney-like sand wedges in thick aeolian sand sheets in the Tuktoyaktuk Coastlands of western Arctic Canada, attributed to rapid aggradation of aeolian sand and rapid wedge growth (Murton and Bateman, 2007). ~~Ice~~ The ~~wedges in the lower sand unit point to moister conditions than the~~ composite wedges in the Lower and ~~upper~~ Upper ~~sand~~ Sand units~~, which~~ imply dry conditions with only little melt water supply. However, as most ice wedges exhibit a significant sediment content, a steady supply of windblown sediment and a rather thin snow cover during ice-wedge formation is likely.

At the top of the ~~upper~~ Upper Ice Complex, ice wedges tend to narrow and partly transform into narrow composite wedges of the ~~upper~~ Upper ~~sand~~ Sand unit (Figure S3). This indicates a rather gradual change of the deposition regime towards higher sedimentation rates and possibly lower melt water supply due to drier conditions. Interestingly, the polygonal pattern has not been affected by this change, as indicated by the consistent frost-cracking positions. The upward transition of wedges from the ~~upper~~ Upper ~~ice~~ Ice ~~complex~~ Complex to ~~upper~~ Upper ~~sand~~ Sand unit, however, was interrupted episodically by thaw, producing a number of thaw unconformities at different depths. In contrast, the erosional event truncating the L~~l~~ower Ice Complex seems to have changed the polygonal pattern in which the L~~l~~ower ~~sand~~ Sand unit has been deposited.

A major erosional surface attributed to gullying by water flowing down a palaeo-hillslope is inferred from the large concave-up lower contact of the ~~upper~~ Upper ~~ice~~ Ice C~~c~~omplex in the northeast part of the headwall (Figure 3). Numerous gullies on the present hillslope near the megaslump are indicated on satellite images between 1968 and 2010 ~~reported by~~ (Kunitsky et al., 2013), which suggests that gullies are characteristic landforms of such terrain under present environmental conditions. Water is supplied to such gullies by snowmelt in spring and rainfall and melt of ground ice in summer. Erosion of the underlying L~~l~~ower ~~sand~~ Sand unit provided substantial accommodation space for development of an unusually thick ~~upper~~ Upper I~~i~~ce ~~complex~~ Complex with wide ice wedges above it. Stratigraphically, this erosional surface is at a similar level as the upper woody ~~trash~~ debris layer that is thought to be of last interglacial age (Ashastina et al., 2017; Ashastina et al., 2018), which in turn suggests that the erosion also probably took place during warm (i.e. interglacial) conditions.

5.3 Yana Highlands' ice-wedge stable isotopes – regional palaeoclimate implications

Unfortunately, no comprehensive modern precipitation stable-isotope data are available for the Yana Highlands. The nearest sites with available data are Zhigansk, about 500 km to the west (Kurita, 2011)~~,~~; Tiksi, about 500 km to the northwest (Kloss, 2008)~~–~~; and Yakutsk, about 650 km to the south (Kloss, 2008; Papina et al., 2017). These sites show similar isotopic characteristics for the cold season (October to March). Mean δ^{18}O values decrease along the north–~~-~~south transect from about –~~-~~29‰ in Tiksi to –~~-~~31‰ in Yakutsk, and *d* ~~excess~~ varies strongly without a clear geographical pattern and shows values between about 8 and 15‰. In general, the mean winter δ-values~~isotopic~~ ~~data~~ plot around the GMWL. However, these sites are characterized by less cold winters compared to the Yana Highlands. Furthermore, they are located east and south, respectively, of the Verkhoyansky Range (Figure 1), ~~that~~ which constitutes an orographic barrier for atmospheric moisture transport ~~from~~ by the westerlies and thereby contributes to the extreme cold and dry winters of the Yana Highlands. Hence, more depleted δ^{18}O values can be expected for winter precipitation.

The Yana Highlands' ice-wedge ~~stable~~ stable-isotope data form two major clusters (Figure 6, Table 2). The regression of the first cluster (cluster 1) plots below but mainly parallel to the GMWL ($\delta D = 7.45\ \delta^{18}O – 10.46, R^2=1$) ~~(Figure 6)~~ and comprises ice wedges B17-IW1 (~~lower sand unit~~Lower Ice Complex), B17-IW5, B17-IW6 (both ~~upper~~ Upper Ice Complex) and A17-IW3 (recent Adycha riverbank). The regression of the second cluster (cluster 2) plots clearly above the GMWL ($\delta D = 6.88\ \delta^{18}O – 21.72, R^2=0.97$) and comprises all data from the ~~upper~~ Upper ~~sand~~ Sand unit (composite wedges B17-IW2, B17-IW3, ice wedge B17-IW4). ~~The sediment-rich ice wedge B17-IW6 (upper Ice Complex) plots in-between the clusters.~~ Furthermore, all except one of the intrasedimental-ice samples as well as all slump outflow samples—interpreted as integrated signal of the entire exposed Batagay sequence—plot well above the GMWL. In summary, the higher the sediment content of our samples, the higher are the *d* ~~excess~~ values and, hence, the offset above the GMWL. The composite and ice wedges from the Upper Sand unit, likely formed in a generally dry environment (section 5.2), exhibit high *d* values (cluster 2). In contrast, the ice wedges from cluster 1, likely formed under moister conditions with more abundant melt water supply, show lower *d* values. This suggests that the divergence from cluster 1 (or the GMWL), i.e. higher *d*, might be an indicator of drier conditions.~~Considering the cryostratigraphic interpretation of composite-wedge and ice-wedge formation, the high *d* excess~~

~~values in the wedges from the upper sand unit might also be related to a generally dry environment during sediment deposition and wedge formation, whereas the lower *d* excess values of the other cluster might point to more abundant melt water supply during ice-wedge formation.~~

Generally, the high *d* ~~excess~~ values indicate a higher kinetic fractionation at the moisture source, e.g. due to initial evaporation under low relative humidity and/or high sea-surface temperature conditions (Pfahl and Sodemann, 2014). As we are dealing with cold-stage MIS 3–2 ground ice, a changed moisture source region might be more likely than generally higher sea-surface temperatures compared to the Late Holocene as reflected by the ice wedge A17-IW3. As the cold season in ~~Eastern~~ east Siberia is characterized by higher *d* ~~excess~~ values than the warm season, one might conclude that ~~cold~~ cold-season precipitation does not only feed the ice and composite wedges but also contributes significantly to the formation of intrasedimental ice. However, secondary fractionation during snow cover evolution under extremely continental conditions with a generally lower snow cover, and snow melt containing only a fraction of the initial snow~~, refreezing~~ might also affect *d* preserved in wedge ice (Opel et al., 2018; Grinter et al., 2019). For intrasedimental ice, too, ~~and~~ multiple freeze–thaw cycles in the active layer ~~may also affect *d* excess in wedge and intrasedimental ice~~have to be taken into account.

The regional palaeoclimatic implications for the Yana Highlands drawn from our ice-wedge δ^{18}O data are summarised in Table ~~3~~4 together with palaeoecological results from Ashastina et al. (2018). ~~Extremely~~ The lowest winter temperatures of our dataset ~~(δ^{18}O values around -35‰)~~ are indicated ~~recorded~~ by δ^{18}O values around –35‰ for~~the~~ ice wedges from the Upper Ice Complex, which ~~has~~ formed during the MIS 3 interstadial (Kargin interstadial in Siberian stratigraphy). Similar values including *d* ~~excess~~ have been reported by Vasil'chuk et al. (2017) for three undated ice wedges from the ~~upper~~ Upper Ice Complex sampled close to the headwall of the Batagay megaslump (Figure 3). ~~Very low winter~~Slightly higher temperatures during the formation of the Lower ~~lower sand unit~~Ice Complex ~~during~~ before MIS 6 ~~(Taz stadial)~~ are ~~also~~ indicated by δ^{18}O values around –33‰. However, given the small size of the corresponding ice wedge, the old age and rather similar isotope values of intrasedimental ice in the host deposits some postdepositional alteration of the originally recorded signal (Meyer et al., 2002a; Meyer et al., 2010a) cannot be excluded. Hence, these values should be treated with caution. ~~Very low to low~~Comparable and slightly higher winter temperatures can be inferred for composite wedges (δ^{18}O values around –33‰ and –32‰) and an ice wedge (δ^{18}O values about –30‰) from the ~~upper~~ Upper ~~sand~~ Sand unit, which is attributed to the transition from MIS 3 to ~~MIS~~ 2. Again, similar values have been reported by Vasil'chuk et al. (2017) for an undated narrow ice wedge from the ~~upper~~ Upper ~~sand~~ Sand unit sampled in another part of the Batagay megaslump (Figure 3). However, the palaeoclimatic significance of the rather small composite wedges with few samples has to be treated with caution. Ice wedge B17-IW4 might even be an epigenetic ice wedge of Holocene age, given the quite similar δ^{18}O values (about –29‰) of the definitively Holocene ice wedge from the Adycha river bank (A17-IW3), which indicate ~~moderate to low~~higher winter temperatures in the last centuries to millennia. These values are close to those of modern winter precipitation at Tiksi, Zhigansk and Yakutsk. As modern ice wedges are ~~there is usually~~ enriched by several per mill in δ^{18}O compared to modern winter snow cover ~~an offset between the stable-isotope composition of modern snow cover and wedge ice~~ (Grinter et al., 2019; Opel et al., 2018), ~~these values~~we suggest that ~~the~~

modern winter precipitation in the Yana Highlands is isotopically distinctly more depleted than that at Tiksi, Zhigansk and Yakutsk.

No palaeoclimatic information based on ice-wedge isotopes is available yet from Batagay for the MIS 4 (Zyryan) and MIS 2 (Sartan) stadials. ~~However, a~~ On~~t~~ Bol'shoy Lyakhovsky Island ~~in northeastern Siberia~~ of the New Siberian Archipelago ice wedges from both periods show $\delta^{18}O$ values about 6‰ lower than those of MIS 3 Ice Complex ice wedges (Wetterich et al., 2011; Opel et al., 2017b; Wetterich et al., 2019). Hence, even more depleted $\delta^{18}O$ values ~~of about −40‰ could~~ might be expected in ~~LGM~~ ice wedges of Last Glacial Maximum age at the Batagay megaslump. However, we note that distinctly depleted $\delta^{18}O$ values for MIS 4 and 2 have been found only at Bol'shoy Lyakhovsky Island.

When interpreting ice-wedge stable isotopes in terms of absolute palaeotemperatures one has to keep in mind that the isotopic composition of the oceanic moisture source has changed over glacial-interglacial timescales, with enrichment in $\delta^{18}O$ in the ocean water during past cold stages. Correcting the ice-wedge stable isotopes for this effect requires detailed knowledge about the moisture source region and in particular a better constrained chronology of ice-wedge isotopes than is available from our dataset.

In general, the inferred lower winter temperatures meet the expectations of an increased continentality during the Late Pleistocene cold stages as well as partly drier conditions indicated by the formation of composite wedges. Palaeoecological analysis (plant macrofossil remains, pollen and beetles) of Batagay megaslump deposits (Ashastina et al., 2018) indicates generally much drier conditions compared to recent times (Table ~~3~~4), in particular during the cold stages. Tree and beetle indicators imply warm summers for most units, whereas macrofossil remains indicate cold to very cold winters for the ~~upper~~ Upper Ice Complex. These patterns are generally in line with our ice-wedge interpretation and support the hypothesized higher continentality.

5.4 Large-scale implications for palaeoclimate and past continentality

~~The spatial significance of our data can be considered in terms of the upper Ice Complex of the Batagay megaslump, formed in the MIS3 Kargin interstadial (about 50 to 30 ka ago) as well as the Holocene.~~

5.4.1 MIS 3 interstadial wedge ice records

To assess the climate and continentality across much of west~~ern~~ Beringia during the MIS 3 ~~Kargin~~ interstadial, we compare our Yana Highlands ice-wedge stable-isotope data to a dataset of 17 other ice-wedge sites (Figure 1, Figure 7). Most of the wedges are from the Yedoma Ice Complex (Schirrmeister et al., 2011b; Schirrmeister et al., 2013), which is widely distributed in east and central Siberia. We selected ~~one~~ all available ice wedges per study site ~~in this analysis and only those~~ that provide both $\delta^{18}O$ and *d* ~~excess~~ data (Table ~~S2~~S3). Additionally, all except two of the considered wedges or their host sediments have been directly dated by radiocarbon methods to between about 50 and 30 ~~ka~~ kyr ago (MIS 3 interstadial). We appreciate that an ice wedge may not contain a full record of this time period and that the climate was not uniform throughout this period.~~;~~ It is, however, not clear yet whether millennial-scale climate oscillations known from the North Atlantic region (e.g. Dansgaard et al., 1993) also characterized the MIS 3 in east Siberia. Following Murton et al. (2017), there are hints that the MIS 3 in northern areas of northeast Siberia was a time of general climate stability even though the interstadial climate was not monolithic. I~~i~~n particular, a warmer period around 40 ~~ka~~ kyr BP is well known from several palaeoecological proxies for some of the study sites (Wetterich et al., 2014) and from ice wedges of the well dated Bykovsky Peninsula section (Meyer et al., 2002a).

The Batagay ~~upper~~ Upper Ice Complex ice wedge B17-IW5 ~~(and the sediment-rich ice wedge B17-IW6, which has not been included in this analysis as well as the data of Vasil'chuk et al. (2017))~~ shows δ^{18}O values of around –~~-~~35‰, which is 6 to 2‰ lower than MIS 3 ice-wedge δ^{18}O data from ~~today’s coastal lowlands of~~ northern Yakutia, the Kolyma region and central Yakutia (Figure 8). As hypothesized, the relatively depleted δ^{18}O values from Batagay clearly point to lower ~~MIS3~~ winter temperatures during MIS 3 in the Yana Highlands than ~~in the other regions~~elsewhere, probably due to the more continental location framed by the partially glaciated Verkhoyansky and Chersky ranges reaching elevations of more than 2,000 m above sea level. Even the ice-wedge δ^{18}O data from highly continental sites in central Yakutia do not reach such low δ~~delta~~ values as observed in the Batagay ice wedges. Interestingly, the lowest MIS 3 δ^{18}O values beside Batagay originate from the northeastern-most site, Novaya Sibir’ Island. If an Atlantic moisture source for MIS 3 wedge ice is assumed, Novaya Sibir’ would represent the farthest location from the source region and therefore show ~~much~~ strongly depleted δ^{18}O values, almost reaching those of Batagay.

The peculiarity of the Yana Highlands is also apparent in the *d* ~~excess~~ data of the MIS 3 ice wedges. The Batagay ice wedges exhibit the highest *d* values, between 8 and 11‰, in the data set. Similar values have been found in ice wedges from central Yakutia, whereas today’s coastal lowlands of northern Yakutia, the Laptev Sea islands and the Kolyma region sites show values between 2 and 7‰ (Figure 9). Again, from all northern sites, Novaya Sibir’ Island shows the value closest to those of the Yana Highlands and central Yakutia.

Little is known about *d* variation in northeast Siberian ice wedges in general, and particularly within specific time periods. Previous studies have interpreted changes in the *d* values between the Late Pleistocene (low values) and Holocene (higher values) as changes in the moisture sources and transport pathways following the retreat of the Eurasian ice sheets (Meyer et al., 2002a; Meyer et al., 2002b). Higher *d* values in central Yakutia and the Verkhoyansk Mountain forelands have also been found in modern winter snow along a west-to-east transect over east~~ern~~ Siberia from Yakutsk to Magadan (Kurita et al., 2005). This spatial pattern has been attributed to the influence of different moisture sources, with greater kinetic effects during initial evaporation, as resulting from a lower relative humidity (Kurita et al., 2005). Analogously, during MIS 3, the Yana Highlands and central Yakutia may have received precipitation from other moisture sources and/or transport pathways compared to more northern sites. Due to their more southern location, the Yana Highlands might have received a contribution of moisture from a more southerly source, e.g. the Mediterranean~~ source~~. Such moisture usually has higher *d* ~~excess~~ values compared to North Atlantic moisture (Gat et al., 2003) and may have reached this region via a different southern moisture transport pathway.

5.4.2 Holocene

The mean $\delta^{18}O$ values of the Holocene ice wedge sampled at the Adycha River also point to lower winter temperatures—due to greater continentality—than other Holocene ice wedges in the data set. The Adycha samples (mean $\delta^{18}O$ –~~-~~29‰) are more depleted than Holocene wedges from northeast Siberian coastal sites, which show typically mean $\delta^{18}O$ values between –~~-~~27 and –~~-~~23‰ (e.g. Meyer et al., 2002b; Meyer et al., 2015; Opel et al., 2017a; Wetterich et al., 2018). Holocene ice wedges from the Bykovsky Peninsula (Meyer et al., 2002a) show exceptional values (mean $\delta^{18}O$ of –~~-~~28 to –~~-~~26‰), which do not fit into the regional pattern and may be related to local climate or environmental effects. In contrast, Holocene ice wedges from central Yakutia exhibit mean $\delta^{18}O$ values of –~~-~~28 to –~~-~~26‰ (Popp et al., 2006), which are closer to those from the Yana Highlands and also reflect the greater continentality and lower winter temperatures than the Holocene coastal sites.

The *d* values from Holocene ice wedges in Siberia are highly variable. Mean *d* values at the coastal sites are higher (compared to MIS 3), ~~with values~~ between 4 and 12‰ (e.g. Opel et al., 2011; Meyer et al., 2002b; Wetterich et al., 2008; Wetterich et al., 2018). In contrast, in the Yana Highlands the Late Holocene mean *d* value of 6‰ is lower compared to ~~the~~ MIS 3, whereas Late Holocene *d* values in central Yakutia (between 6 and 11‰) are rather similar to MIS 3 values (Popp et al., 2006). The exceptional ice wedges from the Bykovsky Peninsula (Meyer et al., 2002a) even reach *d* values of 16‰. In summary, Holocene ~~ice~~ ice-wedge *d* ~~excess~~ values do not show a clear spatial pattern that is readily interpret~~e~~able~~d~~ in terms of moisture sources or continentality.

6 Conclusions and outlook

Our stable-isotope data clearly show that winter temperatures in the Yana Highlands during MIS 3, represented by the ~~upper~~ Upper Ice Complex (Yedoma) at Batagay, and the Holocene were ~~significantly~~ distinctly lower than at other ice-wedge study sites in coastal and central Yakutia. This indicates the persistence of enhanced continentality of the Yana Highlands region during at least part of the Late Pleistocene in west~~ern~~ Beringia and during the Holocene. The stable-isotope data from narrow composite wedges of the ~~upper~~ Upper ~~sand~~ Sand unit (MIS 3–~~-~~2) and an old ice wedge from the ~~lower sand unit~~Lower Ice Complex (pre-MIS 6) are less indicative and require additional studies.

High-resolution systematic sampling and dating now needs to be carried out for all cryostratigraphic units of the Batagay permafrost sequence to validate our findings of increased continentality during MIS 3 and the Holocene, to improve the temporal resolution of the Batagay ice-wedge record, and to elucidate the palaeoclimatic history from other time slices. Of particular interest are the lower and uppermost parts of the ~~upper~~ Upper Ice Complex, likely representing MIS 4 and ~~MIS~~2 stadials, as well as more detailed studies of the yet undated L~~l~~ower Ice Complex~~, possibly representing late MIS7 or early MIS6~~. To establish reliable ice-wedge chronologies for the Upper Ice Complex and Upper Sand unit, radiocarbon dating should include macro remains, dissolved organic carbon and CO_2 from gas bubbles (Lachniet et al., 2012; Kim et al., 2019). Additionally, previous luminescence dating results (Ashastina et al., 2017) need to be validated. ~~Finally, the Batagay~~

~~megaslump may be an appropriate study site to validate and further develop ice-wedge dating approaches using ^{36}Cl/Cl (Blinov et al., 2009) as well as uranium isotope methods (Ewing et al., 2015).~~

Author contributions

Thomas Opel initiated and designed the present study and wrote the paper with contributions by the other co-authors. Thomas Opel, Julian Murton, and Kseniia Ashastina sampled and described ground ice and host sediments, supported by Petr Danilov and Vasily Boeskorov. Hanno Meyer carried out stable-isotope analyses and supported the interpretation. Hendrik Grotheer and Gesine Mollenhauer conducted the radiocarbon dating. Frank Günther provided GIS analysis and maps. Sebastian Wetterich and Lutz Schirrmeister collected ice-wedge data for comparison and supported data analysis and interpretation. All co-authors contributed to the final discussion of the results and interpretations.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We would like to thank Erel Strutchkov for support of fieldwork as well as Luidmila Pestryakova and Waldemar Schneider for organisation of export of samples. Mikaela Weiner supported stable-isotope analysis. Thomas Opel and Sebastian Wetterich acknowledge funding from German Research Foundation (DFG grants OP217/3-1, OP217/4-1 and WE4390/7-1, respectively). Frank Günther was supported by ERC #338335 and by DAAD with funds from BMBF and the EU's Marie Curie Actions Programme, REA grant agreement #605728 (P.R.I.M.E.).

Data availability

The new ice-wedge and new ^{14}C data presented in this paper as well as the ice-wedge data used for spatial comparisons will be made available at https://www.pangaea.de after acceptance of this paper.

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Table 1. Cryostratigraphic units of the Batagay megaslump as presented by Ashastina et al. (2017) and Murton et al. (2017) and the reconciled stratigraphic framework used in this study and proposed for future studies.

Ashastina et al. (2017)		**Murton et al. (2017)**		**This study**
Unit	**Description**	**Unit**	**Description**	**Unit**
Unit I	Active layer	Unit 6	Near-surface sand	Near-surface layer
Unit II	Yedoma Ice Complex	Unit 5	Upper sand	Upper Sand
		Unit 4	Upper Ice Complex	Upper Ice Complex
Unit III	Organic-rich layer	Woody lens	Woody lens	Wood and plant remains
Unit IV	Layered brown sands	Unit 3	Lower sand	Lower Sand
Unit V	Ancient Ice Complex	Unit 2	Lower Ice Complex	Lower Ice Complex
-	-	Unit 1	Diamicton	Diamicton

Table ~~1~~2. Stable isotope (δ^{18}O, δD and *d* ~~excess~~) minimum, mean and maximum values, standard deviations as well as slopes and intercept in the δ^{18}O–~~-~~δD diagram for all ice and composite wedges, intrasedimental ice, outflow water and rain water, respectively.

Ice wedge/ Type of water	Width (m)	Samples (n)	δ^{18}O min (‰)	δ^{18}O mean (‰)	δ^{18}O max (‰)	δ^{18}O sd (‰)	δD min (‰)	δD mean (‰)	δD max (‰)	δD sd (‰)	*d* min (‰)	*d* mean (‰)	*d* max (‰)	*d* sd (‰)	Slope	Intercept	R^2
Batagay megaslump																	
Upper ~~sand~~ Sand unit																	
B17-IW2 (CW)	0.25	4	-33.04	-32.83	-32.47	0.25	-250.2	-247.5	-242.8	3.3	13.7	15.1	16.9	1.5	12.51	163.29	0.92
B17-IW3 (CW)	0.2	2	-32.14	-31.87	-31.60	0.38	-244.2	-240.3	-236.4	5.5	12.9	14.7	16.4	2.4	14.47	220.91	1.00
B17-IW4	0.4	6	-30.10	-29.93	-29.71	0.13	-229.6	-227.8	-223.9	2.2	10.0	11.6	13.8	1.3	15.03	222.01	0.82
Intrased. ice	n/a	3	-32.61	-30.55	-29.21	1.82	-242.2	-220.0	-207.3	19.3	18.7	24.4	28.2	5.1	10.61	104.19	0.99
Upper Ice Complex																	
B17-IW5	1.6	12	-36.17	-34.89	-33.50	0.86	-280.6	-271.0	-260.8	6.4	6.8	8.1	10.3	0.9	7.41	-12.36	0.99
B17-IW6	0.5	4	-35.52	-35.05	-34.27	0.57	-274.9	-269.4	-259.7	7.0	8.5	11.0	14.4	2.5	12.25	159.79	0.99
Intrased. ice	n/a	2	-27.63	-26.19	-24.75	2.04	-198.5	-195.0	-191.5	5.0	6.5	14.5	22.5	11.3	2.44	-131.03	1.00
Lower Sand unit																	
Intrased. ice	n/a	2	-32.31	-32.28	-32.24	0.05	-241.6	-241.6	-241.6	0.1	16.4	16.6	16.8	0.3	1.33	-198.54	1.00
Lower ~~sand unit~~Ice Complex																	
B17-IW1	0.5	6	-33.18	-33.09	-32.91	0.10	-258.3	-256.7	-254.8	1.5	6.9	8.0	9.4	0.8	12.78	166.23	0.80
Intrased. ice	n/a	~~4~~2	-32.56	~~-32.38~~-32.48	~~-32.24~~-32.39	~~0.14~~0.13	-247.4	~~-244.3~~-247.1	~~-241.6~~-246.7	~~3.2~~0.5	12.4	~~14.7~~12.8	~~16.8~~13.1	~~2.3~~0.5	~~20.06~~4.09	~~405.23~~-114.27	~~0.77~~1.00
Other																	

Outflow water	n/a	7	-32.29	-31.73	-31.35	0.34	-244.0	-238.6	-235.4	3.1	14.3	15.2	16.1	0.6	8.84	41.83	0.97
Rain water	n/a	4	-16.82	-14.33	-10.17	2.92	-131.7	112.0	-79.0	23.1	2.3	2.6	2.9	0.2	7.93	1.65	1.00
Adycha River																	
Holocene river bank Adycha River																	
A17-IW3	0.3	10	-30.40	-28.98	-28.15	0.74	-236.6	-226.3	-220.5	5.2	4.4	5.5	7.3	0.9	7.01	-23.25	0.99
Ice-wedge cluster																	
Cluster 1	(B17-IW1, B17-IW5, B17-IW6, A17-IW3)														7.45	-10.46	1.00
Cluster 2	(B17-IW2, B17-IW3, B17-IW4)														6.88	-21.72	0.97

Table ~~2~~3. Radiocarbon ages of organic remains in ice wedges (sample ID includes IW) and host sediments of the Batagay megaslump and at the Adycha River. The samples were radiocarbon dated as gas targets (Lab ID ends with 1.1) and graphite targets (Lab ID ends with 2.1).

Sample ID	Depth (m bs)	Lab ID	$F^{14}C$	Radiocarbon age (yr BP)	Calibrated age 95.4% (cal yr b2k)	Dated material	Remarks
Batagay megaslump							
Upper ~~sand~~ Sand unit							
B17-S2-AMS4-1	11	1689.1.1 1689.2.1	<0.0094 0.0084±0.0002	>37,500 38,348±236	n/a 42,863–42,140	*Empetrum nigrum~~a~~* leaf, twigs, Cyperaceae remains (sediment)	
B17-S2-AMS4-2	11	1690.1.1	<0.0094	>37,500	n/a	Cyperaceae stems and roots (sediment)	
Upper Ice Complex							
B17-IW5-02	20.3	1684.1.1	0.0453±0.0030	24,858±536	30,355–27,926	unidentified plant (twigs, roots and florets) remains (ice wedge)	
B17-IW6-04	25.8	1686.1.1	<0.0094	>37,500	n/a	unidentified plant (bract fragments and roots) and insect (complete pieces and fragments of elytron) ~~unidentified plant and insect remain~~ (ice wedge)	
B17-S2-AMS5	20.3	1691.1.1 1691.2.1	<0.0094 0.0027±0.0002	>37,500 47,550±677	n/a >50,033	leaf fragment, roots (sediment)	
B17-S2-AMS6	25.8	1692.1.1	<0.0094	>37,500	n/a	Cyperaceae remains, roots (sediment)	
Lower ~~sand unit~~Ice Complex							
B17-IW1-04	~50	1683.1.1	0.1400±0.0062	15,792±358	20,044–18,402	hare dropping (ice wedge)	Likely redistributed
B17-S1-AMS2	~49.5	1688.1.1 1688.2.1	<0.0094 <0.0013	>37,500 >53,400	n/a n/a	twigs, Cyperaceae stems and roots (sediment)	
Adycha River							
Holocene river bank Adycha River							
A17-K-03	2	1687.1.1	0.9738±0.0132	213±109	<514	rootlets and ~~larix~~ *Larix* needle (sediment)	

Table ~~3~~4. Summary ~~table on~~ of past climate in the Yana Highlands. Palaeoecological interpretations are from (Ashastina et al., 2018) and based on fieldwork in 2014.

Unit **Ice wedge** **Chronology**	**Cryostratigraphy**	**Interpretation**	**IW isotopes**	**Interpretation**	**Palaeoecological interpretation**
Adycha, river bank Ice wedge A17-IW3 Late Holocene to recent	Narrow ice wedge, little sediment	Moist (high melt water supply)	δ^{18}O: ~~-~~−29‰ *d*~~-excess~~: 7‰	Cold ~~winters~~and rather moist winters	-
Batagay, ~~upper~~ Upper ~~sand~~ Sand unit Composite wedges B17-IW2–~~/~~3 MIS 3–~~/~~2	Narrow composite wedges	Dry (little snow melt water) and/or high sediment supply	δ^{18}O: ~~-~~−33‰, ~~-~~−32‰ *d*~~-excess~~: 15‰	Dry winters colder than in the Holocene ~~Very cold to cold winters dry winters~~	Dry summers, T_{july} >12°C (trees)
Batagay, ~~upper~~ Upper ~~sand~~ Sand unit Ice wedge B17-IW4 MIS 3–~~/~~2	Narrow ice wedge, little to medium sediment content	Rather moist (higher melt water supply compared to composite wedges)	δ^{18}O: ~~-~~−30‰ *d*~~-excess~~: 12‰	Cold and rather dry winters ~~rather dry winters~~ (Epigenetic Holocene IW?)	Dry summers, T_{july} >12°C (trees)
Batagay, ~~upper~~ Upper Ice Complex Ice wedge B17-IW5 MIS 3	Wide ice wedge, little to medium sediment content	(rather) moist (high melt water supply)	δ^{18}O: ~~-~~−35‰ *d*~~-excess~~: 8‰	Coldest and ~~Extremely cold winters~~ rather moist winters	Dry and (very) warm summers, very cold and dry winters (beetles)
Batagay, ~~upper~~ Upper Ice Complex Ice wedge B17-IW6 MIS 3	Medium ice wedge, high sediment content	Rather dry (drier than IW5, moister than IWs 2/3)	δ^{18}O: ~~-~~−35‰ *d*~~-excess~~: 11‰	Coldest and ~~Extremely cold winters~~ rather dry winters	Dry summers, cold winters
Batagay, ~~lower~~ Lower ~~sand unit~~Ice Complex Ice wedge B17-IW1 Pre-MIS 6	Narrow ice wedge, little sediment content	Moist, high melt water supply	δ^{18}O: ~~-~~−33‰ *d*~~-excess~~: 8‰	~~Very cold winters~~Winters warmer than in MIS 3 and rather moist ~~winters~~	~~Dry summers, T_{july} >12°C (trees)~~

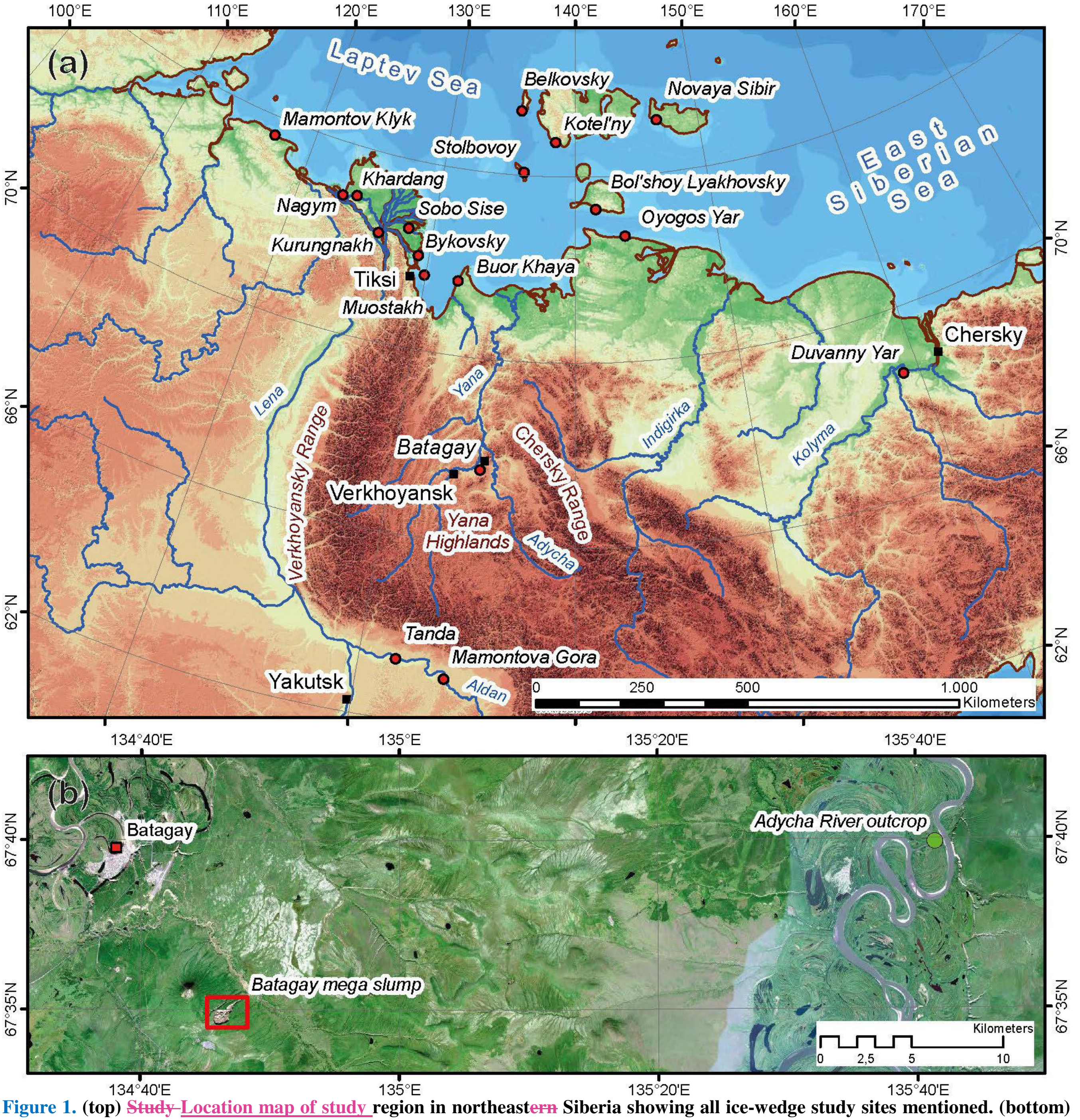

Figure 1. (top) ~~Study~~ Location map of study region in northeast~~ern~~ Siberia showing all ice-wedge study sites mentioned. (bottom) Study sites in the Yana Highlands (Background image: Sentinel-2 mosaic, August 7, August 21, 2017).

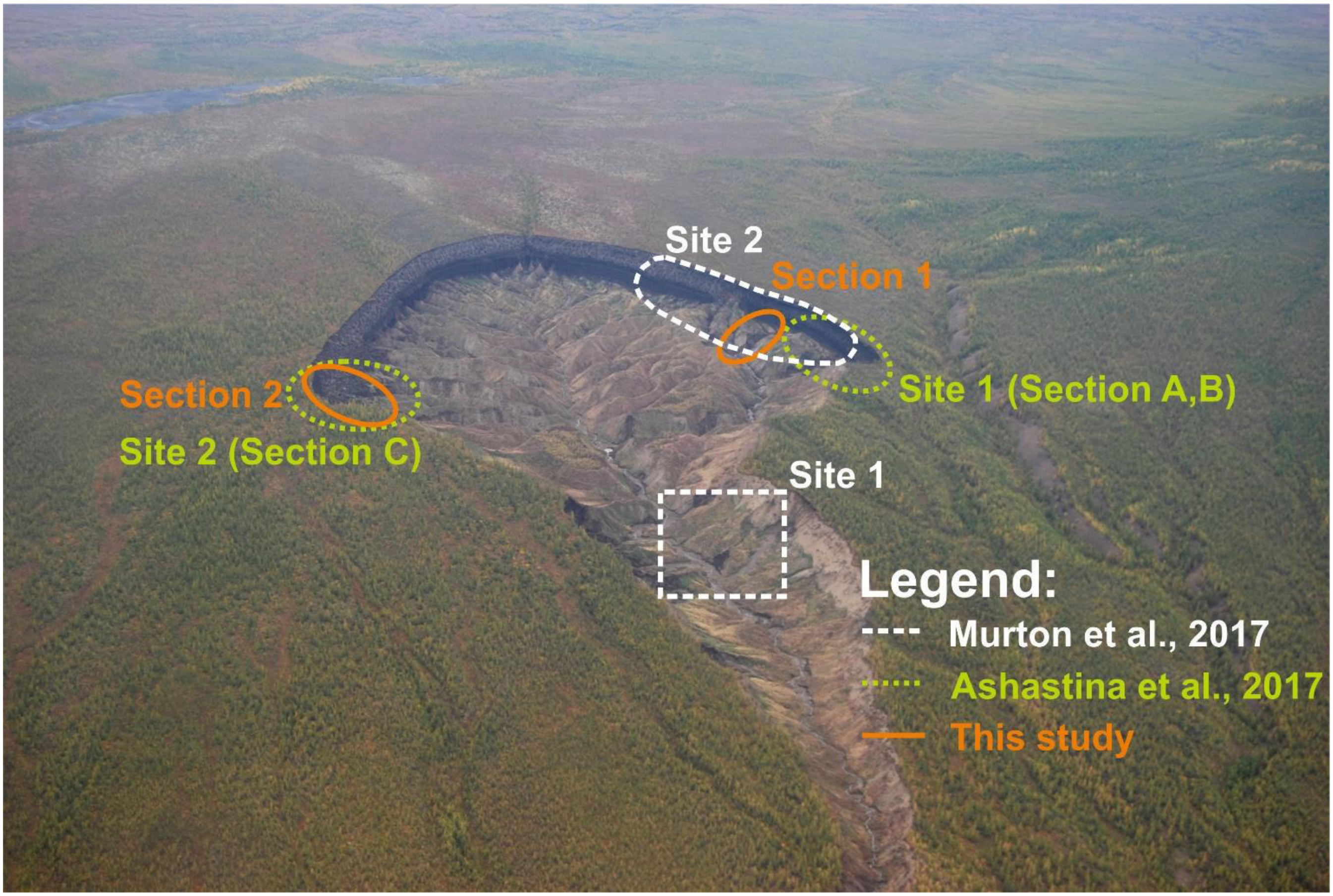

Figure 2. Overview photograph of the Batagay megaslump showing the study sites of (Ashastina et al., 2017; Murton et al., 2017) and this study. Photograph taken by Alexander Gabyshev in 2015.

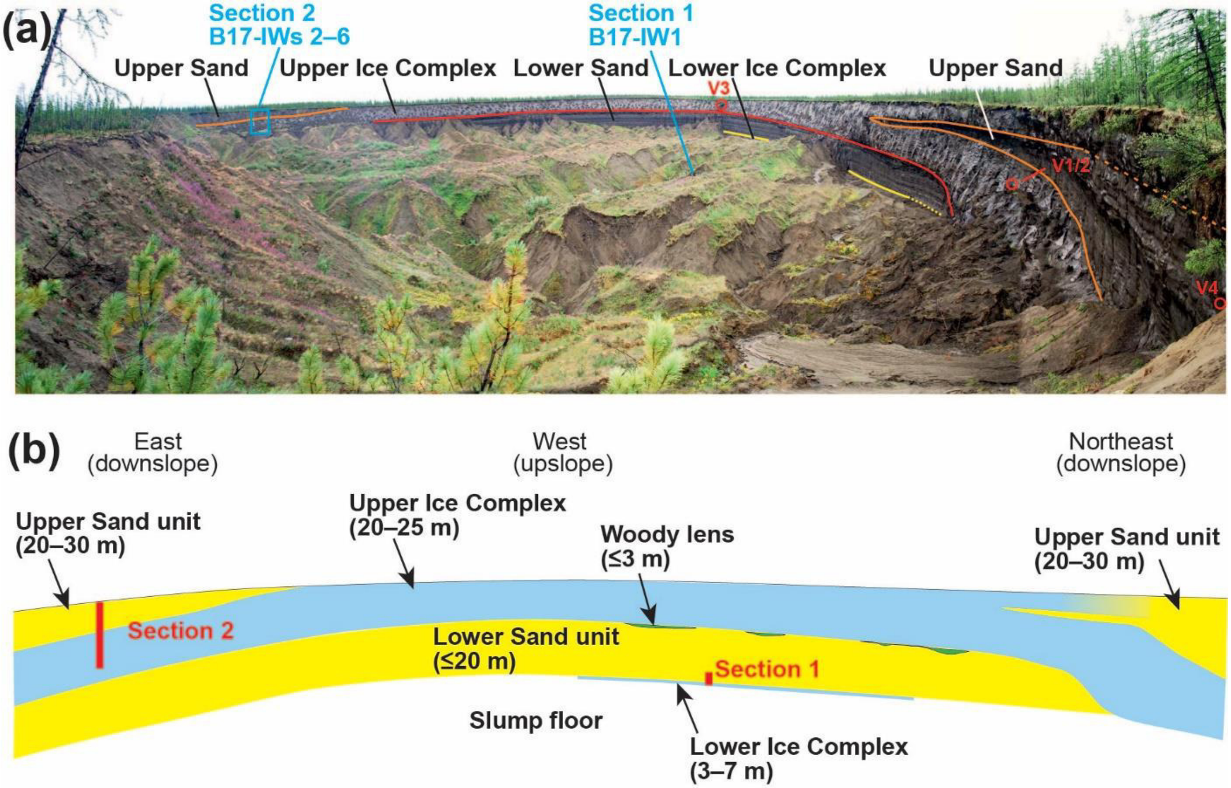

Figure 3. (a) Panoramic photograph of the Batagay megaslump with main stratigraphic units and approximate sampling locations of ice wedges (blue arrows). ~~Furthermore,~~R ~~r~~ed circles and numbers indicate the approximate sampling locations of ice wedges used by (Vasil'chuk et al., 2017)~~.~~, (b) Schematic stratigraphic section of the exposed units along the headwall of the Batagay megaslump with approximate positions of the studied sections.

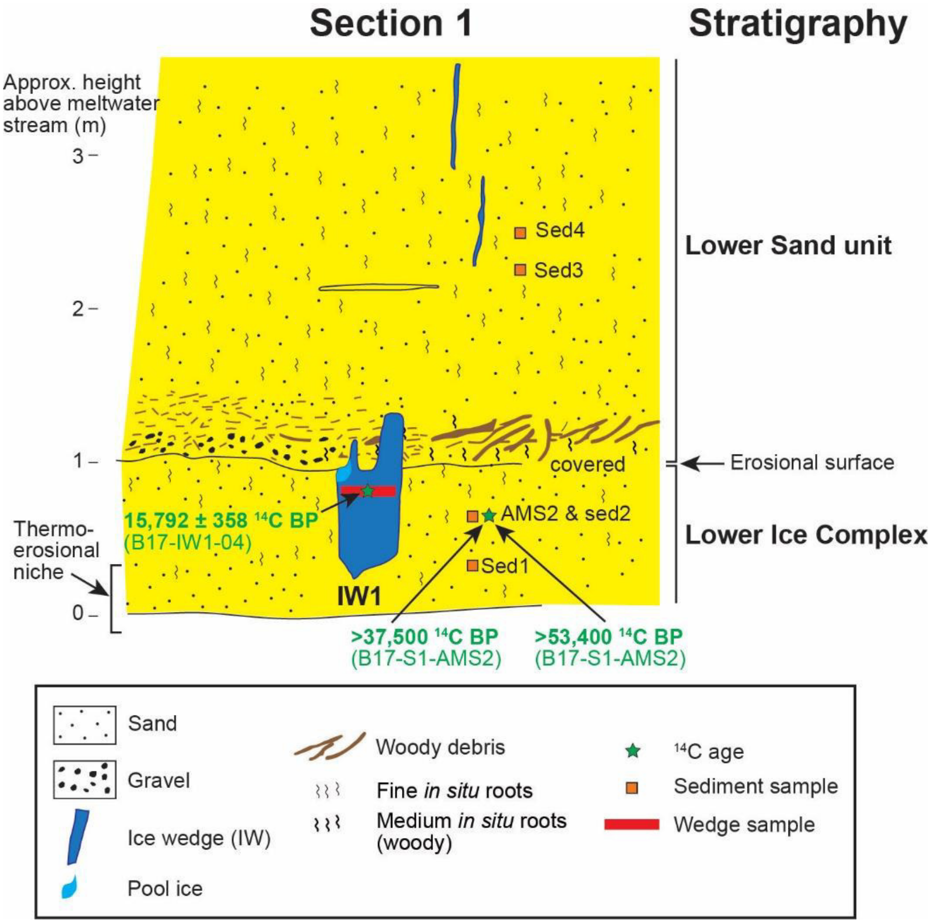

Figure 4. **Schematic ~~cryostratigraphy~~ cryostratigraphic sketch of Section 1, Batagay megaslump.**

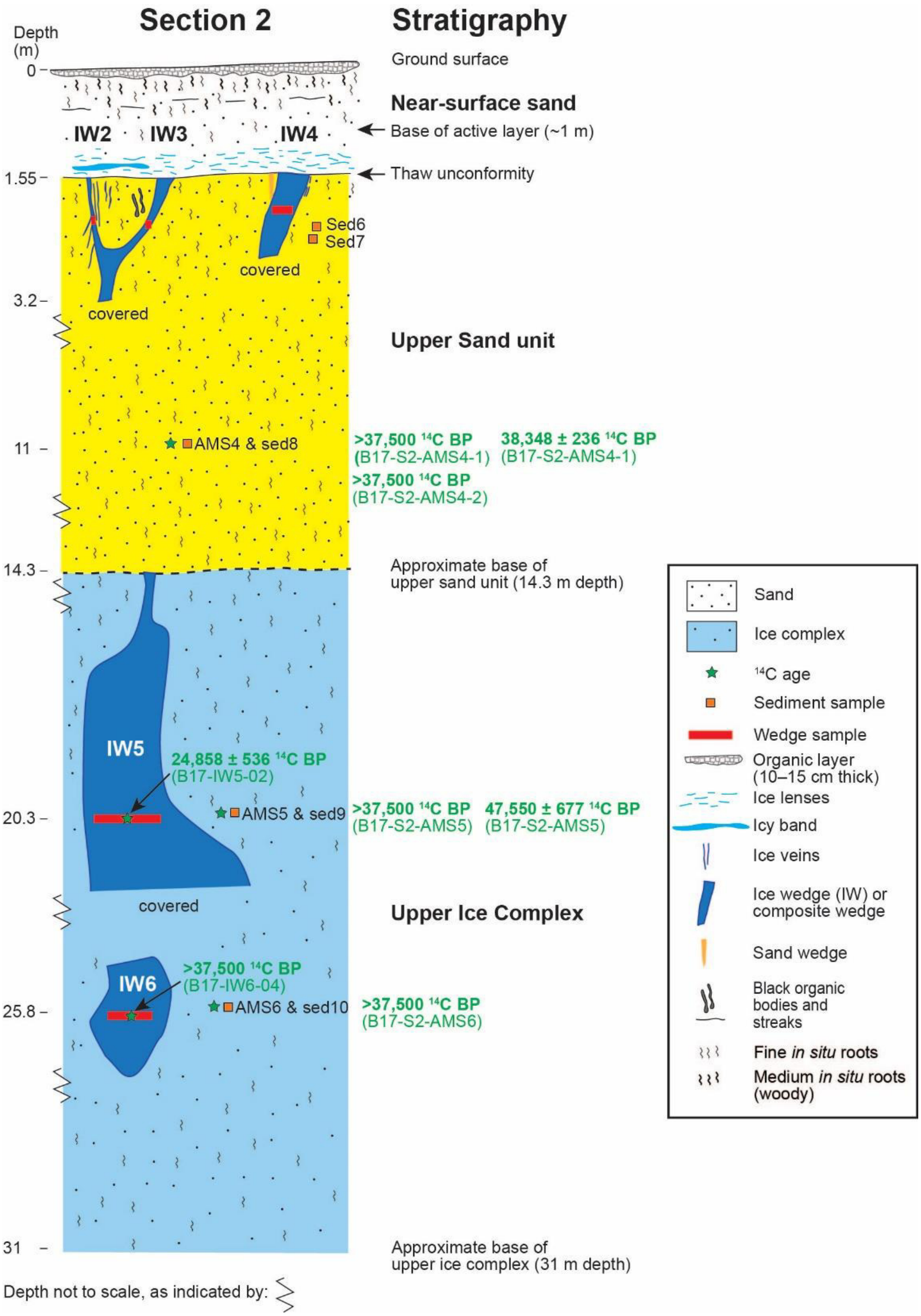

Figure 5. Schematic ~~cryostratigraphy~~ cryostratigraphic sketch of Section 2, Batagay megaslump.

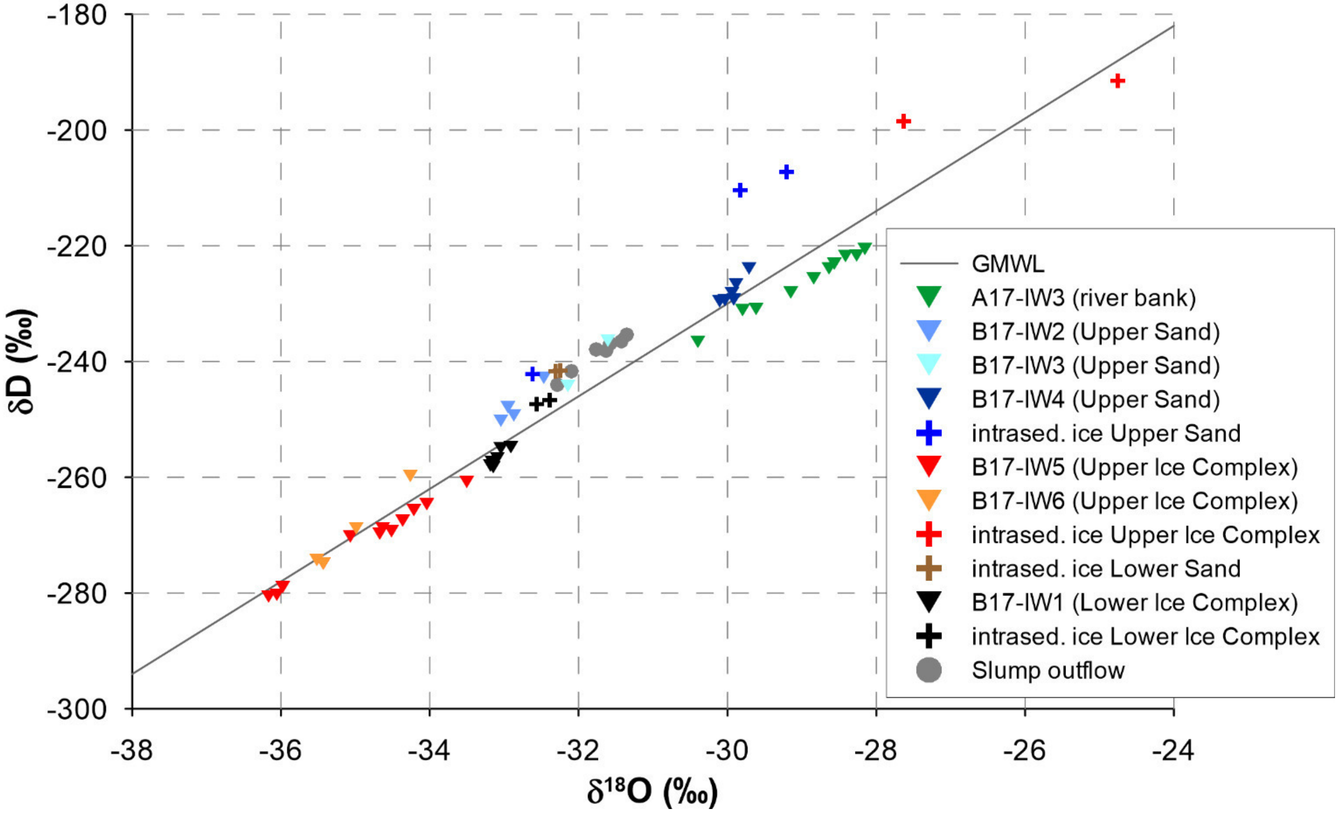

Figure 6. Co-isotopic δ^{18}O–~~-~~δD diagram of ice wedges and intrasedimental ice sampled at the Batagay megaslump and the Adycha River. ~~Furthermore, the~~ The data ~~of~~ from the Batagay megaslump outflow samples ~~are shown which display~~record an integrated signal of the entire Batagay permafrost sequence and modern precipitation.

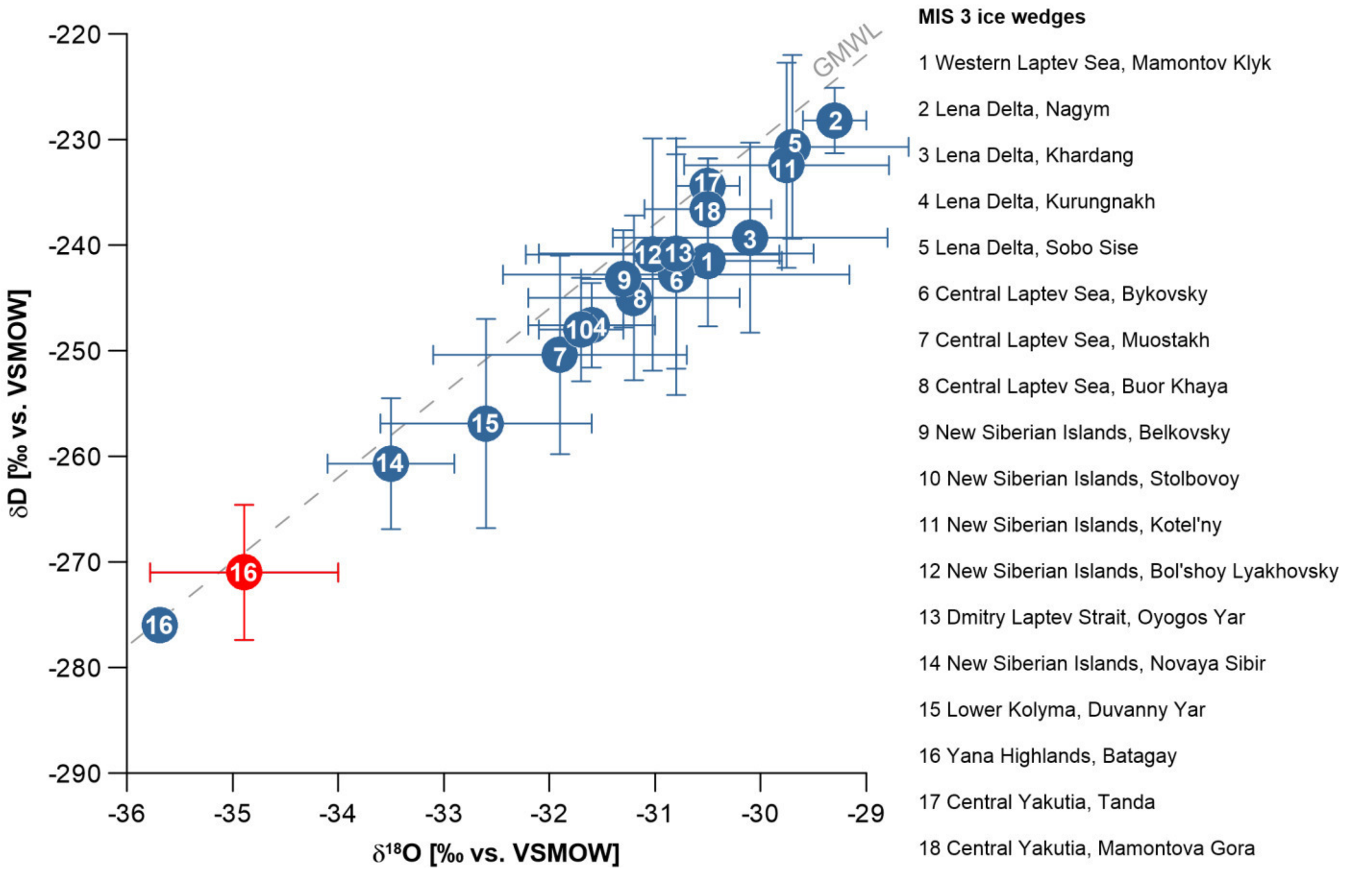

Figure 7. Comparison of stable isotope data from Siberian ice wedges attributed to the ~~Kargin~~ MIS 3 interstadial (about 50 to 30 ~~ka~~kyr), comprising data from the ~~Western~~ western Laptev Sea (Magens, 2005), the Lena River Delta (Schirrmeister et al., 2003; Schirrmeister et al., 2011a; Wetterich et al., 2008; Opel, unpublished), the ~~Central~~ central Laptev Sea (Meyer et al., 2002a; Meyer/Opel, unpublished; Schirrmeister et al., 2017), the New Siberian Islands and the Dmitry Laptev Strait (Schirrmeister, unpublished; Wetterich et al., 2014; Opel et al., 2017b), the Kolyma Lowland (Strauss, 2010), the Yana Highlands (this study; Vasil'chuk et al., 2017), and ~~Central~~ central Yakutia (Schirrmeister, unpublished; Popp et al., 2006). The new data from Batagay are marked in red. Further information is given in Table ~~S2~~S3.

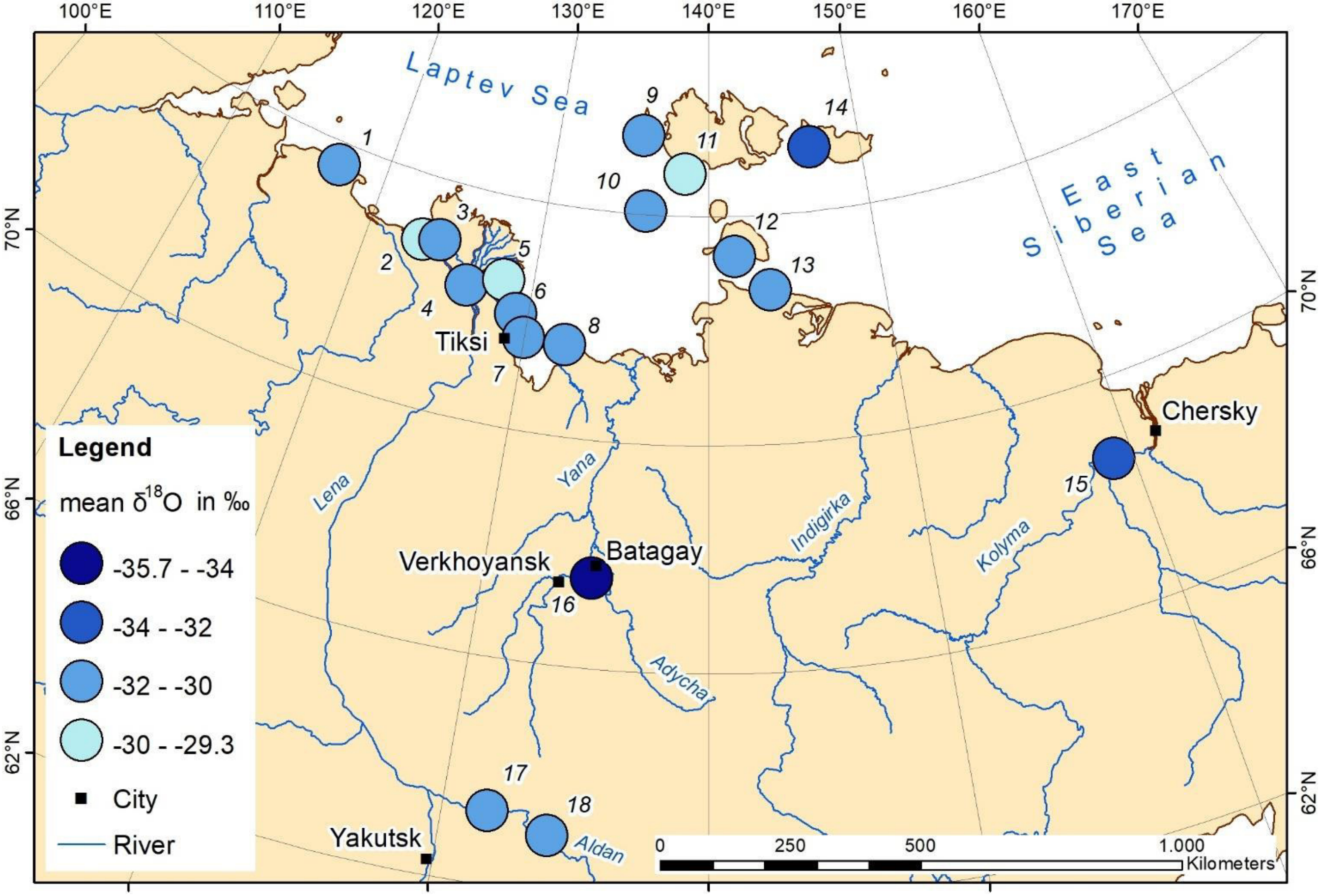

Figure 8. Map of mean δ^{18}O data from Siberian ice wedges attributed to the ~~Kargin~~ MIS 3 interstadial (about 50 to 30 ~~ka~~kyr), Site IDs are given in Figure 7 and further details in Table ~~S2~~S3.

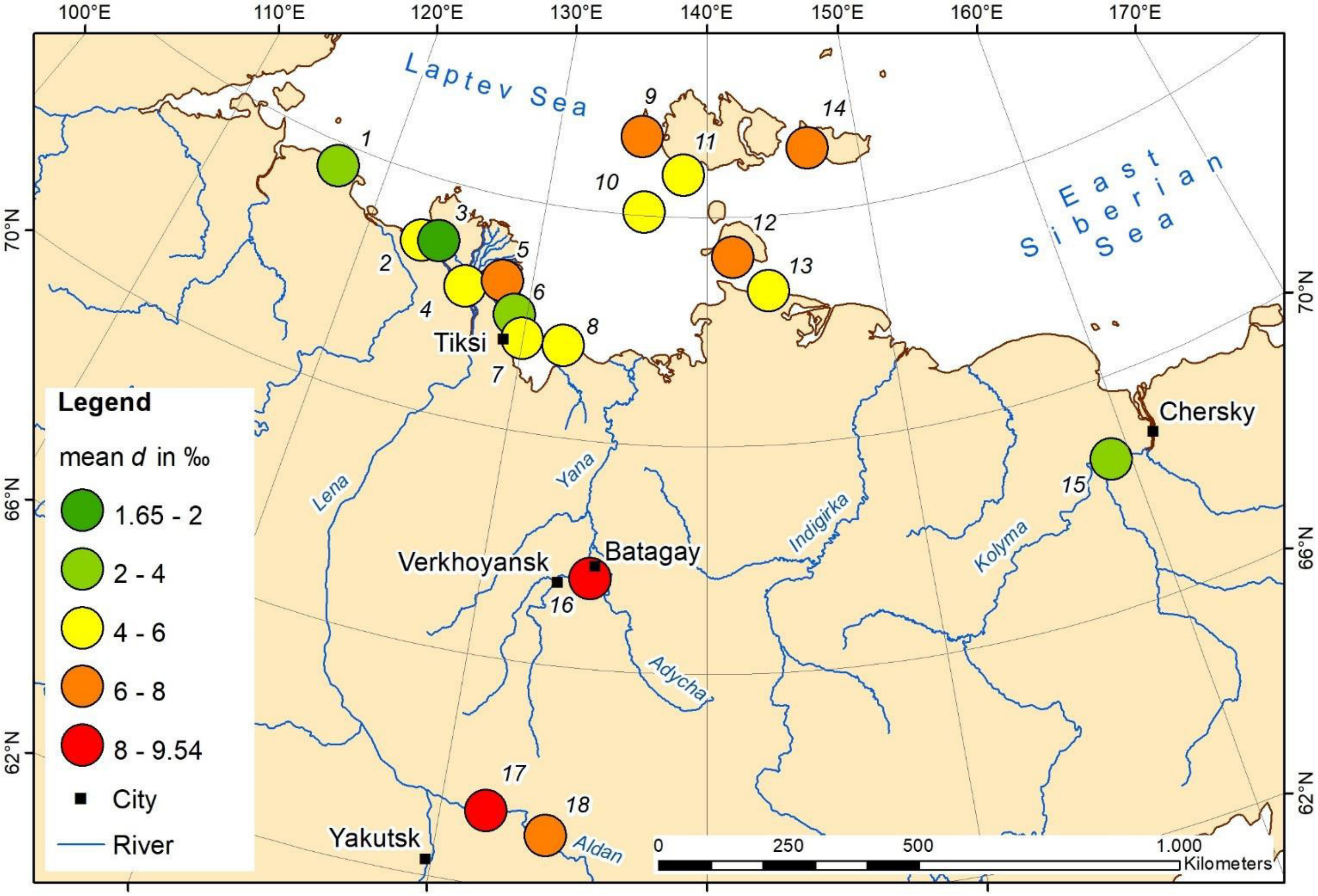

Figure 9. Map of mean *d* data from Siberian ice wedges attributed to the ~~Kargin~~ MIS 3 interstadial (about 50 to 30 ~~ka~~kyr), Site IDs are given in Figure 7 and further details in Table ~~S2~~S3.