Detailed review replies and track changes of

Organic Carbon Characteristics in Ice-rich Permafrost in Alas and Yedoma Deposits, Central Yakutia, Siberia

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Interactive comment on

“Organic Carbon Characteristics in Ice-rich Permafrost in Alas and Yedoma Deposits, Central Yakutia, Siberia” *by* Torben Windirsch et al.

Anonymous Referee #1

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The paper “Organic Carbon Characteristics in Ice-rich Permafrost in Alas and Yedoma Deposits, Central Yakutia, Siberia” by Windirsch et al. reports detailed analyses on carbon and ice contents, stable water isotopes, soil grain size distribution, and age estimates for two long ground profiles in the Central Yakutia, Russia. The presented materials are rare and highly valuable to understand landscape development and con- tents in the permafrost of the Eastern Siberia.

Thank you very much for acknowledging the general importance of the data presented in our paper. We are grateful for the review and acknowledge the reviewer’s comments, which really improved and strengthened the paper.

Although I expect this paper to be finally published in Biogeoscieces, the authors have not fully utilized, described, and discussed the data presented. The importance of this paper is the rareness of the sample core. I encourage the authors to enrich their descriptions about each core unit as a valuable drilling log of a permafrost region. Some portions in Discussion are not logically constructed. For the main datasets of stable water isotopes and carbon parameters, a more in-depth and quantitative discussion is anticipated.

Thank you very much. We worked on the point raised above. Besides detailed work on the manuscript, we added the core log as well as all core pictures to the PANGAEA database.

Although the authors want to focus on the organic carbon characteristics as indicated in the title, more comprehensive discussion and interpretation must be done using available water geochemistry, cryostratigraphy, grain size distribution, magnetic susceptibility, etc. The usage of references or previous studies is poor and is often not clear or inappropriate.

As stated by the reviewer, the focus of the study has been the carbon characteristics. All other data is included to decipher the general changes of the landscapes and to have further evidence on the causes of carbon changes. We agree to add more comprehensive discussion of the background data and extended the result part and discussion for these. Major changes can be found in the result section, as well as in the discussion.

The discussion of sedimentation rates and their changes is problematic and too speculative. Radiocarbon age of bulk soil organic matter (SOM) usually much less reliable than that of macro plant remains. In permafrost environments, old (easily more than ten thousand years) *carbon can co-exist in the same sedimentation stage, or younger carbon can be incorporated in a deeper layer.*

Thank you. We are aware of the dating problem and added this to the results section. Moreover we added an uncertainty statement to the section where we addressed sedimentation rates: “In addition, the dating of bulk sediments very close to the maximum datable age of ~ 50,000 yr BP may cause a high uncertainty in the absolute ages of sediment layers“. The reason for taking bulk samples for dating was also extended by ”We used bulk sediment samples for dating due to a lack of macro-organic remains within the deposits.”

High mobility of SOM and geomorphological processes such as thermokarst and cryoturbation give a large uncertainty to sedimentation processes. Without rigorous consideration about the validity of the age model based on bulk SOM, the discussion about the changes in sedimentation rates does not make sense.

As stated above, we added a statement for the age model. Besides doing the statistical-based modelling, this is the best we could get out of the organic poor sample material.

As the authors explained, the upper part of the Alas1 accumulated by Yedoma deposit thaw. The Yedoma thaw involves differential ground subsidence and mixing of ground material through the thermokarst processes, which induce destruction of original stratification. The authors should discuss the limitations of the obtained dating data and build further discussion only based on reliable information. Below, I listed individual points to be revised or to be clearly explained in the revised manuscript to achieve a publication quality.

Thank you very much for this detailed work on improving the age discussion.

P1-L25-26: What is “a potential theory of Holocene influence”?

With “potential theory of Holocene influence” we tried to put emphasis on the fact that there could have been Holocene input signals in the core. In our case we saw that the water isotope signals are indicating a permanently frozen state, making this Holocene deposition unlikely.
The sentence was changed to: “Pore water isotope data from the Yedoma core indicated a continuously frozen state except for the surface sample, thereby ruling out Holocene reworking.”

P1-L30: What do you mean “. . . the Yedoma core can be duplicated.”?

Thanks for pointing to this unclear wording. This means that similar low-carbon layers were found in the Alas core as well.
We changed it to: ”Similar to the Yedoma core, some sections of the Alas core were also OC poor (< 0.1 wt%) in 17 out of 28 samples.”

P1-L31-36: The authors describe using numerous “different” and “differ” works, but I suggest to revise to explain them more concretely. I could not understand how different.

We change this as suggested:

Changed to “With its coarse sediments with low OC content (OC mean of 5.27 kg/m³), the Yedoma deposits in the Yukechi area differ from other Yedoma sites that were generally characterized by silty sediments with higher OC contents (OC mean of 19 kg/m³ for the non-ice wedge sediment).”

L36: How the Alas core gives clear insights?

The Alas core shows how the Yukechi Yedoma may transform under future thawing processes, as the deposits of the Alas core have once been very similar to “today’s” Yedoma deposits but then started thawing. To clarify this, we have changed the sentence to: “The Alas core, strongly affected by extensive thawing processes during the Holocene, indicates a possible future pathway of ground subsidence and further OC decomposition for thawing Yakutian Yedoma deposits.”

P2-L16: Why Yedoma deposits highly vulnerable to thaw? Usually, high-ice content permafrost is more robust to thaw because of larger latent heat storage than drier permafrost. We can say Yedoma is highly susceptible to thermokarst though.

Thank you for making this point. We clarified as follows: Yedoma is highly vulnerable to thaw induced landscape changes due to loss of excess ice. We added this to the respective sentence. You are right, high ice contents take more energy and time to thaw, but once thawed, Yedoma deposits undergo intense subsidence and reworking processes in contrast to a sediment without excess ice. And, once the ice started melting, as it is happening in current rising air temperatures, this latent heat storage will increase permafrost thawing even further by storing more heat in already melted parts, i.e. the water ponds. Also, thawing is an important part of thermokarst processes, so being vulnerable to thermokarst means being vulnerable to thaw as well.

P2-L24: “That these processes. . .” ???

Its clarified now to: “The occurrence of these draining and refreezing processes can usually be determined by…”

P3-L25: active layer thickness should be larger/smaller rather than higher/lower.

Thank you. Changed accordingly

P4-L24: What do you mean by “. . .if ‘previously’ unfrozen,. . .”?

Previously, in this case, means that these core sections were part of a talik, but were frozen for transportation, storage and subsampling. This only means, that water isotope signals from these sections must be accounted for as “pore water” and not “pore ice”. We described this now more clearly as “Pore ice or, if the sediment was unfrozen during drilling, pore water was extracted using…”

What is “artificial roots (Rhizones)”?

We apologize for the unclear description. “Rhizones” are artificial plant roots manufactured by Rhizosphere Research Products. They are used for extracting and filtering soil water. We added further description on this to the manuscript.

Please describe more details about the water extraction and explain how you avoid evaporation from the sample water.

Now we described it in the following way: "In order to avoid evaporation, the samples were thawed at 4 °C inside their sample bags and sealed tightly after inserting the Rhizones."

P4-L26: Please add information about subsample intervals.

The subsamples were distributed over the core in 50 cm steps. We took more subsamples if there was a particularly interesting section such as abrupt sediment changes, organic remains, unusual cryostructures etc.
We specified our subsampling approach now as follows: "Subsamples were equally distributed along the cores according to visual changes in the core or at least every 50 cm in order to capture the major stratigraphic layers and its specific sediment properties."

P4-L28: Do you have a reason to use "absolute" ice content? I think gravimetric ice content makes clearer what you are dealing with.

We used the absolute ice content, because it is needed to calculate the bulk density. Also, it might be confusing for colleagues working outside the cryosphere to see values > 100%. To clarify this we added: "We decided for the absolute ice content as the gravimetric one, normalized with the dry sample weight, is not suitable for further calculations".

P4-L29: I suggest to distinguish liquid and solid water more clearly. There needs more explanation to "water which froze after drilling."

As the cores were taken in winter, freezing of liquid water in talik areas occurred after bringing these parts to the surface with air temperatures around -20 °C. Therefore, the refreezing could not be avoided. We added a description of the taliks, which are the only "liquid water" areas, in the core descriptions in chapters 4.1 and 4.2 as well as indication in the figures 3 and 5.

P5-3.2.5: Please describe the accuracy of the stable isotope analyses.

We added the standard deviation for all isotopic measurements.
For δ13C: "with an analytical error of ≤ 0.15 ‰."
"The analytical error for δ2H was ≤ 0.8 ‰ and for δ18O it was ≤ 0.1 ‰. The d excess was calculated as well from these values."

P6- 3.2.6: Please explain briefly about the bootstrapping approach.

We restructured the chapter and increased the detailed description on the bootstrapping approach: "We estimated the carbon budget of the Yukechi Alas area after Eq. (1), using a bootstrapping approach.

$$OC\ quantity\ (kt) = \frac{thickness * coverage * \frac{100 - WIV}{100} * BD * \frac{TOC}{100}}{10^3}$$

with deposit thickness in m, coverage in m², WIV in vol %, BD in kg/m³ and TOC in wt%. For all TOC values below the detection limit (0.1 wt%), a value of 0.05 wt% was set. Missing bulk density values, resulting from low ice contents (< 20 wt%) (Strauss et al., 2012), were calculated after Eq. (2), which describes the relation between TOC and bulk density in the examined cores.

$$bulk\ density = 1.3664^{-0.115 * TOC}$$

The core length of the examined cores was assumed to represent the different ground types, resulting in a deposit thickness of 22 m for Yedoma deposits and 20 m for Alas deposits. A mean wedge-ice volume of 46.3 % for Central Yakutian Yedoma deposits and 7 % for Alas deposits of Central Yakutia was assumed following Ulrich et al. (2014). We estimated the deposit coverage of Yedoma and Alas deposits using satellite imagery as shown in figure S1. The ice wedge in YED1 was excluded in the bootstrapping.

Bootstrapping calculations were done after Jongejans and Strauss (2020) for the upper 3 meters, the different core units as well as for the complete cores (Table 2) using the "boot" package in the R environment. Bootstrapping included 10,000 iterations of random sampling with replacement. We used combined BD and TOC values, as they are not independent, and corrected for irregular sampling by value replication according to depth interval. We calculated the mean and standard deviation of all iterations."

P7-L21: What do you mean by "...dated with an infinite radiocarbon sample."?

Sorry for the unclarity here. This means that the sample could not accurately be dated using radiocarbon dating. It was now changed to "The age of Y3 (between 1927 and 1010 cm bs) was determined as an infinite age (below 14C detection limit) of the radiocarbon sample."

P7-L26: Please describe more about ice characteristics in this unit. Add some photos in the manuscript.

We added a photo of the ice wedge ice to figure 3 and added a short description as follows: "Y2 (1010 to 714 cm bs) consisted of massive wedge ice, which contained very little sediment inclusions (Fig. 3b [2]). "

P8-L26: If the active layer thickness reaches to 200 cm, the seasonal thaw depth touches the top of the talik (160cm). Does this mean the thickness of the seasonally freezing layer is 160cm?

Yes, it does mean that the freezing layer in this specific location is 160 cm. The given 200 cm mentioned here is a general value for grassland areas in alases of Central Yakutia, following Fedorov (2006). We changed this statement as follows: "The frozen sediment of the uppermost 160 cm bs represents the seasonally freezing layer."

We added more details to this topic in the study area description: "The modern active layer thickness in Central Yakutia is approximately 1.5 m but it can be larger in grasslands, such as within Alas basins (about 2 m and more), and smaller below the taiga forest (less than 1 m) (Fedorov, 2006). For the Yukechi Alas deposits, the active layer depth can be estimated at around 200 cm and therefore reaches down into an observed talik, following Fedorov (2006). Taliks form because of a recent or already drained lake that prevented winter freezing, or an incomplete refreezing of the active layer.”

Section 4.3: Why some YED1 points plot above the GMWL on the LEL? Could you add some explanation in Discussion? Which portion of the core are they?

The samples you mentioned are from the lowest part of the YED1 core. Due to the permanently frozen state of the core, these isotope values show characteristics of climatic conditions from ~45,000 yr BP. We restructured this paragraph to make it more clear: “δ18O ranged between -25.16 ‰ at the lowermost sample and -30.70 ‰ at 1071.5 cm bs with a much less negative value of -15.53 ‰ closest to the surface. While the uppermost Yedoma sample had a δ^2H value of -120.8 ‰, all other Yedoma samples showed much more negative values between -181.3 ‰ (2209.5 cm bs) and -221.6 ‰ (1071.5 cm bs). Values almost aligned with the global meteoric water line (GMWL) and the local evaporation line (LEL) of Central Yakutia (Wetterich et al., 2008), except for the ice wedge samples of YED1 (Fig. 7a). The isotope data obtained from the ice wedge samples had more negative values for both δ2H (-220.6 ‰ to -228.6 ‰) and δ18O (-29.58 ‰ to -30.55 ‰) in comparison to the remaining YED1 core. The d excess values are lowest in the YED1 ice wedge (lowest value of 9.3). Other values range between 3.5 in the uppermost sample as an outlier and generally range between 14.7 and 29.5 with no clear trend visible.”
We also expanded the discussion on the water isotope data in section 5.2. To strengthen our water isotope expertice we invited Thomas Opel to the author team.

P10-L27-29: Similarities between which units of them?

This is a general statement on the similar materials found in both cores (fine, silty material and coarse, sandy material).

P11-L2-5: Please rewrite this sentence. It is hard to understand probably because of the usage of too many conjunctions.

We have changed this statement: “On the one hand, low TOC content could be a result of high organic matter decomposition during accumulation or during a thawed state, especially in thermokarst deposits. On the other hand, it could reflect low carbon input. The low stable carbon isotope data of our cores (between -24.06 and -27.24 ‰) are comparable to other studied sites from the Yedoma domain (Schirrmeister et al., 2013;Strauss et al., 2013;Jongejans et al., 2018) and suggest that the source signal was more or less constant with time. “

P11-L7-8: I see varying values of d13C with depth in the profiles. What does your “constant” mean? You are comparing one data point in the active layer and data from other depth? I think it is not valid to compare decomposition rates between organic carbon currently decomposing in the active layer and ones formerly exposed to decomposition for an unknown period then frozen. As far as I see the profile, both C/N ratio and d13C fluctuate with depth even in the same unit. Is this reflected by varying decomposition rates?

Thank you very much for this detailed comment. We changed this statement to make it more clear: “Both cores show the lowest δ13C values closest to the surface as the organic material is the most recent and therefore least decomposed. As we look deeper in the cores, δ13C becomes higher (less negative) with no further trend over depth in the Alas and Yedoma deposits; we interpret this to mean material found at depth has already been further decomposed before freezing. Decomposition ceased when the lower samples became frozen, resulting in δ13C values not showing a clear trend at depth."

P11-L16-20: "The similarity of the low C/N ratios from both cores. . ." Which both cores? Your YED1 and Alas1? Or are you comparing with other Yedoma sediments found near the Arctic sea? I could not understand why this similarity supports the sedimentation of organic-poor materials. Physical conditions (such as climate and hydrology) between the comparing regions are quite different.

This is indeed a comparison between YED1 and Alas1 cores. We stated this more clearly: "From the fact that both cores, Alas and Yedoma, show low C/N ratios, …". This comparison supports the explanation of organic-poor material input for the low carbon content, as low carbon contents in syngenetic Yedoma cannot be a result of organic matter decomposition after incorporation into the permafrost. The fact, that very similar to slightly lower values are present in the Alas core, shows that both cores origin from the same material.

P11-L22-: Please show both profiles in one graph for better comparison. The heights of 0 m of the graphs of d18O profiles differ in Fig. 7 b/c, but not 9 m illustrated in Fig. 2. You can reflect the relative height difference in the same graph if you want. Similarly, please add a graph showing d-excess profiles of both cores in Fig. 7 (not in supplemental figures) and discuss evaporation and freeze-out fractionation processes that might have affected to your profiles. I think Fig. S7 should be shown as the main figure, probably, combining with Fig. 7 b/c and d-excess profiles if you want to discuss dD profiles.

Thank you. We combined figure 7 and figure S7 and added d excess plots. We rearranged all plots for better readability.

P11-L21-26: This entire paragraph is not logically described and I do not find sounding discussion. Why the age inversion and stable water isotope signals are related? Why particularly 35 K BP is the timing of the shift in sediment input? "This would have been . . ." What "This" indicates here?

We restructured this paragraph and made it clearer. We also added further discussion in the paragraph that now reads as follows: "We found age inversions in both cores with similar age and depth (YED1 49,232 cal yr BP, 1998.5 cm bs; Alas1 42,865 cal yr BP, 1967.5 cm bs) (Fig. 4 and 6, Fig. S2). While cryoturbation might seem an obvious explanation, we suggest that this process did not play a major role here due to the long-term frozen state of YED1. Rather, we assume that the age inversions indicate a temporary shift in sediment input at approximately 35,000 cal yr BP causing some deposit reworking in the watershed and the incorporation of older material into younger sediments. In addition, the dating of bulk sediments very close to the maximum datable age of ~ 50,000 yr BP may cause a high uncertainty in the absolute ages of sediment layers (Reimer et al., 2013). Therefore, the rather small age inversions (> 49.000 cal yr BP to 49,232 cal yr BP in YED1, and 45,870 cal yr BP to 42,865 cal yr BP in Alas1) could be a result of material mixture in dated bulk samples. The radiocarbon ages above this age inversion align well with a simulated sedimentation rate, as shown in figure S2."

P11-L27: "permanently" means always and forever. You should assign a more specified period of time when you discuss topics like in your manuscript. It is impossible to be in a permanently frozen state throughout the depositional history.

Thank you. We changed this to "perennially frozen conditions since incorporation into permafrost". Of course, after deposition this material has been part of the active layer for a period of time. We hope this is more specific now.

P11-L28: Please clarify depths for "the lower Yedoma pore ice" and "the uppermost sample." "the uppermost sample" is the data at 0m in YED1?

We added the sample depth to the description, and as only the uppermost signal is very different from the remaining core, we removed "lower" from the description.
"...much lower δ18O values for the Yedoma pore ice in comparison to the uppermost sample (4 cm bs in YED1) showing a water isotope signal…"

P11-L31: "The very similar.." to what?

We removed this sentence.

P12-L1: The original data were from Popp et al. (2006)?

Changed accordingly

P12-L2: "offset" of what? Your ice-wedge values against what?

We added detailed explanation to this paragraph as follows: "The stable isotope ratio values of ice wedges (mean δ18O of -30 ‰, mean δ2H of -224 ‰) reflect winter precipitation and fit well into the regional pattern for MIS 3 ice wedges in Central and Interior Yakutia (Popp et al., 2006;Opel et at., 2019) while the d excess shows a much elevated value (16 ‰) compared to the regional pattern (Popp et al., 2006;Opel et al., 2019). It should be noted that the d excess values from the central core parts correspond well to the regional values from Mamontova Gora, Tanda and Batagay (Opel et at., 2019), while the others fit to those of the host sediments and are potentially overprinted by exchange processes between wedge ice and pore ice (Meyer et al., 2010). Due to the low number of datapoints, no meaningful co-isotopic regression could be calculated. The stable isotope composition of pore ice shows a co-isotopic regression of δ2H = 6.61 δ18O - 18.0 (R^2 = 0.97, n = 23), which is typical for Yedoma intrasedimental ice (Wetterich et al., 2011;2014;2016). The isotope values plot well above the GMWL of the cold season (Papina et al., 2017) suggesting a substantial proportion of (early) winter precipitation (usually characterized by high d excess values) for the pore ice, which is also evident for some units of the Batagay megaslump (Opel et al., 2019). The decreasing upward trend of pore ice isotopic δ values might point to a general cooling in Central Yakutia during the covered time span of our study. However, as it is accompanied by an opposite increasing trend in d excess, these values may be overprinted by secondary freeze-thaw processes in the active layer and rather reflect the strength of these fractionation processes (Wetterich et al., 2014)."

P12-L4: As I mentioned above, the age constraints around 40-50 K BP need reconsideration. Furthermore, isotope signals of pore water do not simply show climate change. Lots of complicated fractionations and changes in seasonal meteoric water components could affect the signals.

Please see our comment before.

P12-L5-: This topic sentence doesn't make sense to me from your discussion above. What do you mean "lake converage"? Your discussion mixes decomposition rates during Yedoma deposition and during alas formation.

We restructured and clarified the whole paragraph.

P12-L25-: Cryostructure of frozen sediments mainly depends on soil grain size distribution, freezing rate, and moisture content. Sandy sediments usually have fewer pore spaces comparing to sediments consist of finer soil particles. Sandy sediments tend to have structureless cryostructure because sandy particles have a limited amount of unfrozen water under cryotic conditions.

We appreciate this comment and further explanation. Also, we do not argue with this explanation, as this does not oppose our explanation of refreezing resulting in structureless pore ice due to the sandy sediment.

Section 5.2 the first paragraph: I think the authors are misunderstanding or misinterpreting the papers Wetterich et al. (2009), French and Shur (2010), and Iwahana et al. (2014) as to the mechanism of cryostructure formation and sediment/carbon movements in the ground.

We do not fully understand the reviewer's comment here. The discussions in this paragraph primarily relate to the visually visible cryostructures and the conclusions that can be drawn from them about the freezing processes after sedimentation. Based on our data, we see clear similarities in the cryostructures to those described by Wetterich et al. and French and Shur. In order to avoid further misunderstandings, we have rewritten the paragraph slightly and adjusted the references.

Section 5.2 the second paragraph: Discussion in this paragraph makes sense to me. This discussion should be placed in Section 5.1 as it is tightly related to carbon accumulation and loss at this site.

We moved this part to section 5.1 as suggested

P13-L23: Why "organic-bearing"? I thought you are discussing the transportation of organic-poor sediments. Could you discuss this sandy deposit could be Aeolian or not using your grain size data?

Thank you for your comment. We decided to delete this sentence as is not needed here to support the deposition of organic-poor sediments.

P13-L25: Where the "7000 yr" came from? Aeolian materials cannot be organic-poor?

The 7000 yr originate from the age difference of the radiocarbon ages below and above this sandy Y3 unit. We tried to clarify this as follows: "From our data we see that the sandy layers were deposited in approximately 7000 yr (radiocarbon dates below and above these layers). As the sediments are rather coarse (115.3 µm mean grain size), a fluvial deposition is more likely than an aeolian deposition (Strauss et al., 2012)."
Of course, aeolian materials can be organic-poor, too, but this material is rather coarse at the same time which, in our opinion, makes fluvial transport a more suitable explanation.

P13-L29: What do you want to refer to Diekmann et al. (2017)? The climate changes?

Yes, as Diekmann et al. sum up the available literature on Siberian climate very well. We added more literature to this topic. To improve clarity we rearranged this sentence to "The climatic changes (Diekmann et al., 2017;Murton et al., 2017) and the resulting…"

P14-L4: What the "this" indicate? The deposition of silty organic-bearing material on top of the sandy layers, decreased water availability, or a climatic backshift to colder conditions? In any case, I could not understand the logic.

We apologize for this mistake, the sentences lost their correct order during internal revision. We now rearranged the sentences to: "The climatic changes (Diekmann et al., 2017; Murton et al., 2017) and the resulting higher water availability during the deposition period of the sandy layers may have caused changes in fluvial patterns on the Abalakh Terrace. More water could cause higher flow velocities under warmer climatic conditions and therefore increased erosive power, leading to the formation of new flow channels (Reineck and Singh, 1980). With a climatic backshift to colder conditions during MIS 2, water availability decreased and silty organic-bearing material was deposited by seasonal flooding again on top of the sandy layers. This likely led to lake initiation on top of the Yedoma deposits. The underlying ground began to thaw and subside, forming the Yukechi Alas basin. During this process, ice was lost from the sediment and the ground subsided by at least 9 m (height difference of 9 m between YED1 and Alas1 surface). Surface or lake water was able to percolate through the unfrozen sediments. This becomes visible by the homogeneous water isotope signal similar to the YED1 surface sample (Fig. 7). Under the unfrozen aquatic conditions in the sediment, microbial activity started, resulting in the decomposition of the already small amount of organic material (Cole et al., 2001). When the lake drained, the sediments started to refreeze both upward from the underlying permafrost and downward from the surface, leaving a talik in between (Fig. 5)."

P14-L5: Why you refer to Grosse et al. (2013) for "The underlying ground began to thaw"??

We decided to remove this citation here.

P14-L7: "as visible in the . . ." should be explained concretely.

We added further explanation by: “Surface or lake water was able to percolate through the unfrozen sediments. This becomes visible by the homogeneous water isotope signal similar to the YED1 surface sample (Fig. 7).”

P14-L12: “shrunk . . . from . . . 2200 to 1200cm...” Please discuss the possibility of subsidence using excess ice volume information. Is there enough excess ice content in the initial Yedoma to reduce its volume from 2200 to 1200cm thick?

As we have no field data on the distribution of ice wedges in the Yukechi area, we cannot exactly say if the ice volume would be sufficient for this decrease. Though, the matching characteristics of the stratigraphic units of YED1 and Alas1 and the existence of large ice wedges in this area as reported already by Russian scientists before support the hypothesis of the stated ground subsidence. To clarify this, we added the following text: “The presence of largeice wedges in the area supports this theory of ground subsidence during thaw as it hints on large excess ice contents of the ground (see Fig. S7) (Soloviev, 1959).”

P14-L12-13: Again, what “this” indicates here?

Changed to “These subsidence processes” to be more specific about relations in this paragraph.

P14-L15-16: I don’t understand why you started to discuss the tipping point suddenly. Is this relevant and supported by your results?

We decided to remove this sentence from the discussion.

Section 5.3 the first paragraph: How the 4.40 kg/m3 was derived? Please explain the relation to 4.48 and 6.93 for the two sites?

This number was calculated by upscaling the bootstrapping results to the study area. We added some more explanation here as follows: “Using a bootstrapping approach (Jongejans and Strauss, 2020) we found a much lower organic carbon density of 4.48 ± 1.43 kg/m3 for the top 3 m of the YED1 core. For Alas1, an organic carbon density of 6.93 ± 2.90 kg/m3 was calculated for the top 3 m. Taking the area covered by each deposit type within the Yukechi Alas landscape into account and the ice wedge volumes estimated by Ulrich et al. (2014) (see Section 2 and Fig. S2), this results in a mean organic carbon density of only 4.40 kg/m3 for the top 3 m of dry soil at the Yukechi study site. This landscape scale carbon stock density includes the entire study area (1.4 km^2), including all water bodies (approximately 0.18 km^2), which we assumed to contain no soil carbon”

This could be the first carbon stock measurement below 3m for two sites in the Central Yakutian Yedoma in English literature, but have you checked Russian literature?

We checked on international available and peer-reviewed Russian literature and added some more literature to our manuscript. We avoid citing non-peer-reviewed literature and literature that is not available to an international scientific audience though.

Please discuss how representative your two cores for the Central Yakutian Yedoma.

Thank you, we expanded the discussion accordingly an concluded that our cores seem not representative for other examined Yedoma deposits from further north. However, there are no data available on Central Yakutian deep Yedoma cores in available peer-reviewed literature, which would be necessary for comparison inside this southernmost Yedoma domain. A corresponding paragraph in the conclusions chapter reads as follows: "Hence, the studied Yukechi Yedoma deposits store less carbon than other, comparable Yedoma Ice Complex deposits in the Central Yakutian area. However, there have been comparatively few studies on this so far. The biogeochemical impact of permafrost thawing in the Yukechi area might therefore be smaller than generally assumed for Yedoma deposits, as this area does not feature the high carbon stock estimates and high ice contents of other previously studied localities in Central Yakutia and elsewhere in the Arctic."

P16-L1-2: I could not understand what you wanted to indicate from this sentence. What do you mean by "drainage"? How did the alas core reveal its composition and stratigraphy before lake formation?

We apologize for the misunderstanding and the ambiguities here. The grain size and carbon characteristics of the Alas core can be explained by thawing and subsiding of the local Yedoma, starting from the characteristics found in our YED1 core. Therefore, we can assume that, previous to all thermokarst processes, the deposits found in Alas1 were basically the same as the deposits in the YED1 core are today. We changed the text for more clarity to the following: "The permafrost characteristics found in the Alas core reveal that its composition and stratigraphy before lake formation and disappearance was very similar to the Yedoma core material. Its past development including thaw, the loss of old ice and surface subsidence, along with sediment compaction, shows a possible pathway for the Central Yakutian Yedoma deposits under the influence of global climate change."

Fig. 2: Yedoma lake should be thermokarst lake? Or by local name, "dyuyodya" (Soloviev, 1973) or "dyede" (Crate et al., 2017)? Soloviev, P. A. (1973), Thermokarst phenomena and landforms due to frost heaving in Central Yakutia, Biuletyn Peryglacjalny 23, 135-155. Crate, S., et al. (2017), Permafrost livelihoods: A transdisciplinary review and analy- sis of thermokarst-based systems of indigenous land use, Anthropocene, 18, 89-104, doi: https://doi.org/10.1016/k.ancene.2017.06.001.

Indeed, both lakes are actually thermokarst lakes in different evolutionary stages. In order to distinguish between the two lakes found at our study site, they were named after the deposit type they were found on (Yedoma and Alas). This was also based on Ulrich et al. 2017. Differences in behaviour and distribution of permafrost-related lakes in Central Yakutia and their response to climatic drivers, Water Resources Research, 1167-1188, https://doi.org/10.1016/k.ancene.2017.06.001.
However, we add a note in the figure caption as follows: "the terms "Alas lake" and "Yedoma lake" are chosen after Ulrich et al., 2017a in accordance to the deposit type in which the thermokarst lakes are located; following Crate et al., (2017), the Yedoma lake can also be called "dyede" due to its development stage."

Fig. 3: Include photos of each unit including ice-wedge layer. Put "YED1" in the figure.

changed accordingly

Fig. 5: Please use the same white balance and adjust the exposure/brightness of the core photos as in Fig. 3. Include core photos of the rest two units too. Put "Alas1" in the figure.

changed accordingly; We adjusted the brightness as far as possible without corrupting the image quality and visual appearance of the core.

Fig. 4 & 6: Please used different markers for absolute ice content and bulk density so that people without color printer environment or color-blind can easily distinguish the two. Large caption YED1 and Alas1 within the figures would be helpful.

changed accordingly

Fig. 7 & S7: Combine Fig 7 b/c and S7 and add a graph of d excess. Please use open triangle markers for ice-wedge points. The half-open triangle hinders instant discrimination between markers. Add labels "YED1" or "Alas1" on top of each graph.

changed accordingly; We combined figure 7 and figure S7 and added d-excess plots. For better readability, we rearranged all plots.

Fig. S2: The blue markers with age uncertainties are not discernible. Please revise them for a clearer presentation. I do not think the information on the model confidence by black shades is meaningful and necessary in your radiocarbon age of soil organic matter. For all graphs with depth axis: Please use the meter scale, not cm.

graphics changed accordingly; We will continue to use cm as we go down to 1 cm step accuracy, which is much easier to read in cm units than with a meter scale. We are aware that meter is the SI unit.

Interactive comment on

“Organic Carbon Characteristics in Ice-rich Permafrost in Alas and Yedoma Deposits, Central Yakutia, Siberia”

by Torben Windirsch et al.

Anonymous Referee #2

Received and published: 16 February 2020

The manuscript by Windirsch et al. “Organic Carbon Characteristics in Ice-rich Permafrost in Alas and Yedoma Deposits, Central Yakutia, Siberia” examined and compared the organic carbon storage and characteristics from two rare and deep cores using different methods (C%, soil texture, 14C age, ice content, etc..). Since such deep cores are very rare, this study is very important and gives us valuable inside information about the history of these deep deposits.

Thank you very much for this general statement of importance of our study.

The scientific question and the used methods are well established, however, there is still room for some improvement. Overall, the discussion section is rather weak and speculative, and the based conclusions too shaky. One reason, most of the used methods were nor fully incorporated in the discussion section. Some results as for example 14C inversions or magnetic susceptibility are not really discussed and explained.

We are grateful for the review and acknowledge the reviewer’s comments, which really improve and strengthened the paper.
As suggested by the reviewer we extended and clarified the discussion and strengthened the conclusion.
Please see our comments below.

Nitrogen data not presented, even though obviously available.

They have not been shown as most values did not reach detection limit. This has now been referenced and implemented in the result sections 4.1 and 4.2. Moreover, the data presented in the manuscript are available on the PANGAEA repository.

Conclusion to short, missing main points as for example that the global estimate of SOC in Yedoma might be by far overestimated and possibly not so vulnerable due to rather low ice contents

Yedoma ice contents are low in this specific case, which is described in the conclusions. With one site we can not revise circumarctic estimates. Therefore, general Yedoma vulnerability is not the topic of this discussion. As the drained thermokarst basins are 9 m deeper there is a substantial potential for Yedoma for severe changes. Using this study to revise studies basing on a Yedoma wide study site set (Strauss et al 2017, Schirrmeister et al 2011) is not appropriate to our mind.

But nevertheless, as we state we make this point in the discussion but this is not one of the main conclusions.

Also, recent publications suggest Yedoma being not extremely vulnerable. Missing older Russian Literature

We checked on international available and peer-reviewed Russian literature and added some more suitable literature. We avoid citing non-peer-reviewed literature and literature that is not available to an international scientific audience. We would be happy to include more literature. Please use the comment function to add specific literature.

Besides this, we concluded that Yedoma is highly vulnerable to thaw induced landscape changes due to loss of excess ice. However, as stated by Kuhry et al, the carbon stored in Yedoma deposits might not be highly vulnerable.

We now implemented Kuhry et al. (2020) to the paper which was not published at the first submission of our paper.

Below I list more specific points, which should be addressed before final publication.

P.1 L. 15:"has not yet", actually parts of Yedoma are already in the active carbon cycle;

We changed this to "this carbon becomes available to the recent carbon cycle.", as some of it is still frozen and immobilized.

P1 L: 30"very carbon poor", please add number;

Thank you, changed accordingly: We added "(< 0.1 wt%)" to the description, which is the detection limit for measuring the total organic carbon content.

P2 L2 "provide"???, and why is it important;

We changed this to "Permafrost deposits present one of the largest terrestrial carbon reservoirs."

P2 L6, reference on co2 in the atmosphere not appropriate. Use actual data source;

We changed the reference to 868 Gt which was calculated using the CO2 concentration of 407 ppm, measured in 2018. This was calculated using the conversion formula given by Friedlingstein et al (2019). Global carbon budget using a factor of 2.124 for conversion between ppm CO2 and Gt carbon after Ballantyne et al (2012) for well-mixed atmospheric conditions. The text now reads: "The estimated amount of frozen and unfrozen carbon stored in the terrestrial permafrost region is 1330 to 1580 gigatons (Gt) (Hugelius et al., 2014;Schuur et al., 2015), which is up to 45% more than what is currently present in the atmosphere (~ 864 Gt, based on 407 ppm CO2 measured in 2018) (Ballantyne et al., 2012; Friedlingstein et al., 2019)."

P2 L16 "vulnerable" recent paper by Kuhry et al. states that Yedoma is rather stable.;

Concerning landscape vulnerability: the general high ice content in Yedoma deposits makes them vulnerable to dramatic landscape changes caused by thaw under climate warming;

Concerning C vulnerability: Kuhry et al (2020) does not state the opposite but concludes that thaw vulnerability does not mean a high vulnerability/lability of SOM. This sentence was changed as follows: "In the context of global climate change, such high ice content with pore ice and syngenetic ice wedges render Yedoma deposits highly susceptible to thaw induced landscape changes (Schirrmeister et al., 2013) and ground volume loss causing surface subsidence."

P2 L20 Is this the case only for carbon stored within Yedoma deposits???;

Thank you, we changed "Yedoma deposits" to "permafrost".

P2 L21 released how? I guess you mean as carbon dioxide.;

We specified this by adding "... in form of gases such as carbon dioxide or methane,..."

P2 L25, please add ref.;

We added "(Strauss et al., 2013)" to the corresponding sentence.

P2 L27 Explain why below 3m less understood?

This is due to the fact that only very few studies have been examining long permafrost cores. We clarified that in the text: "...especially below 3 m, are still poorly studied, as only few studies examining long Siberian permafrost cores have been conducted (Zimov et al., 2006;Strauss et al., 2013;Shmelev et al., 2017)."

P2 L29 missing space;

changed as suggested

P2 L32 "822 Gt" this is wrong, the number refers not only to Yedoma, but refers to combined permafrost SOC in soils (0–3 m), deltaic alluvium and Yedoma region sediments.

Thank you for notifying. We changed it to „permafrost region"

P3 L5 Your 'only' 2 research questions are going under in the paragraph. Please make them stand out.

We made the research questions more visible by adjusting the paragraphs.

P3 L24 "in Siberia", is there no data for MAAT at least for Central Yakutia?

Thank you for your suggestion. We changed this to "The contemporary mean annual air temperature in Central Yakutia (measured at Yakutsk Meteorological Station) is -9.7 °C."

P3 L27, No more data or drilling campaigns since Soloviev, 1973?

There are actually few accessible studies on the thickness of the Yedoma in Central Yakutia. The most cited studies are indeed Soloviev, 1959 and 1973.

We changed this statement and include both references as follows: "The Yedoma deposits in this region can be more than 30 m in thickness as was already shown by older Russian works (Soloviev, 1959, 1973)."

P4 L23 "approximately every 50cm? Why this distance? Why not using visual changes in the core for the increments?

The cores were indeed sub-sampled after visible stratigraphic changes. However, larger homogeneous sections were sampled approximately every 50 cm. We specified our subsampling approach as follows "Subsamples were equally distributed along the cores. According to visual changes, we covered all visible stratigraphic layers and we sampled at least every 50 cm in order to capture specific sediment properties."

P6 L4 check paragraph spacing.

Thank you, we adjusted it.

P6 Since the main question is carbon, a chapter on how carbon estimates were calculated would be more then appropriate.

Thank you. The methods of our carbon budget calculation are explained in chapter 3.2.6. We renamed the chapter title to "Statistics and bootstrapping approach for carbon budget estimations" to make this clearer.

P7L18 "material composition???" soil texture.

Changed accordingly

P9 L6 please remove rather, enough with the given SD.

Changed accordingly

P9, when you compare the grain sizes, you change between median and mean, why?

We corrected this and now use the mean for all data.

P10 L1 I don't fully understand the SOC calculations. How many samples were used for boot strapping? Please add a table comparing these two cores with SOC data, TN data, DBD data, to 3 m meter, to the different used units and to the total.

Thank you. We expanded the explanation on the bootstrapping approach. Also, we added a table to show SOC contents for the individual core units, based on the bootstrapping results. As TN data are not used in the bootstrapping approach, we did not include them in table 2. These data are shown in the PANGAEA repository as most values are below the detection limit. Please see our comment further above.

P11L1-5. And what exactly are you arguing? Also, a lot of speculations. Please stick to the point. Also, the rather obvious reason for the low C comes first on page 13!

This was a misuse of "arguing", we apologize. We changed the sentence into: "On the one hand, low TOC content could be a result of high organic matter decomposition during accumulation or during a thawed state, especially in thermokarst deposits. On the other hand, this could reflect low carbon inputs. The low stable carbon isotope data of our cores (between -24.06 and -27.24 ‰) are comparable to other studied sites from the Yedoma domain (Schirrmeister et al., 2013;Strauss et al., 2013;Jongejans et al., 2018), and suggest that the source signal was more or less constant with time.". The reason for low C is discussed in more detail later in chapter 5.2.

P11L13-15 But then the frozen sections should have the same C/N ratio, but they don't?

They do not have the same C/N ratio, as the Alas1 core was once thawed completely, as far as we conclude from the water isotope data. To highlight this we change this part as follows: "In comparison to the mean C/N ratio of 10 in YED1, the mean C/N ratio of 8 for Alas1 may indicate that the Alas deposits were only slightly more affected by decomposition due to a temporary thawed state. The development of a talik in Alas1 probably led to increased decomposition of these sediment sections and thus leading to a reduced C/N ratio. As the carbon was freeze-locked in the YED1 core and therefore was not decomposed since deposition, this similarity in mean C/N ratios indicates that the original carbon state for the deposits at both coring sites were similar, assuming the same carbon source for both deposits."

P11 L18 "decomposed" if, then rather pre-decomposed.

Changed accordingly

P11 L21-26 Ok, so what is the reason for inversions? Section by far too short. And no discussion on the other dates.

We restructured this paragraph and clarified. We also added further discussion in the paragraph that now reads as follows: "We found age inversions in both cores with similar age and depth (YED1 49,232 cal yr BP, 1998.5 cm bs; Alas1 42,865 cal yr BP, 1967.5 cm bs) (Fig. 4 and 6, Fig. S2). While cryoturbation might seem an obvious explanation, we suggest that this process did not play a major role here due to the long-term frozen state of YED1. Rather, we assume that the age inversions indicate a temporary shift in sediment input at approximately 35,000 cal yr BP causing some deposit reworking in the watershed and the incorporation of older material into younger sediments. In addition, the dating of bulk sediments very close to the maximum datable age of ~ 50,000 yr BP may cause a high uncertainty in the absolute ages of sediment layers (Reimer et al., 2013). Therefore, the rather small age inversions (> 49.000 cal yr BP to 49,232 cal yr BP in YED1, and 45,870 cal yr BP to 42,865 cal yr BP in Alas1) could be a result of material mixture in dated bulk samples. The radiocarbon ages above this age inversion align well with a simulated sedimentation rate, as shown in figure S2."

P11 L32 "indicate colder climate conditions" How, and what does it mean for the core? Any refs for that?

We deleted this sentence, as it was unnecessary information without important implications for the core.

P12 L2 "explained by climatic variations" Is this an assumption or is there data? Need refs for this statement.

We restructured the whole paragraph and added more detail on isotope data and d excess: "The stable isotope ratio values of ice wedges (mean δ18O of -30 ‰, mean δ2H of -224 ‰) reflect winter precipitation and fit well into the regional pattern for MIS 3 ice wedges in Central and Interior Yakutia (Popp et al., 2006;Opel et at., 2019) while the d excess shows a much elevated value (16 ‰) compared to the regional pattern (Popp et al., 2006;Opel et al., 2019). It should be noted that the d excess values from the central core parts correspond well to the regional values from Mamontova Gora, Tanda and Batagay (Opel et at., 2019), while the others fit to those of the host sediments and are potentially overprinted by exchange processes between wedge ice and pore ice (Meyer et al., 2010). Due to the low number of datapoints, no meaningful co-isotopic regression could be calculated. The stable isotope composition of pore ice shows a co-isotopic regression of δ2H = 6.61 δ18O - 18.0 (R^2 = 0.97, n = 23), which is typical for Yedoma intrasedimental ice (Wetterich et al., 2011;2014;2016). The isotope values plot well above the GMWL of the cold season (Papina et al., 2017) suggesting a substantial proportion of (early) winter precipitation (usually characterized by high d excess values) for the pore ice, which is also evident for some units of the Batagay megaslump (Opel et al., 2019). The decreasing upward trend of pore ice isotopic δ values might point to a general cooling in Central Yakutia during the covered time span of our study. However, as it is accompanied by an opposite increasing trend in d excess, these values may be overprinted by secondary freeze-thaw processes in the active layer and rather reflect the strength of these fractionation processes (Wetterich et al., 2014)." Moreover, we strengthened our stable water isotope expertise by inviting Thomas Opel to the author team.

P13 The final reason for the low C% should be mentioned earlier. Also, this page can be shortened.

Thank you for this comment. We agree and moved this interpretation into section 5.1. We also restructured and shortened this chapter.

P15 L15 & 23, repetitive sentence. Also, main conclusion, Yedoma SOC estimates likely too high.

We removed the repetition. Thanks for this comment but following Schneider von Deimling et al (2015) the SOC estimations for Yedoma could still be correct, giving the Yukechi site as a low-carbon example. Also, due to the sediment diversity within the YED1 and Alas1 cores, the Yukechi Alas landscape does not represent a typical Yedoma composition.

P15 L28. “high ice content.... vulnerable” actually the opposite. You showed very little ice content except one one ice wedge. Yedoma “had an estimated” ice wedge and lenses content of up to 90%. These two cores have far less. So these Yedoma deposits are not very vulnerable.

The high volumetric ice content in Yedoma deposits is mainly due to the presence of large ice wedges in the area (please see new figure S7), as in this case in our Yedoma core. We have chosen the Yedoma coring location in the centre of a polygon for not hitting an ice wedge. In this context, the Alas core was not included, as it represents already reworked Yedoma deposits in which the Pleistocene ice has largely melted. The pore ice content of the Central Yakutian Yedoma sediment deposits is comparatively smaller, but the sensitivity of the sediments to thawing processes is retained as for the ice wedges. This is also shown by the numerous large thermokarst landscape features in the region, but also by the currently observed very rapid thawing processes.

Organic Carbon Characteristics in Ice-rich Permafrost- in Alas and Yedoma Deposits, Central Yakutia, Siberia

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Abstract. Permafrost ground is one of the largest repositories of ~~stored~~ terrestrial ~~natural~~organic carbon and might become or is already a carbon source ~~with~~in response to ongoing global warming. In particular, syngenetically frozen ice-rich Yedoma deposits originating from the late Pleistocene store a large amount of organic carbon~~. This~~ (OC). After thaw, this carbon ~~has not yet become part of~~ becomes available to the recent carbon cycle. With this study of Yedoma and associated Alas deposits in Central Yakutia, we ~~aim~~aimed to ~~understand~~assess the local sediment ~~genesis~~deposition regime and its effect on permafrost carbon storage. For this purpose, we investigated the Yukechi Alas area (61.76495° N, 130.46664° E), a thermokarst landscape degrading into Yedoma in Central Yakutia. ~~Two~~We retrieved two sediment cores (Yedoma upland, 22.35 m ~~depth~~deep, and Alas basin, 19.80 m ~~depth) were drilled~~deep) in 2015~~. We~~ and analyzed ~~for ice content, total carbon and total nitrogen content, total organic carbon content, stable oxygen and hydrogen isotopes, stable carbon isotopes, mass specific magnetic susceptibility, grain size distribution, and~~biogeochemistry, sedimentology, radiocarbon ~~ages. Samples taken from both cores were radiocarbon-dated up to 50,000 years before present.~~dates and stable isotope geochemistry. The laboratory analyses of both cores revealed very low ~~carbon~~total OC (TOC) contents ~~down to several meters depth.~~(< 0.1 wt%) for a 12 meter section in each core, while the remaining sections ranged from 0.1 to 2.4 wt% TOC. Those core parts holding very little to no detectable ~~carbon consist~~OC consisted of coarser sandy material estimated to an age between 39,000 and 18,000 years before present. For this period, we assume ~~sediment input~~deposition of organic-poor material. ~~Water~~Pore water stable isotope data ~~derived~~ from ~~pore ice within~~ the Yedoma core ~~indicate~~indicated a continuously ~~cold~~frozen state ~~of~~except for the ~~lower core parts~~surface sample, thereby ruling out ~~a potential theory of~~ Holocene ~~influence~~reworking. In consequence, we ~~conclude~~see evidence that no strong organic matter (OM) decomposition took place in the sediments of the Yedoma core until today. ~~In contrast, the~~The Alas core from an adjacent thermokarst basin was strongly disturbed by lake development and permafrost thaw~~, and accordingly its sediment and carbon characteristics differed from those of the Yedoma core. The Alas core shows homogeneous ice content and the water isotope characteristics of a slightly more decomposed organic material; the findings of very carbon-poor core sections from the Yedoma core can be duplicated.~~. Similar to the Yedoma core, some sections of the Alas core were also OC poor (< 0.1 wt%) in 17 out of 28 samples. The Yedoma deposition was likely influenced by fluvial regimes in nearby streams and the Lena River shifting with climate. ~~The~~With its coarse sediments with low ~~carbon~~OC content ~~and the clear stratigraphical layering~~(OC mean of ~~different sediment types suggest that~~5.27 kg/m^3), the Yedoma deposits in the Yukechi area differ from other Yedoma sites ~~regarding carbon stock and sedimentological composition. We~~in North Yakutia that were generally characterized by silty sediments with higher OC contents (OC mean of 19 kg/m^3 for the non-ice wedge sediment). Therefore, we conclude that sedimentary composition and deposition regimes of Yedoma may differ ~~significantly~~considerably within the Yedoma domain. The resulting heterogeneity should be taken into account for future upscaling approaches on the Yedoma carbon stock. The Alas core ~~gives clear insights into~~, strongly affected by extensive thawing processes during the ~~future development of Cenral~~Holocene, indicates a possible future pathway of ground subsidence and further OC decomposition for thawing Central Yakutian Yedoma deposits.

1 Introduction

Permafrost deposits ~~provide important~~represent one of the largest terrestrial ~~storage for~~ carbon reservoirs. Perennial freezing largely prevents decomposition and ~~therefore~~ preserves organic material. These permafrost soil conditions ~~can be~~are found in the ground of approximately one quarter of the Northern Hemisphere's land surface (Zhang et al., 1999). The estimated amount of frozen and unfrozen carbon stored in the terrestrial permafrost region is 1330 to 1580 gigatons (Gt) (Schuur et al., 2015), which is up to 45% more than the amount that is currently present in the atmosphere (870 Gt, using 409 ppm CO_2 measured in 2019) (Strauss et al., 2017). Permafrost formation(Hugelius et al., 2014; Schuur et al., 2015), which is approximately 45% more than what is currently present in the atmosphere (~ 864 Gt, based on 407 ppm CO_2 measured in 2018) (Ballantyne et al., 2012; Friedlingstein et al., 2019). Permafrost aggregation and conservation is highly dependent on long-term climatic conditions, both directly via air temperature and indirectly by the presence or absence of insulating vegetation and snow cover (Johansson et al., 2013). Currently, these permafrost conditions are under threat by rapidly increasing global, and in particular Arctic air temperatures which have resulted in widespread permafrost warming in recent years (Biskaborn et al., 2019); a permafrost loss of up to 70% by 2100 in the uppermost 3m is expected in a business-as-usual scenario (IPCC, 2019). Gradual permafrost losses of up to 70% by 2100 in the uppermost 3 m are expected in a business-as-usual climate scenario (Chadburn et al., 2017; IPCC, 2019), and even deeper if accounting for deep thermokarst-induced rapid thaw (Nitzbon et al., 2020), while rapid permafrost thaw is not considered at all (Turetsky et al., 2020).

A special type of permafrost is the Yedoma ice complex deposit (in the following referred to as Yedoma), formed fromsyngenetically by late Pleistocene deposition of fine-grained sediments syngenetically with large volumes of ground ice. Yedoma is ice-rich (50–90 volume percent [vol%] ice) and usually has organic carbon contents of 2 to 4 weight percent (wt%) with an estimated deposit thickness up to 40 m (Schirrmeister et al., 2013; Strauss et al., 2013). In Central Yakutia, the contextcryostratigraphic characteristics of global climate change, such high ice content with pore ice andthese syngenetic ice wedges render YedomaLate Pleistocene deposits highly vulnerable to thawhave been previously studied by various researchers (Soloviev, 1959; Katasonov and Ivanov, 1973; Katasonov, 1975; Péwé et al., 1977; Péwé and Journaux, 1983). Thawing leads to ground subsidence that is associated and often combined. In the context of global climate change, such high ice content with intrasedimental ice and syngenetic ice wedges render Yedoma deposits highly vulnerable to thaw induced landscape changes (Schirrmeister et al., 2013) and ground volume loss causing surface subsidence. Thawing leads to ground subsidence that is often associated with thaw lake development (Grosse et al., 2013). Thaw lake development, surface subsidence, lake drainage, and refreezing of formerly unfrozen thermokarst lakethe sediments result in a thermokarst basin landform called Alas in Central Yakutia (Soloviev, 1973). During these thawthermokarst processes, the carbonorganic material stored within the Yedoma depositspermafrost becomes exposed to decomposition in the thaw bulbs (taliks) underneath the thermokarst lakes. It is subsequently released into the atmosphere as a result of microbial activity in unfrozen and aquatic conditions in form of gases such as carbon dioxide or methane, amplifying global climate change (Schuur et al., 2008). After a lake drainage event, the resulting thermokarst deposits in the Alas basins refreeze and thisthe remaining Pleistocene soil carbon, as well as carbon from new plant biomass forming in thermokarst lakes and basins, becomes protected from decomposition again. That these processes have occurred can usually be determined by higher carbon content and, at the same time, lower carbon stocks, compared to the adjacent deposits. The occurrence of these draining and refreezing processes can usually be determined by higher carbon content compared to the adjacent deposits (Strauss et al., 2013).

The resulting landscape patterns of Yedoma uplands and Alas basins form a heterogeneous landscape mosaic (Morgenstern et al., 2011).(Morgenstern et al., 2011). The heterogeneity and carbon characteristics within these deposit types, especially below 3 m, are still poorly studied. In Central Yakutia, several, as only very few studies examining long Siberian permafrost studiescores have been conducted, especially on surface dynamics and temperature changes (Zimov et al., 2006; Strauss et al., 2013; Shmelev et al., 2017). Studies from this area mostly examine natural Yedoma exposures as for example in the Batagay mega thaw slump (Ashastina et al., 2017). In Central Yakutia, several permafrost studies have been conducted, especially on thermokarst processes, related surface dynamics and temperature changes (Fedorov and Konstantinov, 2003a; Ulrich et al., 2017a; Ulrich et al., 2017b; Ulrich et al., 2019). Other studies show a direct relation between dense vegetation cover and low permafrost carbon storage due to warmer permafrost conditions as a result of ground insulation (Siewert et al., 2015). Hugelius et al. (2014) estimate the carbon stock of permafrost in the circumarctic Yedomapermafrost region to be approximately 822 Gt carbon. However, despite the still high vulnerability of deeper deposits to thaw due toby thermokarst and thermo-erosion (Turetsky et al., 2019) only very few studies report(Turetsky et al., 2019), only very few studies report organic carbon characteristics for permafrost deposits deeper than 3 m. This lack of data results in very high uncertainties for the impact of deep thaw in ice-rich permafrost regions and consequences for the carbon cycle. (Kuhry et al., 2020).

By investigating deeper permafrost sediments in the continuous permafrost region of Central Yakutia, we aimaimed to understand the processes involved in organic carbon deposition and reworking in Yedoma and thermokarst deposits of this important region. fast changing permafrost landscape (Nitze et al., 2018).

Our main research questions are: (1) WhichWhat are the sedimentological processes that influenced the carbon stocks found in the Yedoma and Alas deposits of the Yukechi area? (2) How did these sedimentological processes affect the local carbon storage? We will use grain size distribution analysis, mass specific magnetic susceptibility (MS), total organic carbon (TOC) and total nitrogen (TN) analysis, and isotope measurements to identify the sedimentological processes that contributed to the formation of the Yukechi landscape. A bootstrapping approach on the measured carbon characteristics will give us estimated carbon stocks for the present deposit types and the whole area in general. This will help in predicting the future development of this landscape and the fate of its currently stored carbon.?, and (2) How did the sedimentological processes affect the local carbon storage?

2 Study site

The Yukechi Alas landscape (61.76495° N; 130.46664° E) covers an area of approximately 1.4 km² and is located on the Abalakh Terrace (~ 200 m above sea level~~ [asl]~~)) in the Lena-Aldan interfluve of Central Yakutia (Fig. 1a) (Ulrich et al., 2019). It is characterized by Yedoma uplands and drained Alas basins indicating active thermokarst processes (Fedorov and Konstantinov, 2003a). Yedoma deposits cover 66.4 % of the area. The lakes cover about 13.0 % of the Yukechi Alas landscape, and approximately 20.6 % of the area consists of basins covered by grasslands, which ~~hence~~ contain Alas deposits (Fig. S1).

Today, Central Yakutia is characterized by an extreme continental subpolar climate regime with very low winter air temperatures down to minima of -63 °C in January (Nazarova et al., 2013). Holocene summer climate reconstructions indicate climate settings with slightly colder conditions (T_{July} for 10,000 to 8,000 yr BP and 4,800 to 0 yr BP is 15.6 ± 0.7 °C,) compared to modern climate (T_{July} is 16.6 to 17.5 °C) and a mid–Holocene warming phase between about 6,000 and 4,500 yr BP (T_{July} ~ 1.5 °C higher than today) (Nazarova et al., 2013; Ulrich et al., 2017b). The ~~modern Holocene~~contemporary mean annual air temperature ~~(MAAT) ~~in ~~Siberia~~Central Yakutia (measured at Yakutsk Meteorological Station) is -~~8.6~~9.7 °C~~ (Fedorov, 2006).~~. The modern active layer thickness in Central Yakutia is approximately 1.5 m but it can be ~~higher~~larger in grasslands, such as within Alas basins (about 2 m and more), and ~~lower~~smaller below the taiga forest (less than 1 m) (Fedorov, 2006). For the Yukechi Alas deposits, the active layer depth can be estimated at around 2 m and therefore reaches down into an observed talik, following Fedorov (2006). Taliks form because of a recent or already drained lake that prevented winter freezing, or an incomplete refreezing of the active layer.

~~Yedoma deposits in this region can be 20 to 30 m in thickness as was shown by former drilling campaigns (Soloviev, 1973).~~The Yedoma deposits in this region can be more than 30 m in thickness as was already shown by older Russian works (Soloviev, 1959; 1973). Lakes are found in partially drained basins as well as on the surrounding Yedoma uplands (Fig. 1b). The land surface within the Alas basins is covered by grasslands while the boreal forest found on the Yedoma uplands mainly consists of *Larix cajanderi* with several *Pinus sylvestris* communities (Kuznetsova et al., 2010; Ulrich et al., 2017b). Central Yakutian Alas landscapes are characterized by extensive land use (mainly horse and cattle herding and hay farming) (Crate et al., 2017).

Lake dynamics have been monitored at the Yukechi Alas study site for several decades by the Melnikov Permafrost Institute in Yakutsk (Bosikov, 1998; Fedorov and Konstantinov, 2003b; Ulrich et al., 2017a) and have partially been linked to local land use (Crate et al., 2017).

Figure 1 – Study site overview; a: location of the Yukechi Alas study site in Central Yakutia on the edge of the Abalakh Terrace~~;~~ (Circumpolar digital elevation model, Santoro and Strozzi, 2012); b: locations of the Alas1 and the ~~YED11~~YED1 coring site within the Yukechi Alas landscape (Planet OrthoTile, acquisition date: 7 July 2018~~).~~; Planet Team (2017)).

3 Methods

3.1 Field work

Field work took place in March 2015 during a joint Russian-German drilling expedition. Two long permafrost sediment cores were obtained, one from Yedoma deposits and one from the adjacent drained Yukechi Alas basin (Fig. 1b). The surface of the Alas sample site (61.76490° N, 130.46503° E; h = 209 m ~~asl~~above sea level) is located approximately 9 m lower than the surface of the sampled Yedoma site (61.75967° N, 130.47438° E; h = 218 m ~~asl~~above sea level) (Fig. 2). The distance between the two coring locations is 765 m. Both cores were drilled from dry land surface, kept frozen, and sent to ~~the Alfred Wegener Institute (AWI) in~~ Potsdam, Germany, for ~~lab~~laboratory analysis. The Yedoma core (YED1) reached a depth of 22.35 m below surface (bs) and includes an ice wedge section from approximately 7.0 to 9.5 m bs. A talik section due to not completely refrozen active layer as identifies at 100 to 200 cm bs. The Alas core (Alas1) reached 19.80 m bs. A talik section was found in the Alas core reaching from approximately ~~1.6 m~~160 down to ~~7.5 m~~750 cm bs.

Figure 2 – Setting of the drilling locations for the Alas1 and YED1 cores showing distance and height difference between the locations (vertical scale exaggerated~~).~~); the terms "Alas lake" and "Yedoma lake" are chosen after Ulrich et al., 2017a in accordance to the deposit type in which the thermokarst lakes are located; following Crate et al., (2017), the Yedoma lake can also be called "dyede" due to its development stage.

3.2 Laboratory analyses

~~Laboratory work was carried out at AWI.~~ The frozen cores were split lengthwise using a band saw and were subsequently subsampled. Each subsample consisted of approximately 5 cm core material. Subsamples were equally distributed along the cores. According to visual changes, we covered all visible stratigraphic layers and ~~taken approximately~~we sampled at least every 50 cm ~~or~~ in order to capture ~~the major stratigraphic layers.~~specific sediment properties. The samples were ~~then~~ weighed and thawed. ~~Pore~~Intrasedimental ice or, if ~~previously~~ the sediment was unfrozen~~, pore~~ during drilling, intrasedimental water was extracted using artificial plant roots (Rhizones) consisting of porous material with a pore size of 0.~~1~~15 µm and applied vacuum. In order to avoid evaporation, the samples were thawed at 4 °C inside their sample bags and sealed tightly after inserting the Rhizones. These water samples were then analyzed for stable oxygen and hydrogen isotopes (see section 3.2.5). The ice wedge ice was subsampled using a saw ~~and also analyzed~~ for the analysis of stable oxygen and hydrogen isotopes.

3.2.1 Ice content, bulk density, and subsampling

The weighed sediment samples were freeze-dried and weighed again afterwards for determining the absolute ice content in weight percent (wt~~%.~~%). We decided for the absolute ice content as the gravimetric one, normalized with the dry sample weight, is not suitable for further calculations. Ice content within talik areas represents the water content, water which froze after drilling. Bulk density was calculated from the absolute ice content, assuming an ice density of 0.9127 g/cm^3 at 0 °C and a mineral density of 2.65g/cm^3 (Strauss et al., 2012).

3.2.2 Elemental analyses

Subsamples used for elemental analyses were homogenized using a planetary mill equipped with agate jars and agate marbles.(Fritsch Pulverisette 5). Subsamples were then weighed into tin capsules and steel crucibles for the elemental analyses. Total carbon (TC), total nitrogen (TN,), and total organic (TOC) content were measured viathrough combustion and analyses of resulting gases using a vario EL III and a varioMAX C Element Analyzer. Results give the carbon and nitrogen amounts in relation to the sample mass used for analysis in wt%. The carbon nitrogen ratio (C/N) was calculated from the TN and TOC. This content. Besides showing an input signal, we used this ratio can be used as a rough indicator for the state of degradation or source of organic matter. Assuming a constant source, a higher ratio indicates better-preserved organic matter (Stevenson, 1994; Strauss et al., 2015).

3.2.3 Magnetic susceptibility and grain size analysis

Subsamples taken for grain size analysis were first measured for mass specific MSmagnetic susceptibility using a Bartington Magnetic Susceptibility Meter Model MS2 and a frequency of 0.465 kHz. This allows us to differentiate between different mineral compositions (Butler, 1992; Dearing, 1999).

. Values are given in SI units (10^{-8} m³/kg).

For grain size analysis, the samples were treated with hydrogen peroxide and put on a shaker for 28 days to remove organic material. The pH was kept at a reaction-supporting level between 6 and 8. Subsequently, the samples were centrifuged and freeze–dried. OneOf each sample, 1 g of each sample was mixed with tetra-Sodium Pyrophosphate 10–hydrate ($Na_4P_2O_7*10H_2O$) (dispersing agent) and dispersed in an ammonia solution. The grain size distribution and proportions were finally determined using a Malvern Mastersizer 3000 equipped with a Malvern Hydro LV wet–sample dispersion unit. Statistics of the grain size measurements were calculated using Gradistat 8.0 (Blott and Pye, 2001).(Blott and Pye, 2001). Results are used to identify different stratigraphic layers via material composition and to deduce sedimentary processes.

3.2.4 Radiocarbon dating

Radiocarbon dating was done for nine samples using the Mini Carbon Dating System (MICADAS) at AWI Bremerhaven. The results were calibrated using Calib 7.1 (Stuiver et al., 2018). We used bulk sediment samples for dating due to a lack of macro-organic remains within the deposits. The curve used for calibration was IntCal13 (Reimer et al., 2013) and results are given in calibrated years before present (cal yr BP).The results were calibrated with the software Calib 7.1 (Stuiver et al., 2018) using the IntCal13 calibration curve (Reimer et al., 2013). Results are given in calibrated years before present (cal yr BP). The age–depth model was developed using the "Bacon" package in the R environment (Blaauw and Christen, 2011) (Fig. S2).

3.2.5 Stable isotopes

~~Stable~~Besides showing a source signal (Meyers, 1997), stable carbon isotopes can be used as a proxy for the degree of decomposition of organic material, as during decomposition and mineralization ~~C^{12}~~12C is lost, resulting in a higher share of ~~C^{13}~~13C and hence a higher $\delta^{13}C$ ratio (Fig. S3) (Diochon and Kellman, 2008).

Twenty-three subsamples for $\delta^{13}C$ analysis were ground and carbonates were removed by treating the samples with hydrochloric acid for three hours at 97.7 °C. The samples were then vacuum-filtered, dried, and weighed into tin capsules for analysis. The ~~measurement of~~ stable carbon isotopes ~~was carried out~~were measured using a Delta V Advantage Isotope Ratio MS supplement equipped with a Flash 2000 Organic ~~Elementar~~Elemental Analyzer. The results are compared to the Vienna Pee Dee Belemnite (VPDB) standard and given in per mille (‰) (Coplen et al., 2006)~~.~~ with an analytical accuracy of ≤ 0.15 ‰.

Stable hydrogen and oxygen isotopes can be used as a temperature proxy. Lower δ^2H and $\delta^{18}O$ values indicate ~~a~~ lower ~~mean temperature; with higher~~ temperatures ~~evaporation increases, which leads to an increased loss of H^1 and O^{16} and raises the δ^2H and $\delta^{18}O$ ratios (Yao et al., 2006).~~during precipitation. Samples taken from the ice wedges ~~are supposed to~~generally yield a winter temperature signal~~, but~~ (Opel et al., 2018), whereas pore ice and pore water ~~signal~~signals are a mix of different seasons with a higher uncertainty due to alteration and fractionation during deposition and ~~freezing~~ multiple freeze-thaw cycles as well as evaporation (Meyer et al., 2000).

~~Our δ^2H and $\delta^{18}O$ samples were measured using a Finnigan MAT Delta–S mass spectrometer and the equilibration technique was after Horita et al. (1989). In total, 29 samples were measured, of which 16 originated from YED1 pore ice, 8 originated from YED1 wedge ice, and 5 from Alas1 pore ice or pore water. The results are given in per mille related to standard mean ocean water (‰ vs. SMOW).~~

Our δ^2H and $\delta^{18}O$ samples were measured at AWI Potsdam Stable Isotope Laboratory using a Finnigan MAT Delta–S mass spectrometer with the equilibration technique after Horita et al. (1989). In total, 29 samples were measured, of which 16 originated from YED1 pore ice, 8 originated from YED1 wedge ice, and 5 from Alas1 pore ice or pore water. The results are given in per mille related to standard mean ocean water (‰ vs. SMOW). The analytical accuracy for δ^2H was ≤ 0.8 ‰ and for $\delta^{18}O$ it was ≤ 0.1 ‰ (Meyer et al., 2000). The d excess ($d=\delta^2H-8*\delta^{18}O$) was calculated as well from these values.

3.2.6 Statistics and bootstrapping approach for carbon budget estimations

For the mean grain size, the medianmean of each core unit, consisting of several samples' mean values, is given. The interquartile range of 25 % and 75 % is given.

To calculate the carbon quantity ofWe estimated the examined soil cores, we used carbon budget of the Yukechi Alas area after Eq. (1), using a bootstrapping approach using the "boot" package in the R environment..

$$OC\ quantity\ (kt) = \frac{thickness * coverage * \frac{100-WIV}{100} * BD * \frac{TOC}{100}}{10^3} \qquad (1)$$

with deposit thickness in m, coverage in m², WIV in vol %, BD in 10³ kg/m³ and TOC in wt%. For all TOC values below the detection limit (0.1 wt%), a value of 0.05 wt% was set. Missing bulk density values, resulting from low ice contents (< 20 wt%) (Strauss et al., 2012), were calculated after Eq. (12), which describes the relation between TOC and bulk density in the examined cores.

$$(1)\quad bulk\ density = 1.3664^{-0.115*TOC}$$

Bootstrapping calculations were made for the sediment part of the cores. The ice wedge in YED1 was excluded in the bootstrapping. The calculations were done for separate depth levels: For the top 3 m of each core and for both complete cores with 10,000 iterations each.

For carbon budget estimations of the Yukechi Alas area, the $bulk\ density = 1.3664^{-0.115*TOC}$ (2)

The core length of the examined cores was assumed to represent the different ground types, resulting in a general depthdeposit thickness of 22 m for Yedoma deposits and 20 m for Alas deposits. A mean wedge-ice volume of 46.3 % for Central Yakutian Yedoma deposits and 7 % for Alas deposits of Central Yakutia was assumed following Ulrich et al. (2014).Ulrich et al. (2014). We estimated the deposit coverage of Yedoma and Alas deposits using satellite imagery as shown in figure S1. The ice wedge in YED1 was excluded in the bootstrapping.

Bootstrapping calculations were done after Jongejans and Strauss (2020) for the upper 3 meters, the different core units as well as for the complete cores (Table 2) using the "boot" package in the R environment. Bootstrapping included 10,000 iterations of random sampling with replacement. We used combined BD and TOC values, as they are not independent, and corrected for irregular sampling by value replication according to depth interval. We calculated the mean and standard deviation of all iterations.

4 Results

4.1 Characteristics of the Yedoma deposits

The Yedoma core YED1 visually appears rather heterogeneous (Fig. 3a) with material varying from fine gray material (Fig. 3b[1]) to sandy grayish brown material (Fig. ~~3b[2]). Between 0 and 691cm bs and between 1920 and 2235~~3b[3]) (Windirsch et al., 2020a). Between 2235 and 1920 cm bs and between 691 and 0 cm bs, brown to black dots up to 2 cm in diameter may be organic-rich material. Cryostructures include structureless to micro-lenticular ice and larger ice veins and bands. The core penetrated an ice wedge between ~~691 and~~ 1005 and 691 cm bs, ~~in which only~~so we could take ice ~~but no sediment~~ samples ~~could be collected.~~only. The core contains an unfrozen layer close to the surface between approximately ~~100~~200 and ~~200~~100 cm bs, representing a thin initiating talik layer underneath the 100 cm thick frozen active layer (Fig. 3a, red). All laboratory results are listed in detail in the PANGAEA repository (Windirsch et al., 2019).~~Taliks form because the active layer does not freeze completely anymore in some regions.~~

Figure 3 – a: overview of the Yedoma core; depth given in cm bs; state after core retrieval is given by colors: blue = frozen, red = unfrozen; location of the ice wedge is ~~marked~~labelled; brown ~~marks~~illustrates silty sediments, yellow ~~marks~~represents sandy sediments; b: detailed pictures of the YED1 core; (1) 332–317~~-332~~ cm bs, picture of unit Y1 showing black organic-rich inclusions within the grey silty matrix; (2) 960–944 cm bs, picture of the wedge ice in Y2; (3) 1549–1532~~-1549~~ cm bs, picture of Y3, showing the coarse sandy material with no visible cryostructures or organic material; (4) 2133–2117 cm bs, picture of Y4, showing the grey silty matrix with some dark organic dots.

We divided the Yedoma core into four main Yedoma units (Y) (Fig. 4). Y4 is the lowest (2235 to 1920 cm bs) and oldest (radiocarbon age of 49,323 cal yr BP~~) stratigraphical~~) stratigraphic unit. The absolute ice content slightly increased towards the surface (35.8 to 36.6 wt%, peak value of 53.6 wt% in between). MS also increased from 60.~~7267~~7 to 155.~~359 * 10^{-8} m^3/kg.~~4 SI. The grain size was rather consistent with a ~~median~~mean value of ~~$25.3^{+0.9}_{-0.7}$~~ 24.3 ± 3 µm and the ~~material composition~~soil texture varied between sand and silt (Fig. S4, S5). We found TOC contents of up to 1.7 wt% (mean of 1.3 wt~~%) were found.~~%). The C/N ratios within this unit varied between 9.2 and 10.6, and $\delta^{13}C$ values ranged between -25.27 and -24.66 ‰ vs. VPDB (Fig. S3). TN values only reached the detection limit of 0.1 wt% in 9 out of 36 samples in the whole YED1 core. As just these 9 samples exceeded the detection limit (highest value 0.16 wt% at 2036 cm bs), only they have been used for C/N ratio calculations.

The radiocarbon sample age of Y3 (between 1927 and 1010 cm bs) ~~was dated with~~ yielded an infinite ~~radiocarbon sample~~age (> 49,000 yr BP) with ^{14}C below detection limit. There is a transition zone between Y4 and Y3 represented by a diagonal sediment boundary in the core between 1927 and 1920 cm bs (see Fig. 3a). Y3 showed distinctly lower absolute ice contents (< 32.1 wt%). MS varied between 120.~~468~~5 and 285.~~023 * 10^{-8} m^3/kg.~~0 SI. Higher sand contents (> 56.9 vol%) led to an increase in ~~mean~~ grain size (72.1 to 191.6 µm~~);~~) with a mean grain size ~~only~~of 120.5 ± 35.5 µm. Grain size decreased down to 33.3 µm in the uppermost sample of Y3~~. No measurable~~ and no detectable TOC was found in this unit.

Y2 (1010 to 714 cm bs) consisted of ~~ice~~ massive wedge ice~~.~~, which contained very little sediment inclusions (Fig. 3b [2]). Thus, only water isotopes (δ^2H and $\delta^{18}O$ ~~were~~) could be measured and analysed. The results are described in section 4.3.

Y1 (714 to 0 cm bs) is the uppermost and youngest unit with carbon ages ranging between 40,608 (589.5 cm bs) and 21,890 cal yr BP (157.5 cm bs). Ice content decreased from the ice wedge towards the surface~~. Values ranged~~ ranging from 14.6 wt% (110 cm bs) to 57.4 wt% (688 cm bs). MS decreased towards the surface ~~ranging~~ from 108.~~12 * 10^{-8} m^3/kg~~1 to 15.~~36 * 10^{-8} m^3/kg~~4 SI in the uppermost sample, with a maximum of 118.~~63 * 10^{-8} m^3/kg~~6 at 298 cm bs. This unit consisted of fine sediment with a ~~median~~mean grain size of ~~$20.3^{+0.9}_{-2.2}$~~19.9 ± 4.2 µm. It contains up to 1.4 wt% TOC (298 cm bs). C/N values were in the range of 9.1 to 12.9. The lowest $\delta^{13}C$ value was found at 21 cm bs with -28.07 ‰ vs. VPDB; the lower part of this section showed a mean value of -24.42 ± 0.6 ‰ vs. VPDB.

Figure 4 - Characteristics of the Yedoma core YED 1: radiocarbon ~~age~~ages, absolute ice content, bulk density, magnetic susceptibility (MS~~,~~), grain size composition, mean grain size, total organic carbon (TOC~~,~~) content, carbon-nitrogen (C/N) ratio and stable carbon isotope ($\delta^{13}C$) ratio; hollow ~~triangle~~circle indicates an infinite radiocarbon (dead) age; grey/white areas mark the different stratigraphic units (Y1 to Y4).

The ~~cumulative~~ grain size ~~results~~distributions (Fig. S5) illustrate the differences between the core units. Silt is the dominant grain size class in Y4 and Y1, whereas unit Y3 is ~~clearly~~ dominated by sand.

~~Our results reveal only small amounts of TOC in the Yedoma deposit. The TOC values were smaller than 0.1 wt% in 24 of 36 samples. Y3 contained no detectable TOC.~~

The calibrated radiocarbon ages of the Yedoma deposits are listed in Table 1 and assigned to the different core units. Our age–depth model (Fig. S2a) indicates a steep age-depth relationship from approximately 1200 to 2235 cm bs and a rather well defined, gradual age-depth relationship from 1200 cm bs towards the surface (Fig. S2a).

The bootstrapping approach resulted in a mean soil organic carbon (SOC) estimation of 4.48 ± 1.43 kg/m³ for the top 3 m of the YED1 core and a mean of 5.27 ± 1.42 kg/m³ for the entire core~~.~~ (table 2). We calculated a carbon inventory of 56.8 ± 15.2 kt for the Yukechi Yedoma deposits by upscaling the carbon storage to the complete Yedoma coverage in the Yukechi Alas landscape (66.4 %, ~ 917,000 m²) (Fig. ~~S1). In this calculation we assumed a Yedoma thickness of 22 m, similar to the length of the YED1 core, and we used the average TOC densitiy of YED1 (5.27 kg/m³).~~S1).

4.2 Characteristics of the Alas deposits

The Alas1 core contains a large proportion of unfrozen sediment (i.e. talik; ~ 750 to 160 ~~to 750~~ cm bs) (Fig. 5a, red), which led to the loss of some core sections during drilling. The absolute ice content given for samples retrieved from this zone represents absolute water content; samples were frozen directly after core recovery and field description. The core's visual appearance was more homogeneous compared to YED1 regarding color (greyish brown) and material (clayish silt ~~[Fig. 5b(1)] to sandy silt [Fig. 5b(2)]).~~(Fig. 5b[2]) to sandy silt (Fig. 5b[4])) (Windirsch et al., 2020b). Cryostructures of the frozen core below 750 cm bs included horizontal ice lenses up to 5 cm thickness and structureless non-visible ice. Blackish dots and lenses (up to 1 cm in diameter) hint that organic material is included in the sediments. ~~We estimated the active layer to reach down to approximately 200 cm bs based on Fedorov (2006).~~The frozen sediment of the uppermost 160 cm bs represents the seasonally freezing layer.

Figure 5 – a: overview of the Alas1 core; depth given in cm bs; state after core retrieval is given by colors: blue = frozen, red = unfrozen; light brown marks silty material, yellow marks sandy material, dark brown marks silty material containing more organic material; b: detailed pictures of the Alas1 core; (1) ~~828–840~~88–64 cm bs, picture of A1 showing the silty grey matrix including dark organic structures; (2) 840–828 cm bs, picture of the sandy A2 unit; (~~2)~~ 3) 1169–1148 cm bs, picture of A3 showing a silty grey matrix with some darker organic dots; (4) 1781–1767~~–1781~~ cm bs picture of the fine-grained silt-dominated A4 unit including black organic-rich inclusions.

We divided the Alas1 core into four stratigraphic units (A1 to A4), according to ~~cryolithologic composition~~soil texture and, if applicable, carbon content (Fig. 6). The oldest unit is A4 (1980 to 1210 cm bs) with radiocarbon ages of 42,865 cal yr BP (1967.5 cm bs) and 45,870 cal yr BP (1530.5 cm bs). An age inversion was detected here. Absolute ice content ~~was rather stable~~did not show a specific trend and ranged from 15.3 wt% at 1400.5 cm bs to 25.4 wt% at 1220 cm bs. MS ranged between 62.~~146 * 10^{-8} m^3/kg~~1 (1967.5 cm bs) and 133.~~930 * 10^{-8} m^3/kg~~9 SI (1759 cm bs) with much higher values in ~~the~~a sand intrusion ~~(~~found between 1530.5 and 1312 cm bs (266.~~667 * 10^{-8} m^3/kg~~7 at 1464 cm bs, 268.~~690 * 10^{-8} m^3/kg~~7 at 1400.5 cm bs). The mean grain size was ~~rather~~ constant (~~median of 27.4$^{+3.6}_{-10.0}$~~35.9 ± 36 µm) except for ~~a~~the sandy intrusion ~~between 1530.5 and 1312 cm bs (~~(152.9 µm at 1464 cm bs, 72.6 µm at 1400.5 cm bs~~)~~), leading to a high standard deviation (Fig. S4, S6). While TOC values were below detection limit within this sandy material, the other parts of A4 held TOC amounts of up to 1.8 wt% (1759 cm bs). The C/N ratio ranged between 5.8 (1274 cm bs) and 8.9 (1759 cm bs) with a mean value of 7.4 (Fig S2). The δ^{13}C values showed a range of -25.67 to -24.06 ‰ vs. VPDB (Fig. S3). Only the TN values that exceeded the detection limit, which was the case in 8 out of 28 samples in the entire Alas1 core, have been used for C/N ratio calculations.

A3 ranged from 1210 to 925 cm bs. The absolute ice content was stable around 22.7 ± 2.9 wt%. MS increased towards the surface from 72.~~102 * 10^{-8} m^3/kg~~1 SI (1205.5 cm bs) to 122.~~629 * 10^{-8} m^3/kg~~6 SI (955 cm bs). A3 was characterized by less coarse material compared to A4~~,~~ (Fig. S6), with a ~~median~~mean grain size of ~~20.4$^{+5.1}_{-3.2}$~~19.7 ± 3.7 µm. All TOC values were below detection limit, so no C/N could be calculated and no δ^{13}C could be measured.

The characteristics of A2 (925 to 349 cm bs) were similar to those of the sand intrusion found in A4. A radiocarbon age of 27,729 cal yr BP was measured at 812.5 cm bs. The absolute ice content had a mean ~~value~~ of 15.2 wt% and decreased from 16.7 wt% at 919.5 cm bs to 12.9 wt% at 395 cm bs. MS decreased upwards from 302.~~337~~3 to 129.~~232 * 10^{-8} m^3/kg~~2 SI. The mean grain size at the bottom of this unit was 102.3 µm (919.5 cm bs), increased to 221.9 µm at 812.15 cm bs towards the surface, and reached the lowest value of 41.2 µm at the upper boundary of A2~~.~~ (Fig. S6) with an overall mean of 108.0 ± 59.5 µm. All TOC values were below the detection limit.

The uppermost stratigraphic unit A1 starts at 349 cm bs. It is the youngest unit of Alas1 with a radiocarbon sample at 199 cm bs dated to 15,287 cal yr BP. The absolute ice content slightly increased from 19.1 wt% (344.5 cm bs) to 23.1

wt% (9 cm bs) throughout this unit. MS decreased towards the surface, starting at 126.~~692 * 10^{-8} m^3/kg~~7 (344.5 cm bs) and reaching 50.~~772 * 10~~-8 ~~m^3/kg~~ at 9 cm bs. The mean grain size decreased again, compared to A2, representing silty material with values of ~~$18.5^{+1.4}_{-1.6}$ µm.~~ $18.5^{+1.4}_{-1.6}$ µm. The mean grain size for this unit was 20.0 ± 4.6 µm. TOC was only detectable in the uppermost sample with a value of 2.4 wt% (9 cm bs). The C/N ratio for this sample was 12.0 and the $\delta^{13}C$ was -27.24 ‰ vs. VPDB.

Figure 6 - Characteristics of the Alas1 core: radiocarbon ~~age~~ages, absolute ice content, bulk density, magnetic susceptibility (MS~~,~~), grain size composition, mean grain size, total organic carbon (TOC~~,~~) content, carbon-nitrogen (C/N) ratio and stable carbon isotope ($\delta^{13}C$) ratio; grey/white areas mark the different stratigraphic units (A1 to A4).

The radiocarbon ages are listed in Table 1. The age-depth model (Fig. S2b) shows a rather continuous ~~steepness~~slope for all calibrated ages of Alas1.

Bootstrapping resulted in a mean SOC value of 6.93 ± 2.90 kg/m³ for the top 3 m of the Alas1 core~~.~~ (table 2). The calculation for the whole core resulted in a mean value of 6.07 ± 1.80 kg/m³ carbon. For the whole Alas area within the Yukechi Alas landscape (20.6 %, ~ 284,000 m²) (Fig. S1 [green]), we calculated a total organic carbon stock of 32.0 ± 9.6 kt using an estimated deposit thickness of 19.8 m.

4.3 Water isotope analysis of the YED1 and Alas1 core

Stable hydrogen and oxygen isotope results are shown in figure 7. ~~There was a~~We found clear downward ~~trend~~trends of $\delta^{18}O$ and δ^2H values becoming more negative between ~~400 and~~ 1000 and 400 cm bs in the YED1 core (Fig. 7b). ~~It was shown that lower $\delta^{18}O$ values are linked to lower δ^2H values (Fig. S7), as there was a downward trend of δ^2H values over depth in this core section as well.~~ Below 1000 cm bs, both δ^2H and $\delta^{18}O$ become less negative with increasing depth. $\delta^{18}O$ ranged between -25.16 ‰ at the lowermost sample and -30.70 ‰ at 1071.5 cm bs with a much less negative value of -15.53 ‰ closest to the surface. While the uppermost Yedoma sample had a δ^2H value of -120.8 ‰, all other Yedoma samples showed much more negative values between -181.3 ‰ (2209.5 cm bs) and -221.6 ‰ (1071.5 cm bs). Values almost aligned with the global meteoric water line (GMWL~~) and~~), but partly also the local evaporation line (LEL) of Central Yakutia (Wetterich et al., 2008), except for the ice wedge samples of YED1 (Fig. ~~7a).~~7a). The isotope data obtained from the ice wedge samples had more negative values for both δ^2H (-220.6 ‰ to -228.6 ‰) and $\delta^{18}O$ (-29.58 ‰ to -30.55 ‰) in comparison to the remaining YED1 core. The d excess values are lowest in the YED1 ice wedge (lowest value of 9.3). Other values range between 3.5 in the uppermost sample as an outlier and generally range between 14.7 and 29.5 with no clear trend visible.

Most of the Alas samples were too dry to extract pore water for water isotope analysis, resulting in a low number of water samples for this core (Fig. 7c). These Alas1 samples showed ~~less~~little variance in δ^2H and $\delta^{18}O$ data, ranging from -13.33 ‰ (103 cm bs) to -15.48 ‰ (1154 cm bs) for $\delta^{18}O$ and -130.4 ‰ (61 cm bs) and -137.6 ‰ (1464 cm bs) for δ^2H. d excess values are lower towards the surface (-22.8 at 61 cm bs, -24.3 at 103 cm bs) and range from -14.1 to -12.2 in the lower core part.

Figure 7 – The characteristics of water stable isotopes in the studied sediment cores.; a: stable hydrogen (δ^2H) and oxygen (δ^{18}O) isotope ratios of YED1 pore ice (black triangles), YED1 ice wedge ice (semi-hollow triangles), and Alas1 pore ice and pore water (black dots) [‰ vs. SMOW]; global meteoric water line GMWL: y=8xδ^2H=8*δ^{18}O+10; local evaporation line LEL of Central Yakutia (based on data compiled until 2005 after Wetterich et al., 2008); b: oxygen isotopes, hydrogen isotopes and d excess values of YED1 plotted over depth; c: oxygen isotopes of YED1 (b), hydrogen isotopes and d excess values of Alas1 (c) plotted over depth.

5 Discussion

5.1 Carbon accumulation and loss at the Yukechi study site

We found surprisingly low TOC values in certain core sections of the Yedoma and Alas deposits. These low values appear in correlation withrelation to coarser sediments (fine sand), while the rather fine sediment layers (silt and sandy silt) store more TOC. The similarities in sediment structure and composition of the two cores, in particular between units Y1, Y4 and A4 in terms of grain size composition and OC content, and the increased accumulation rates towards the core bottoms (Fig. S2) indicate that the sedimentary sources regime waswere the same for both cores until approximately 35,000 cal yr BP (Fig. 4 and 6).

On the one hand, low TOC content could be a result ofcaused by high organic matter decomposition during accumulation or during a thawed state, especially in thermokarst deposits. On the other hand, it could simply reflect low carbon inputs. A suitable explanation for a low-input. In our case, we argue that scenario is a change in the sedimentary regime due to fluvial transportation processes as is explained in more detail in chapter 5.2. The low stable carbon isotope data of our cores, assuming that the source signal was more or less constant with time, are (between -24.06 and -27.24 ‰ and‰) are at the low end, but comparable to other studied sites from the Yedoma domain (Schirrmeister et al., 2013; Strauss et al., 2013; Jongejans et al., 2018).. Our C/N data suggest a more or less homogeneous source signal of the organic material. Both cores show the lowest δ^{13}C values closest to the surface as the organic material is the most recent and therefore least decomposed. As we lookIn deeper insections of the cores, δ^{13}C becomes is higher (less negative and constant) with no general trend over depth in the Alas and Yedoma deposits; we. We interpret this to mean greateras an indication of higher decomposed material already being present before freezing. We see that decomposition at depth. Decomposition ceased when the lower samplesdeposits became frozen, resulting in a constant δ^{13}C values not showing a clear trend at depth. The stable C/N ratios in both cores support this hypothesis and are in line with the results found by Strauss et al. (2015) and Weiss et al. (2016). for other Yedoma and Alas sites in Siberia. In comparison to the mean C/N ratio of 10 in YED1, the mean C/N ratio of 8 for Alas1 may indicateindicates that the Alas deposits were only slightly more affected by decomposition. due to their temporary thawed state during lake phase. As the carbon was freeze-locked in the YED1 core and thereforethe entire time since being frozen, it was not decomposed since deposition, this similarity in mean C/N ratios indicates that the original carbon state for the deposits at both coring sites were similar, assuming the same carbon source for both deposits. The slightly lower C/N values found in Alas1 likely resulted from decomposition well after original deposition. It is more likely that the initiation of a talik led to increased decomposition of these sediment sections.

. The Yukechi C/N values are on the low end of C/N ratios known from other Yedoma deposits, e.g. from Bykovsky Peninsula (Schirrmeister et al., 2013) and Duvanny Yar (Strauss et al., 2012). The similarity of the low C/N ratios from both cores supports the hypothesis of an input of organic-poor and already pre-decomposed material is rather than the complete post-deposition decomposition of the organic matter in the now organic-free core segments, as the latter would require unfrozen conditions for extended periods in deep layers at the coring sites.

We found age inversions in both cores at similar age and depth (YED1 49,232 cal yr BP, 1998.5 cm bs; Alas1 42,865 cal yr BP, 1967.5 cm bs) (Fig. 4 and 6, Fig. S2). The stable water isotopes signal of YED1 shows characteristics different from precipitation water or the Alas1 water isotope results throughout the core (Fig. 7, Fig. S7) which is evidence that YED1 has not been thawed since accumulation. Rather, these findings suggest a temporary shift in sediment input at approximately 35,000 cal yr BP. This would have been caused by reworking of sediments or the remobilization of older material by transport processes and the incorporation of this older material in younger sediments.

The permanently frozen conditions of the Yedoma deposits at YED1 are supported by the water isotope signals (Fig. 7) with much lower $\delta^{18}O$ values for the lower Yedoma pore ice, compared to the uppermost sample showing a water isotope signal of very recent climate. If the Yedoma core had been thawed at some point, intruding water would have led to a rather homogeneous oxygen isotope signal throughout the core. This e.g. can be seen in the Alas core. Also, the intact ice wedge supports the hypothesis of a permanently frozen state throughout the depositional history at YED1. The very similar isotope signals derived from the ice wedge indicate even colder climate conditions during the formation of that ice wedge. Brosius et al. (2012)fact that both cores, Alas1 and YED1, show similar $\delta^{2}H$ and $\delta^{18}O$ values in Central Yakutia for an ice wedge dating to late Pleistocene (-242 ‰ for $\delta^{2}H$ and -30.9 ‰ for $\delta^{18}O$). The offset in comparison to the ice wedge we examined can be explained by climatic variations. The negative trend in the $\delta^{18}O$ values of YED1, starting from the bottom towards the ice wedge, is likely linked to a cooling climate in Central Yakutia from approximately 49,000 to 41,000 cal yr BP (Fig. 7b).

These findings low C/N ratios. The carbon characteristics indicate that the low carbon content must resultresults from low carbon input rather than high decomposition rates in both cores, as no evidence for conditions favoring high decomposition rates was found. Furthermore, the very similar sediment characteristics of both cores suggest that the Alas deposits originate from in situ thaw and reworking of the local Yedoma. Therefore, low carbon content is likely not the result of high decomposition during the thawed lake phase rates during lake coverage.aquatic conditions of a lake-covered state, but a legacy of the source material. For thisa decomposition during lake phase scenario, organic carbon parameters would differ largely in carbon content and isotope signature from those of the still-frozen Yedoma (Walter Anthony et al., 2014).

~~The age-depth models of both cores show steep curves, hence higher sedimentation rates at the bottom of both cores, which slow down towards the surface (Fig. 4 and 6, Fig. S2). This indicates that during the early phase of the sediment accumulation (~ 45,000 to 35,000 cal yr BP) the depositional environment at Alas1 was the same as at YED1. The steepness of the age–depth model suggests an upward decrease in the accumulation rate, or can be interpreted as an increase in surface erosion towards the top of the YED1 core (Figure S3a). Especially the sandy core part of Y3 accumulated quickly with the next radiocarbon sample below dated to 49,232 cal yr BP (71.5 cm below the bottom of Y3) and the next radiocarbon sample above dated to 40,608 cal yr BP (420 cm above the top of Y3). These 917 cm of Y3 therefore accumulated in less than 8,624 years, while in Y1, the accumulation of 714 cm took more than 18,718 years (40,608 cal yr BP at 589.5 cm bs, 21,8900 cal yr BP at 157.5 cm bs) (Table 1). The continuous steepness shown by the age-depth model of Alas1 (Fig. S2b) suggests a rather stable accumulation rate throughout the deposition of these sediments.~~

We found age inversions in both cores with similar age and depth (YED1 49,232 cal yr BP, 1998.5 cm bs; Alas1 42,865 cal yr BP, 1967.5 cm bs) (Fig. 4 and 6, Fig. S2) which is typical for many Yedoma sites (Schirrmeister et al., 2002). While cryoturbation might seem an obvious explanation, we suggest that this process did not play a major role here due to the long-term frozen state of YED1. Rather, we assume that the age inversions indicate a temporary shift in sediment input at approximately 35,000 cal yr BP. This could have caused some in-deposit reworking in the watershed and the incorporation of older material into younger sediments. In addition, the dating of bulk sediments very close to the maximum datable age of ~ 50,000 yr BP may cause a high uncertainty in the absolute ages of sediment layers (Reimer et al., 2013). Therefore, the rather small age inversions (> 49,000 cal yr BP to 49,232 yr BP in YED1, and 45,870 cal yr BP to 42,865 cal yr BP in Alas1) could be a result of material mixture in dated bulk samples. The radiocarbon ages above this age inversion align well with a simulated sedimentation rate, as shown in figure S2.

5.2 Yedoma and Alas ~~coherence~~development

The differences in ice content between both cores and the ~~homogeneity of~~ homogeneous ice content throughout the whole Alas1 core indicate that thaw processes influenced the Alas deposit ~~was influenced by thaw processes. This is underlined~~. As described above, this is supported by the water isotope signals, which are quite homogeneous throughout Alas1~~, suggesting~~. This is the quantitative evidence that these deposits have been previously thawed under thermokarst influence ~~and were in a state of meltwater saturation in a talik.~~. The homogeneity in water isotopes is an outcome of percolating surface water during a thawed state. Subsequent talik refreezing ~~resulted in~~in sandy sediments lead to the formation of structureless pore ice, forming a taberal deposit (Wetterich et al., 2009). ~~This is a result of percolating surface water during a thawed state. The saturation with surface water results in homogeneous isotope~~

~~signals throughout thawed core segments. Refreezing starting from the surrounding frozen ground rather than from the surface, as a talik is still present in the upper core part, resulted in structureless, invisible to microlenticular ice structures, due to the sandy material providing relatively large pore spaces (French and Shur, 2010). Due to the formation of those small ice structures, no sediment was moved here by the formation of e.g. large ice veins, resulting in an unmixed and still clearly structured sediment, including the contained carbon (Iwahana et al., 2014).~~Refreezing, in our case, started from the surrounding frozen ground rather than from the surface, as a talik is still present in the upper core part. This allowed for the formation of structureless, invisible to microlenticular ice structures in the sandy material providing relatively large pore spaces (French and Shur, 2010). Due to the formation of those small ice structures, no sediment mobilization by the formation of, for example, large ice bands occurred in this core, resulting in an unmixed and clearly layered sediment. This also excludes cryoturbational processes as an explanation for the age inversions that we found.

~~Taking~~The perennially frozen conditions since incorporation into ~~account that there~~permafrost of the Yedoma deposits at YED1 are supported by the water isotope signals (Fig. 7) with much lower $\delta^{18}O$ values for the Yedoma pore ice in comparison to the uppermost sample (4 cm bs in YED1). The latter shows a water isotope signal reflecting very recent climate and freezing, thawing and evaporation processes in the active layer. If the Yedoma core had been thawed at some point, intruding water would have led to a more homogeneous oxygen isotope signal throughout the core as it is obvious in the Alas core. Also, the intact ice wedge gives evidence for a perennially frozen state throughout the depositional history at YED1. The stable isotope ratio values of wedge ice (mean $\delta^{18}O$ of -30 ‰, mean $\delta^{2}H$ of -224 ‰) reflects winter precipitation and fits well into the regional pattern for Marine Isotope Stage (MIS) 3 ice wedges in Central and Interior Yakutia (Popp et al., 2006; Opel et al., 2019) while the d excess shows a much elevated value (16 ‰) compared to the regional pattern (Popp et al., 2006; Opel et al., 2019). The d excess values from the middle part of the ice wedge correspond well to the regional values from Mamontova Gora, Tanda and Batagay (Opel et al., 2019), while the others fit to those of the host sediments and are potentially overprinted by exchange processes between wedge ice and pore ice (Meyer et al., 2010). Due to the low number of datapoints, no meaningful co-isotopic regression was calculated. The stable isotope composition of pore ice shows a co-isotopic regression of $\delta^{2}H = 6.61\ \delta^{18}O - 18.0$ ($R^2 = 0.97$, $n = 23$), which is typical for Yedoma intrasedimental ice (Wetterich et al., 2011; 2014; 2016). The isotope values plot well above the regional Local Meteoric Water Line of the cold season (Papina et al., 2017), suggesting a substantial proportion of (early) winter precipitation – usually characterized by high d excess values – for the pore ice, which is also evident for some units ~~with~~ of the Batagay megaslump (Opel et al., 2019). The decreasing trend of pore ice isotopic δ values from the bottom to the top indicates a general cooling in Central Yakutia during the covered time span of our study. However, as it is accompanied by an opposite increasing trend in d excess, these values may be overprinted by secondary freeze-thaw processes in the active layer and rather reflect the intensity of these fractionation processes (Wetterich et al., 2014).

The age-depth models of both cores show steep curves and higher sedimentation rates at the bottom of both cores, which slow down towards the surface (Fig. 4 and 6, Fig. S2). This indicates that during the early phase of the sediment accumulation (~ 45,000 to 35,000 cal yr BP), the depositional environment at Alas1 was the same as at YED1. The steepness of the age–depth model suggests an upward decrease in the accumulation rate or can be interpreted as an increase in surface erosion towards the top of the YED1 core (Figure S3a). Especially the sandy core part of Y3 accumulated rapidly, as indicated by the radiocarbon sample below dated to 49,232 cal yr BP (71.5 cm below the bottom of Y3) and the next radiocarbon sample above dated to 40,608 cal yr BP (420 cm above the top of Y3). These 917 cm of Y3 therefore accumulated in less than 8,600 years, while in Y1, the accumulation of 714 cm took more than 18,700 years (40,608 cal yr BP at 589.5 cm bs, 21,890 cal yr BP at 157.5 cm bs) (Table 1). The continuous steepness of the age-depth model of Alas1 (Fig. S2b) suggests a rather constant accumulation rate throughout the deposition of these sediments.

Due to the alternation of coarse and carbon-poor material ~~and very little organic carbon~~ (i.e. Y3 and A2, see Fig. 4 and 6) ~~that alternate~~ with ~~finer and more~~ fine carbon-rich material (i.e. Y1 and Y4 in Fig. 4, A4 in Fig. 6), ~~there must have been~~we suggest shifts in the sedimentary regime at the Yukechi study site (Soloviev, 1973; Ulrich et al., 2017a; Ulrich et al., 2017b)~~.~~. This hypothesis is supported by the MS results, which give higher values for sandy core parts, hinting at a different material source, compared to the silty and carbon-bearing core units. Due to the great thickness of ~~the~~those sandy layers (core units 1 to 4, Fig. 4 and 6~~)~~), the most suitable explanation is material transport by tributaries on top of the (former) Yedoma uplands of the Abalakh Terrace. ~~Tributary paths changed over time, resulting in flooding connections to and then disconnections from our study area. During~~We interpret that the sandy material in the studied cores was deposited during the river-connected flooding ~~times~~phases at our study site~~, the sandy material was deposited. Fluvial~~. Moreover, fluvial transport gives a suitable explanation for ~~absent~~low carbon content as organic matter decomposition is often much higher under aquatic conditions (Cole et al., 2001). ~~High~~Furthermore, high flow velocity ~~also plays an important role in deposition processes, as higher flow velocities~~ allow for larger particles to be deposited, but keep ~~the~~ lighter particles, like organic material, in suspension (Anderson et al., 1991; Wilcock and Crowe, 2003; Reineck and Singh, 2012).

Another explanation for the occurrence of these carbon-poor sandy layers are shifts in wind direction and wind speed and therefore the sediment carrying capacity of the wind (Pye, 1995). A shift in eastern Siberian climate during the beginning of the ~~Karginian~~Kargin interstadial (MIS 3, ~ 50,000 yr BP) resulted in higher winter temperatures (Diekmann et al., 2017) and therefore higher pressure gradients within the atmosphere, leading to greater wind speeds. ~~That~~This in turn resulted in higher sediment carrying capacity of the wind ~~and would provide~~which provides a suitable explanation for the sediment differences. Also, sand dunes of the Lena River valley (Huh et al., 1998) could have provided sufficient sandy material throughout the formation of the sand layers found in the Yukechi deposits (Y3 and A2 in Fig. 4 and 6). The radiocarbon ages of these coarser core segments (Y3 and A2 in Fig. 4 and 6) dated between 39,000 and 18,000 cal yr BP match the timing of these climatic changes. ~~Increasing~~Increased wind speeds at the beginning of a warmer interstadial phase during the MIS 3 (Karginian climate optimum, 50,000 to 30,000 yr BP) and a subsequent decrease in wind speed during the ~~cooler~~colder stadial MIS 2 are a suitable explanation (Diekmann et al., 2017). Those increased wind speeds could have led to further transport of the coarser material from the source area, enabling these materials to reach our study area (Anderson et al., 1991). ~~Under such conditions the fine and organic-bearing material would have been deposited even farther away (Pye, 1995).~~

~~However, because of~~ From our data we see that the ~~thickness of these~~ sandy layers ~~of up to 10 m, continuous~~were deposited in approximately 7000 yr (radiocarbon dates below and above these layers). As the sediments are rather coarse (115.3 µm mean grain size), a fluvial deposition is more likely than ~~continuous~~an aeolian deposition ~~over several thousand years. In our opinion, the deposition period of approximately 7000 yr and~~ (Strauss et al., 2012). Moreover, the lack of organic material ~~indicates~~makes fluvial deposition~~.~~

~~We believe~~ the more plausible process. Thus, we think that periodic flooding events of Lena River tributaries near our study area are a more likely~~.~~ source for the sediments. The original Yedoma deposits of the Yukechi area were most likely formed by deposition of silty sediments and fine organic material during seasonal alluvial flooding~~, depositing silty sediment and small portions of organic material.~~. The climatic changes (Diekmann et al., 2017; Murton et al., 2017) and the resulting higher water availability during the~~ dated~~ deposition period of the sandy layers may have caused changes in fluvial patterns on the Abalakh Terrace. More water could cause ~~greater~~higher flow velocities under warmer climatic conditions and therefore increased erosive power, leading to the formation of new flow channels (Reineck and Singh, 1980). ~~The increased flooding frequency combined with greater flow velocities resulted in the sedimentation of more coarse, sandy material (Wilcock and Crowe, 2003), while lighter organic material and silt were kept suspended and transported further, out of the Yukechi area.~~

With a climatic backshift to colder conditions during MIS 2, water availability decreased~~,~~ and silty organic-bearing material was deposited by seasonal flooding again on top of the sandy layers. This likely led to lake initiation on top of the Yedoma deposits. The underlying ground began to thaw ~~(Grosse et al., 2013), forming the Yukechi Alas basin. As a result, ice was lost from the sediment and the ground subsided by at least 9 m (see section 3.1,~~ and subside, forming the Yukechi Alas basin. During this process, ice was lost from the sediment and the ground subsided by at least 9 m (height difference of 9 m between YED1 and Alas1 surface). Surface or lake water was able to percolate through the unfrozen sediments~~, as~~. This becomes visible ~~in~~by the homogeneous water isotope signal similar to the YED1 surface sample (Fig. 7~~, Fig. S7~~). Under the unfrozen aquatic conditions in the sediment, microbial activity started, resulting in the decomposition of the already small amount of organic material (Cole et al., 2001). When the lake drained, the ~~sediment~~sediments started to refreeze both upward from the underlying permafrost and downward from the surface, leaving a talik in between (Fig. 5). The subsided ground indicates that core unit A4 (Fig. 6) lies beneath the lowest unit of the Yedoma core, Y4 (Fig. 4), while units A1 to A3 shrank due to thawing from approximately 2200 to 1200 cm length. ~~This~~The presence of large ice wedges in the area supports this theory of ground subsidence during thaw as it hints to large excess ice contents of the ground (see Fig. S7) (Soloviev, 1959). These subsidence processes might represent the future path of the Yukechi Yedoma deposits, as already an initiating talik of approximately 150 cm was found at the YED1 site (Fig. 3a). This is caused by ground temperature warming which itself is affected by snow layer thickness and air temperatures and more, and could lead to Alas development (Ulrich et al., 2017a). ~~Maybe a tipping point at YED1 towards the development of characteristics similar to those found at Alas1 has already been passed.~~

5.3 Central Yakutian Yedoma deposits in a circumarctic and regional context

~~Strauss et al. (2017) calculated~~Strauss et al. (2017) report a mean organic carbon density for the upper 3 m of Yedoma deposits in the Lena-Aldan interfluve of 25 to 33 kg/m^3~~. Using a bootstrapping approach after Jongejans et al. (2018), based on our measured values~~ based on data of Romanovskii (1993) and Hugelius et al. (2014). Using a bootstrapping approach (Jongejans and Strauss, 2020) we found a much lower organic carbon density of 4.48 ± 1.43 kg/m^3 for the top 3 m of the YED1 core. For Alas1, an organic carbon density of 6.93 ± 2.90 kg/m^3 was calculated for the top 3 m. ~~This~~Taking the area covered by each deposit type within the Yukechi Alas landscape into account and the ice wedge volumes estimated by Ulrich et al. (2014) (see Section 2 and Fig. S2) into account, this results in a mean organic carbon density of only 4.40 kg/m^3 for the top 3 m of dry soil at the Yukechi study site. This landscape scale carbon stock density includes the entire study area (1.4 km²), including all water bodies (approximately 0.18 km²), which we assumed to contain no soil carbon. This means that both ~~our~~the average Yukechi site ~~average~~ carbon density and our individual ~~cores~~cores' carbon densities are substantially below the range (25 to 33 kg/m^3) ~~measured~~reported by Strauss et al. (2017). This strong difference between previously published and our new data from the same region can only be explained by high depositional heterogeneity of the Central Yakutian permafrost landscapes that was not represented in the earlier dataset of Strauss et al. (2017) in sufficient detail. ~~Findings~~Geographically, the Yukechi area is located in one of the southernmost Yedoma areas in the Yedoma domain, which could be a reason for the differences to previously studied Arctic deposits (Schirrmeister et al., 2013; Strauss et al., 2013; Jongejans et al., 2018). Results of Siewert et al. (2015) for the Spasskaya Pad/Neleger site in a similar setting also differ greatly from our findings at the Yukechi site, showing carbon densities of approximately 19.3 kg/m^3 for the top two meters of larch forest-covered Yedoma deposits and approximately 21.9 kg/m^3 for the top two meters of grassland-covered Alas deposits in a setting similar to the Yukechi site~~ (Spasskaya Pad/Neleger site) . However, with our low-carbon site we are reporting the first carbon stock estimation for Central Yakutian Yedoma deposits below 3 m. ~~.

~~In general, Yedoma deposits are estimated to hold 14 ± 8 kg/m^3 organic carbon in the top 3 m (Strauss et al., 2012) and 19 +13/-11~~In general, Yedoma deposits are estimated to hold 10 +7/-6 kg/m^3 for the whole column within the Pleistocene Yedoma deposits (approximate depth of 25 m) (Strauss et al., 2013). Jongejans et al. (2018) calculated a ~~slightly~~ larger organic carbon stock of 15.3 ± 1.6 ~~g~~kg/m³ for Yedoma deposits found on the Baldwin Peninsula in

Alaska. Another study by Shmelev et al. (2017) stated a Yedoma carbon stock of 14.0 ± 23.5 kg/m³ for a study region in northeastern Siberia between the Indigirka River and the Kolyma River.

Assessing the carbon inventory of the full-length Central Yakutian cores examined in this study, we estimated an organic carbon density of 5.27 ± 1.42 kg/m³ for the sediments of the YED1 core down to a depth of 22.12 m bs, excluding the ice wedge. The organic carbon density at this site within the Yukechi Yedoma is approximately fourtwo to three times lower than estimated in previous studies of deep Yedoma deposits (Strauss et al., 2013; Shmelev et al., 2017; Jongejans et al., 2018). This also shows that, evenEven when including roughly 10 m of organic carbon-free material, the higher carbon densities for the whole cores (compared to the carbon densities of the first 3 m) show that large portions of organic carbon must beare stored below 3 m, as the organic carbon density increases from measurements of the top 3 m to measurements of the whole core.. The Alas1 core contains slightly more organic carbon with a mean value of 6.07 ± 1.80 kg/m³ organic carbon for the whole core (19.72 m).), which is about 20 % of the mean thermokarst deposit carbon content of 31 +23/-18 kg/m³ stated by Strauss et al. (2017). Within the Alas core, organic carbon storage is slightly higher in the top 3 m (~(approximately 14 % more than below). This mightlikely is a result fromof former lake coverage and the relatedthat led to accumulation of organic-richer lake sediments found in the upper part of Alas1. Most likely there was enhanced growth of aquatic plants with at the same time reduced decomposition of the input organic material. due to anaerobic conditions during the lake phase.

6 Conclusions

In our study, we investigated two deep permafrost sediment cores from a Yedoma upland and an Alas basin in the Central Yakutian Yedoma region. Concerning our first research question, 'Which are the sedimentological processes that influenced the carbon stocks found in the Yukechi area?' weWe conclude the following: Lowthat low organic carbon contents encountered in sections of both cores are not caused by decomposition of originally high organic matter decomposition contents but rather originate fromare a legacy of the accumulation of organic-poor material during the late Pleistocene MIS 3 and MIS 2 periods. The most likely landscape scenario causing the differences in sediment and organic carbon characteristics during the Pleistocene deposition is the temporary existence of tributary rivers on the Abalakh Terrace, with highvarying flow velocities and alternating paths as a result of climatic changes, and differences in or local landscape dynamics. While with the onset of the Holocene the sedimentation as a result.

Concerning our second research question, 'How did these sedimentological processes effecton the local carbon storage?' weYedoma upland ceased, the Alas was affected by thaw, subsidence and lake formation processes, resulting in a compaction of sediments in situ as well as causing higher C inputs under lacustrine conditions in the upper parts of the sediments.

We further show that the Yedoma deposits contained in these cores,at this site down to a depth of 22 m, are characterized by rather low organic carbon contents, often less than 1 wt% TOC, resulting in a mean C storagedensity of only ~ 5 kg/m³. These low organic carbon contents are not caused by high organic matter decomposition rates but rather originate from the accumulation of organic-poor material during the late Pleistocene (MIS 3 and MIS 2 periods). This is corroborated by very similar findings in the examined Alas core.

As a resultHence, the studied Yukechi Yedoma deposits store less carbon than other, comparable Yedoma Ice Complex deposits in the Central Yakutian area. However, there have been comparatively few studies on this so far. The biogeochemical impact of permafrost thawing in the Yukechi area might therefore be smaller than generally assumed for Yedoma deposits, as this area does not feature the high carbon stock estimates and high ice contents of other previously studied localities in Central Yakutia and elsewhere in the Arctic.

Nevertheless, the high ice content and the presence of ice wedges make these deposits vulnerable to deep thaw processes, which will result in further ground subsidence and hence landscape changes (e.g. evolution of thermokarst lakes, infrastructure damage, etc.). Recent ongoing degradation was detected on the Yedoma upland, where the winter season temperatures are no longer cold enough to refreeze the active layer completely anymore. This phenomenon could be widespread in the sub-Arctic.

The permafrost characteristics found in the Alas core reveal that its composition and stratigraphy before lake formation and drainagedisappearance was very similar to the Yedoma core material. Its past development ofincluding thaw, the loss of old ice, and surface subsidence, along with sediment compaction, shows a possible pathway for the Central Yakutian Yedoma deposits under the influence of global climate change.

Data availability

The measurement data and laboratory results are available via PANGAEA at https://doi.org/10.1594/PANGAEA.898754The measurement data and laboratory results are available via PANGAEA at https://doi.org/10.1594/PANGAEA.898754 (Windirsch et al., 2019). A detailed core log is available for YED1 at https://doi.org/10.1594/PANGAEA.914874 and for Alas1 at https://doi.org/10.1594/PANGAEA.914876 (Windirsch et al., 2020a, b).

(Windirsch et al., 2019).

Supplement link

Author contribution

JS designed the study concept. TW conducted the laboratory work, analyzed the laboratory results, prepared the graphics, and led the writing of this paper. GG and AF led the drilling expedition in 2015. JS, MU, and PK participated in the drilling fieldwork. GG and JS supervised the data analyses and provided expertise on thermokarst processes and cryostratigraphy. LS provided expertise on grain-size characteristics and Central Yakutian permafrost genesis. MF designed the maps and provided expertise on Yedoma and thermokarst-affected carbon. LJ developed the bootstrapping routine and provided expertise on carbon stock upscaling. JW developed the age-depth models and worked on age calibration and contextualization. TO interpreted the water isotope results and provided context for the isotope data. JS took part in the laboratory work and provided expertise in permafrost carbon processes. All authors contributed to commenting and editing the manuscript.

Competing interests

The authors declare no conflict of interest.

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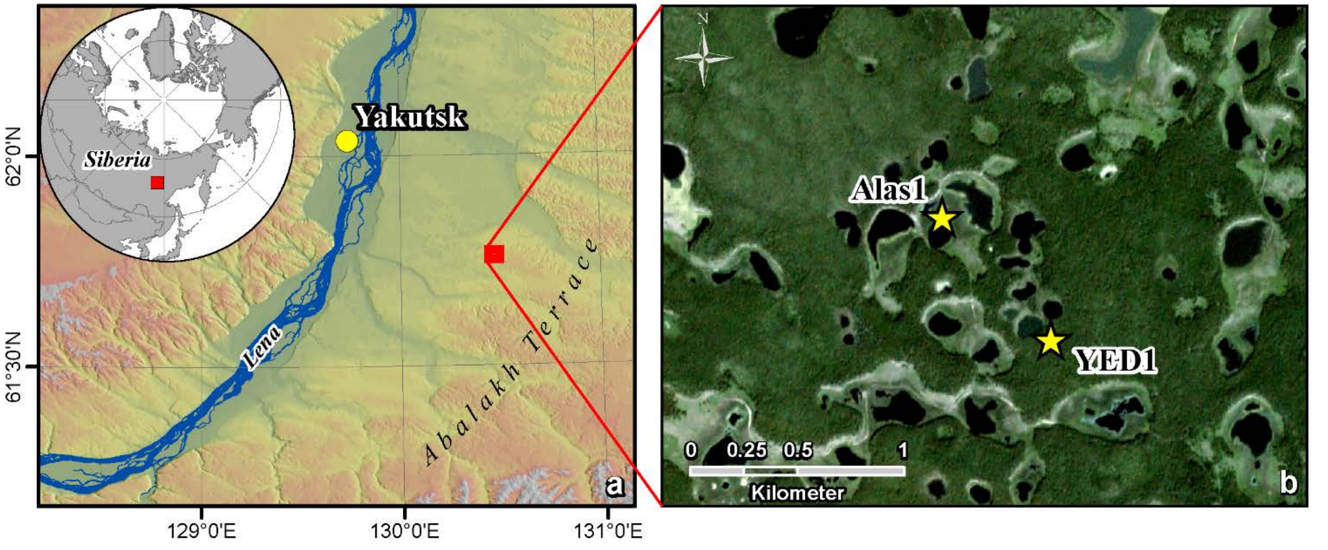
Table 11 - Radiocarbon measurement data and calibrated ages for YED1 and Alas1 bulk organic material samples.

Core	Mean sample depth [cm bs]	^{14}C age [yr BP]	+/- [yr]	F14C	+/- [%]	Calibrated ages (2 σ)* [cal yr BP]	Mean age [cal yr BP]	Core unit	AWI no.
YED1	157.5	18064	±104	0.1055	0.83	21582–22221	21890	Y1	1543.1.1
	298	25973	±88	0.0394	1.09	29822–30640	30268	Y1	1544.1.1
	589.5	35965	±184	0.0114	2.29	40116–41118	40608	Y1	1545.1.1
	1636	> 49000	N/A	± 0.0017	infinite age6.66	> 49000N/A	N/A	Y3	1547.1.1
	1998.5	45854	±501	0.0033	6.23	48202–calib. limit	49232	Y4	1548.1.1
Alas1	199	12826	±57	0.2026	0.70	15144–15548	15287	A1	1549.1.1
	812.5	23615	±151	0.0529	1.88	27478–27976	27729	A2	1550.1.2
	1530.5	42647	±364	0.0049	4.53	45172–46619	45870	A4	1551.1.1
	1967.5	39027	±251	0.0078	3.12	42478–43262	42865	A4	1552.1.1

* calibrated using Calib 7.1 (Stuiver et al., 2018) equipped with IntCal 13 (Reimer et al., 2013)



* calibrated using Calib 7.1 (Stuiver et al., 2018) equipped with IntCal 13 (Reimer et al., 2013)

Table 2 – SOC contents for the individual core units, based on the bootstrapping results; calculations were done for 1 m²; the measurement data used in the bootstrapping approach (bulk density, TOC density) are provided in the data sheet in the PANGAEA repository; * refers to samples with TOC content < 0.1 wt%; for organic carbon pool calculations, we assumed a TOC of 0.05 wt% for these samples; note: we excluded unit Y2 in the calculations.

Core	Depth [cm bs]	Number of samples used in bootstrapping	Mean dry bulk density [10^3 kg/m³]	Mean TOC content [wt%]	Mean SOC content (bootstrapping results) [kg/m³]
YED1	0 – 300	7	1190	0.42	4.48 ± 1.43
	0 – 714 (unit Y1)	13	1090	0.59	8.31 ± 1.41
	1010 – 1927 (unit Y3)	18	1172	0.10	0.86 ± 0.32
	1927 – 2235 (unit Y4)	5	910	1.14	11.50 ± 1.36
	total core	36	1105	0.46	5.27 ± 1.42
Alas1	0 – 300	5	1257	0.51	6.93 ± 2.90
	0 – 349 (unit A1)	6	1214	0.44	5.00 ± 2.55
	349 – 925 (unit A2)	6	998	0.05*	0.50 ± 0
	925 – 1210 (unit A3)	4	1299	0.05*	0.66 ± 0.01
	1210 – 1980 (unit A4)	12	1377	0.83	11.03 ± 1.62
	total core	28	1250	0.47	6.07 ± 1.80

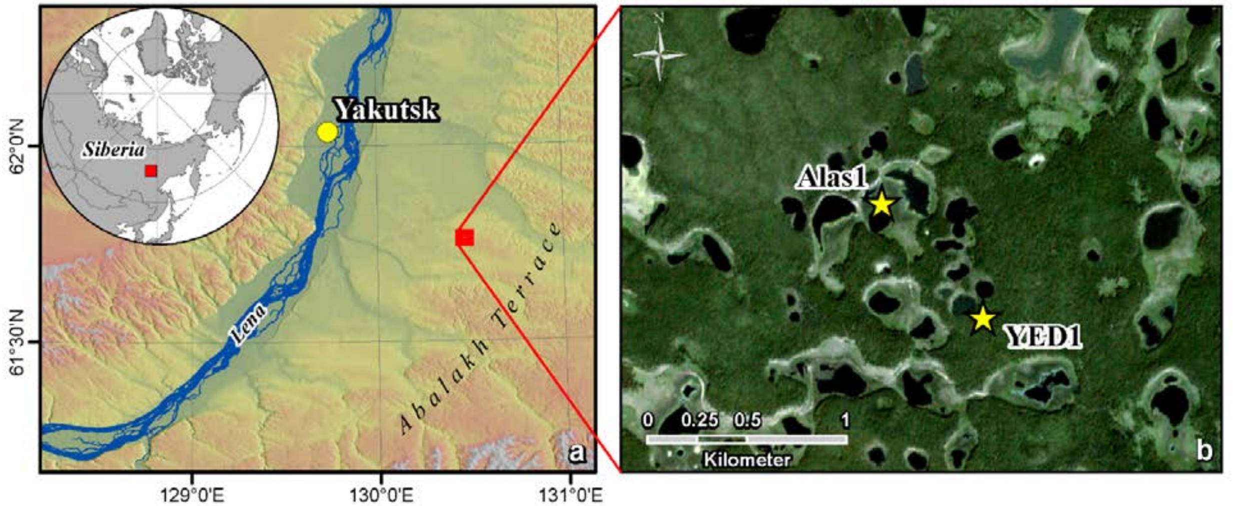
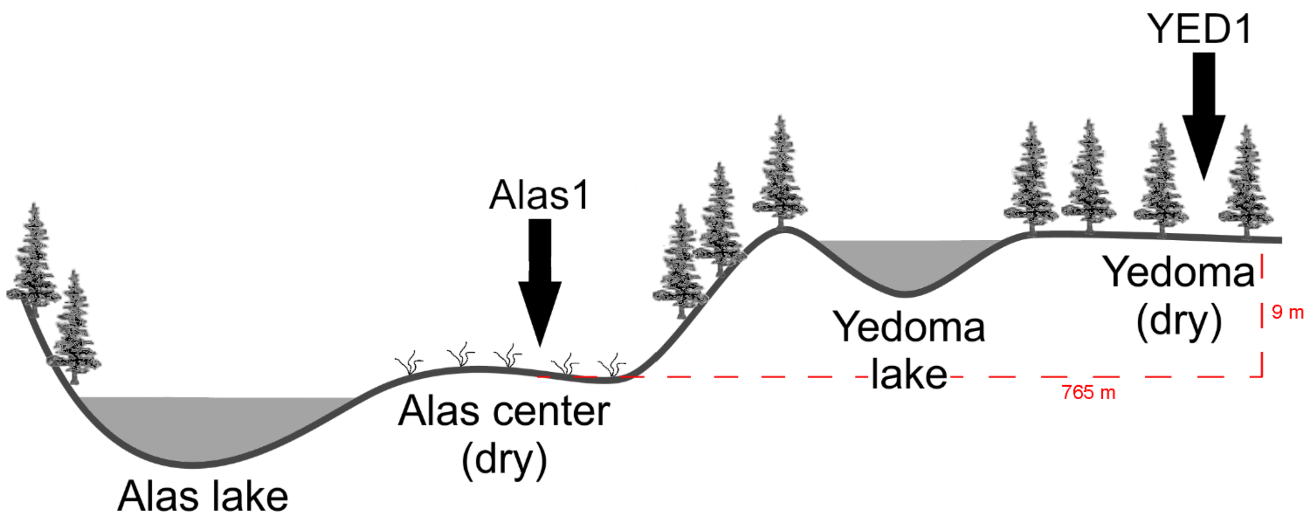


Figure 1 – Study site overview; a: location of the Yukechi Alas study site in Central Yakutia on the edge of the Abalakh Terrace; (Circumpolar digital elevation model, Santoro and Strozzi, 2012); b: locations of the Alas1 and the YED1 coring sites within the Yukechi Alas landscape (Planet OrthoTile, acquisition date: 7 July 2018).; Planet Team (2017)).


YED1
Alas1
Yedoma
(dry)
9 m
Yedoma
lake
765 m
Alas center
(dry)
Alas lake

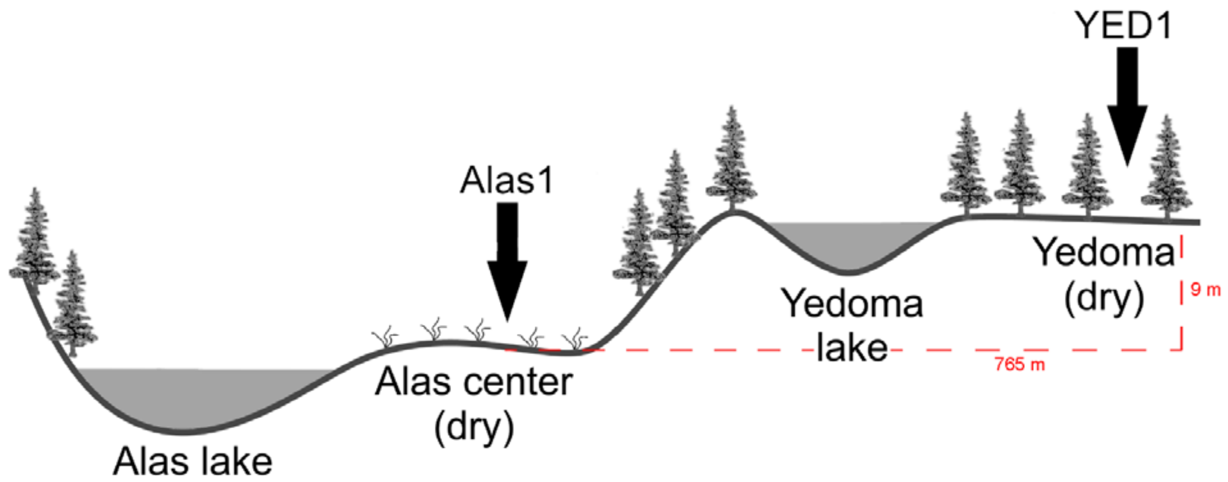
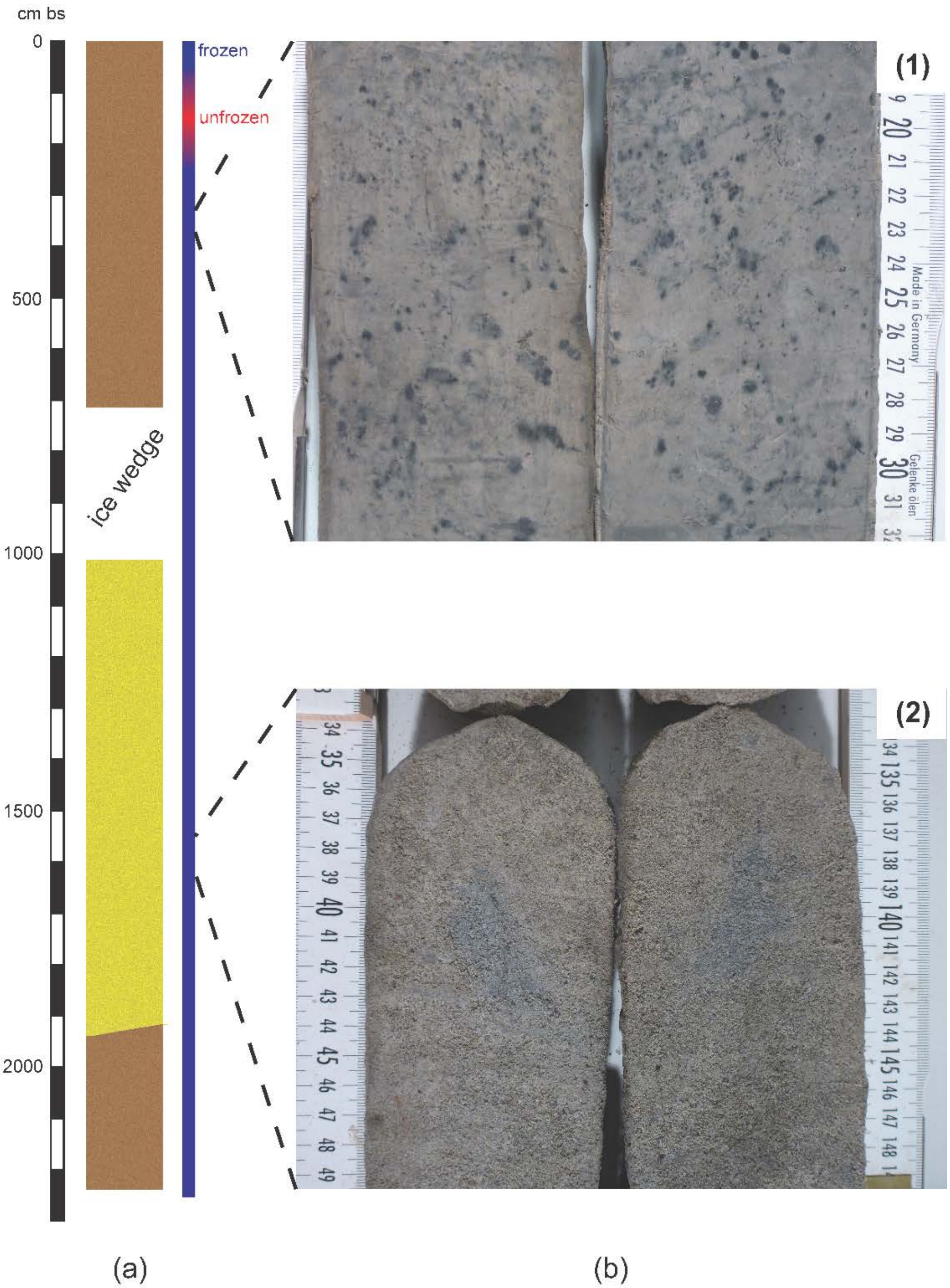


Figure 2 – Setting of the drilling locations for the Alas1 and YED1 cores showing distance and height difference between the locations (vertical scale exaggerated~~).~~); the terms "Alas lake" and "Yedoma lake" are chosen after Ulrich et al., 2017a in accordance to the deposit type in which the thermokarst lakes are located; following Crate et al., (2017), the Yedoma lake can also be called "dyede" due to its development stage.


cm bs
0
500
1000
1500
2000
ice wedge
frozen
unfrozen
(1)
(2)
(a)
(b)

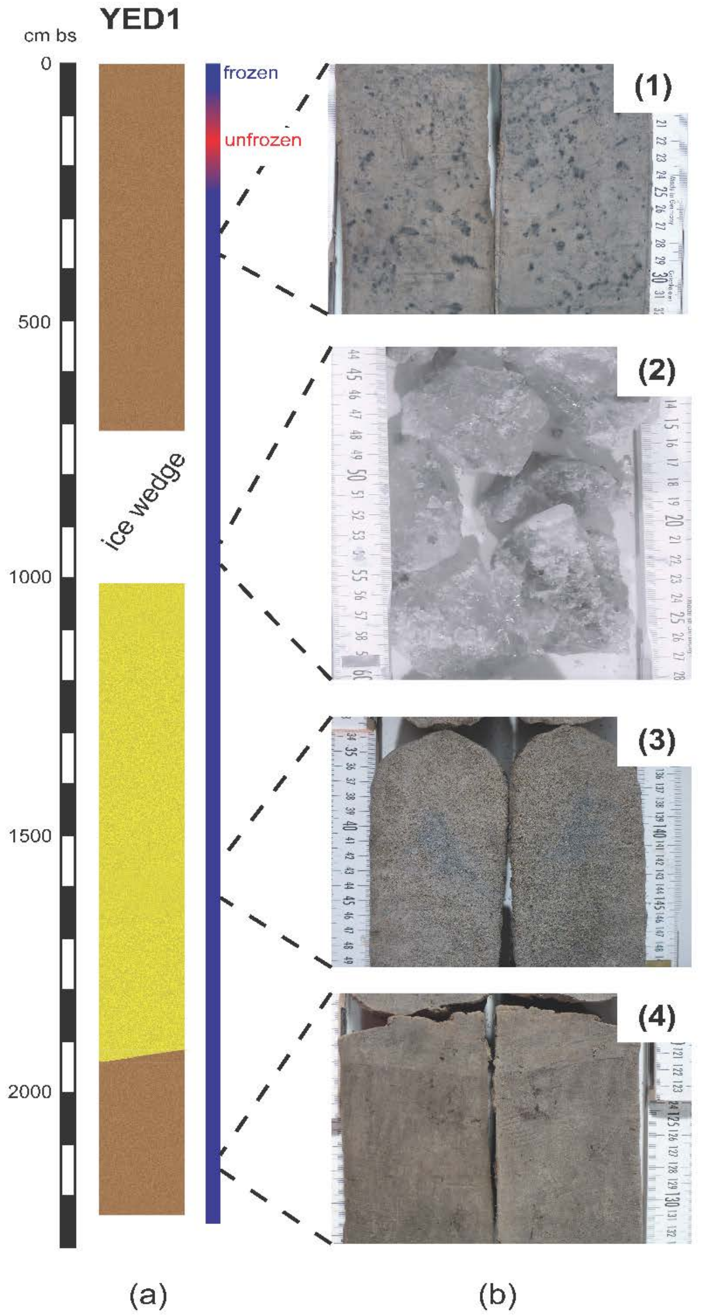
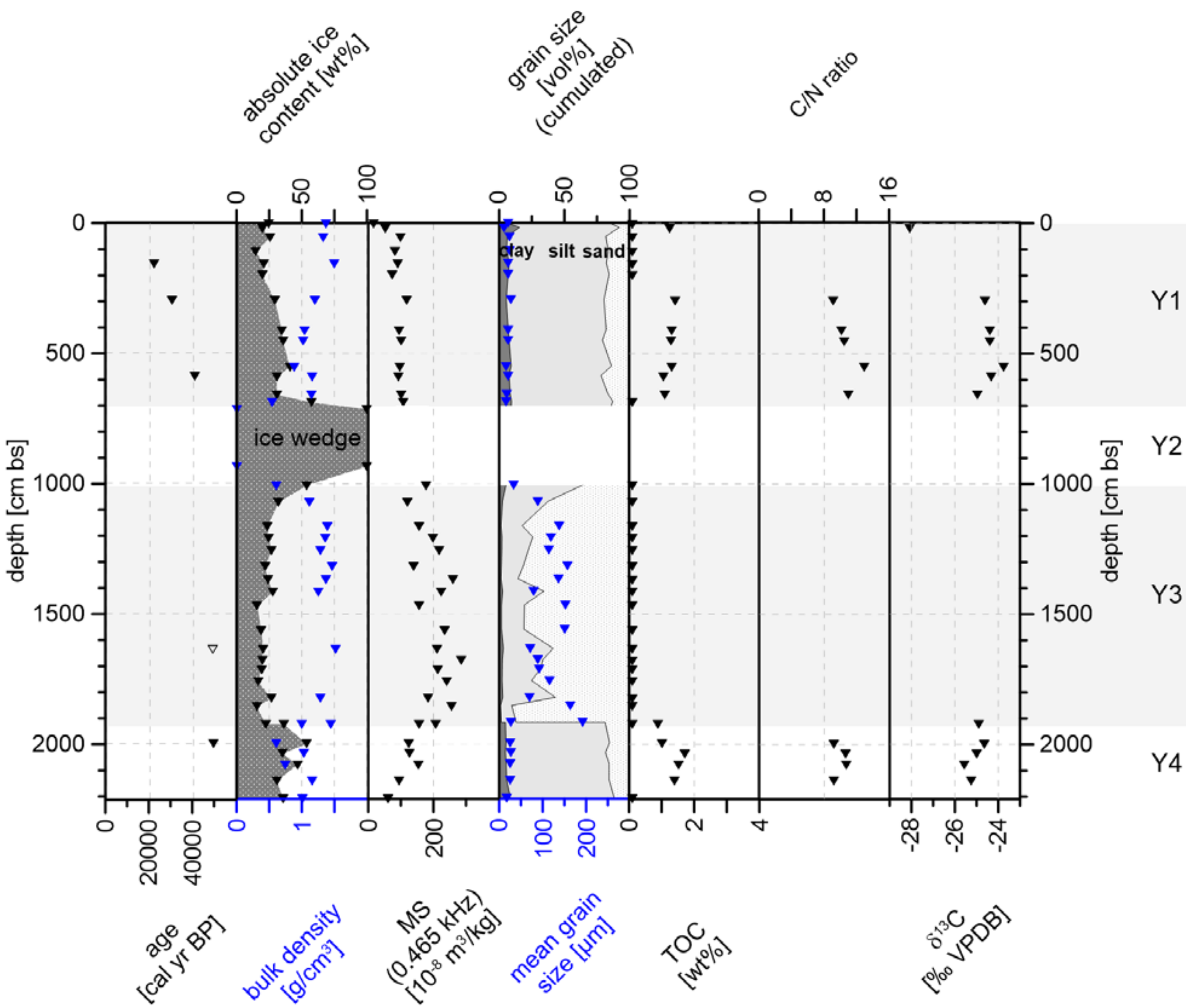


Figure 3 – a: overview of the Yedoma core; depth given in cm bs; state after core retrieval is given by colors: blue = frozen, red = unfrozen; location of the ice wedge is ~~marked~~labelled; brown ~~marks~~illustrates silty sediments, yellow ~~marks~~represents sandy sediments; b: detailed pictures of the YED1 core; (1) 332–317–~~332~~ cm bs, picture of unit Y1 showing black organic-rich inclusions within the grey silty matrix; (2) 960–944 cm bs, picture of the wedge ice in Y2; (3) 1549–1532-

~~1549~~ cm bs, picture of Y3, showing the coarse sandy material with no visible cryostructures or organic material~~.~~; (4) 2133–2117 cm bs, picture of Y4, showing the grey silty matrix with some dark organic dots.


absolute ice content [wt%]
grain size [vol%] (cumulated)
C/N ratio
clay silt sand
ice wedge
depth [cm bs]
depth [cm bs]
Y1
Y2
Y3
Y4
age [cal yr BP]
bulk density [g/cm³]
MS (0.465 kHz) [10⁻⁸ m³/kg]
mean grain size [µm]
TOC [wt%]
δ13C [‰ VPDB]

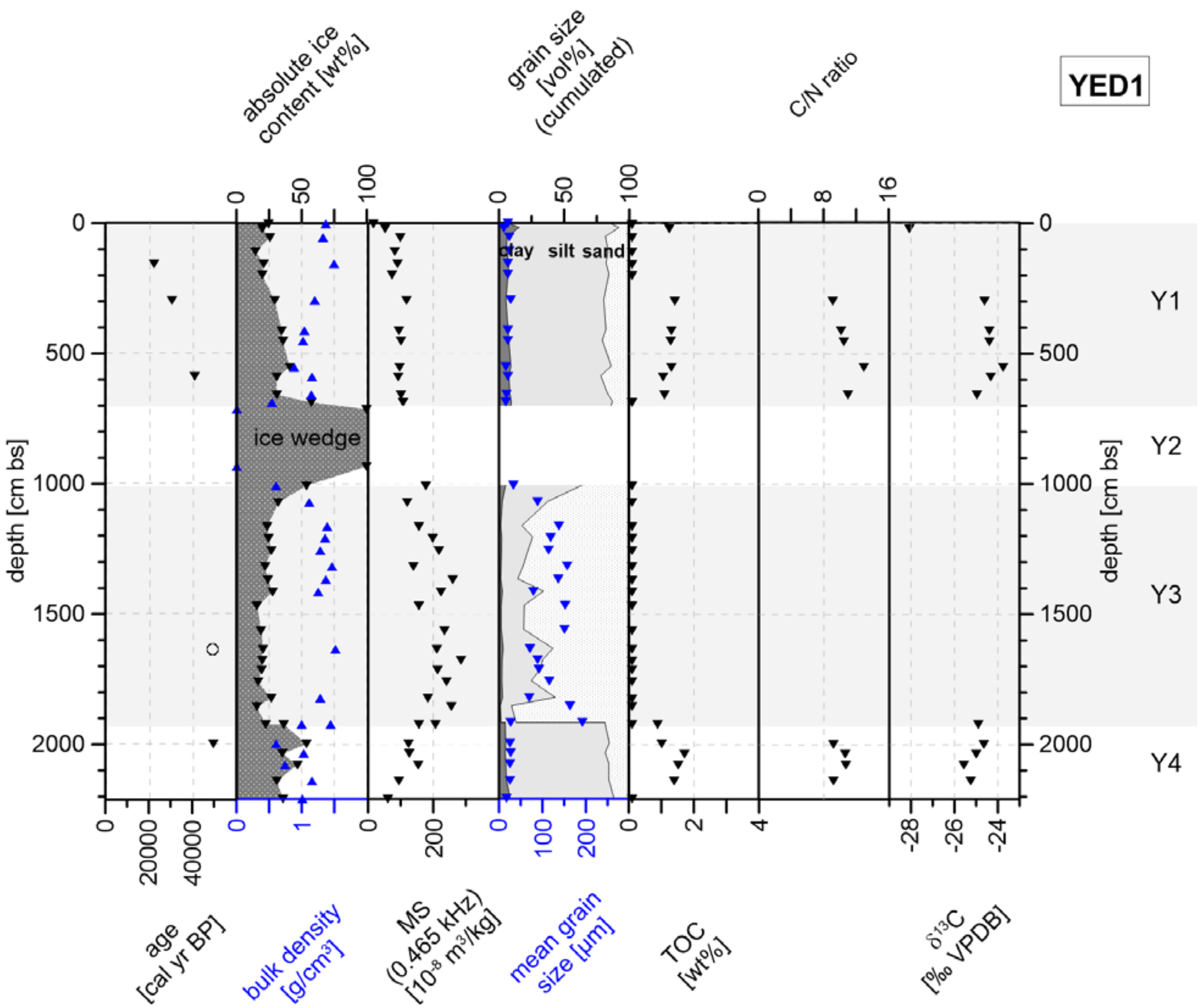
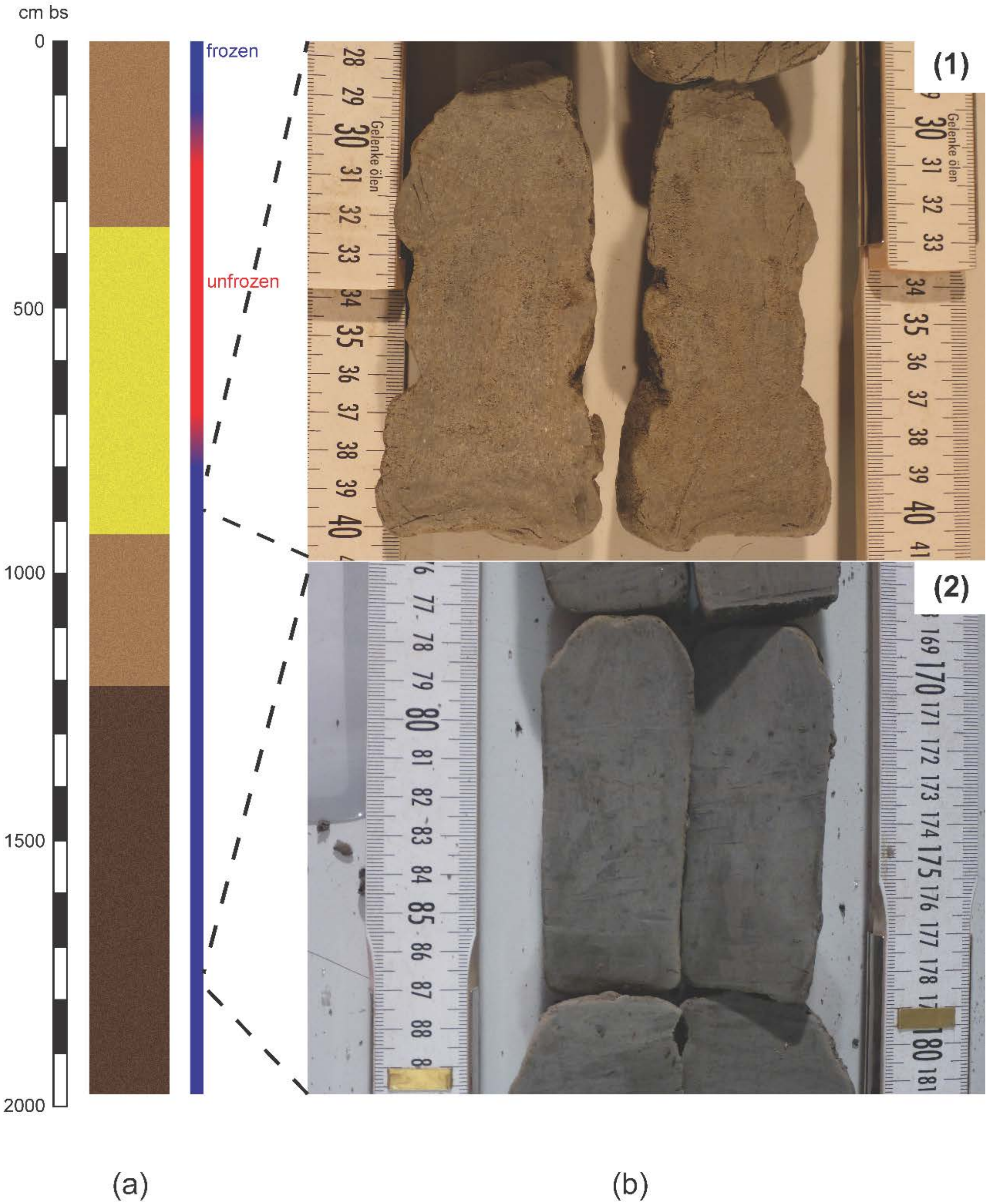


Figure 4 ~~-~~– Characteristics of the Yedoma core ~~YED 1~~YED1: radiocarbon ~~age~~ages, absolute ice content, bulk density, magnetic susceptibility (MS~~,~~), grain size composition, mean grain size, total organic carbon (TOC~~, –~~) content, carbon-nitrogen (C/N) ratio~~,~~ and stable carbon isotope ($\delta^{13}C$) ratio; hollow ~~triangle~~circle indicates an infinite radiocarbon age; grey/white areas mark the different stratigraphic units (Y1 to Y4).


cm bs
0
500
1000
1500
2000
frozen
unfrozen
(1)
(2)
(a)
(b)

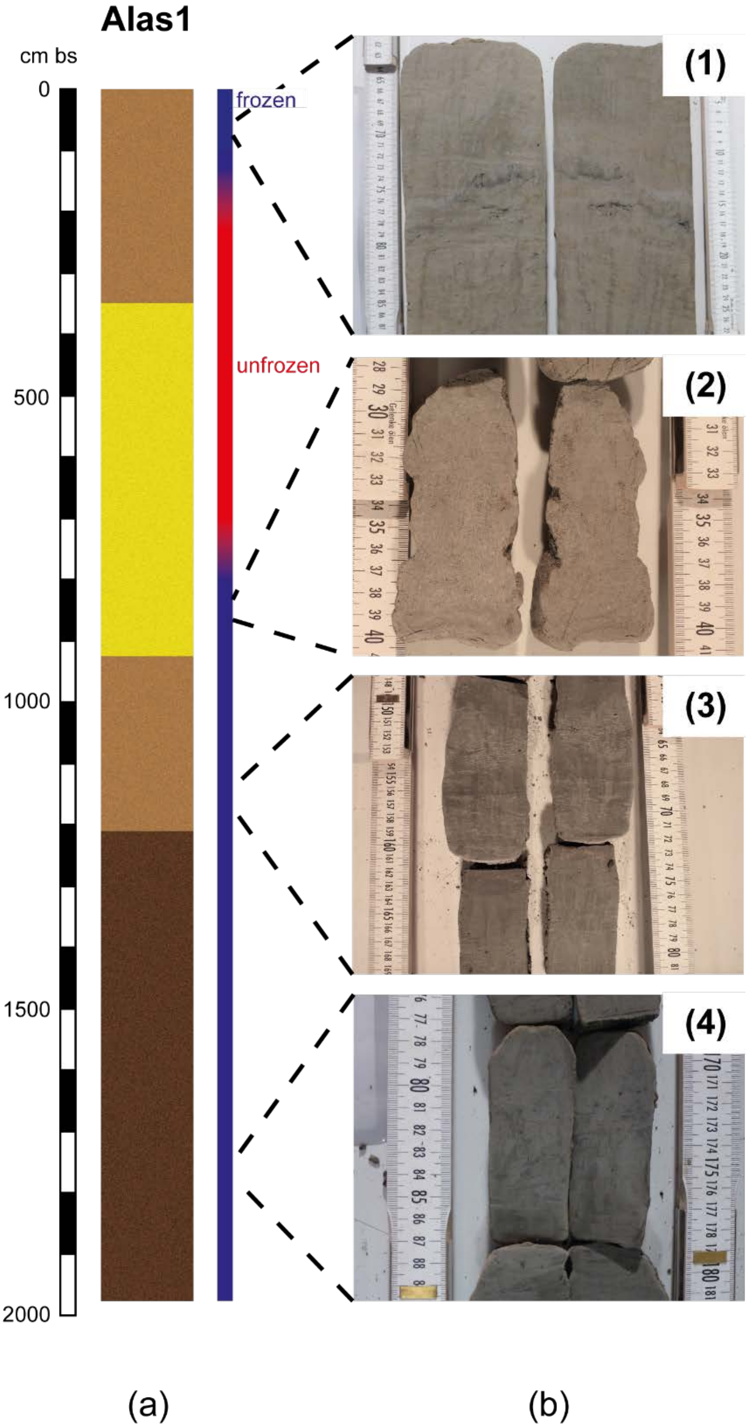
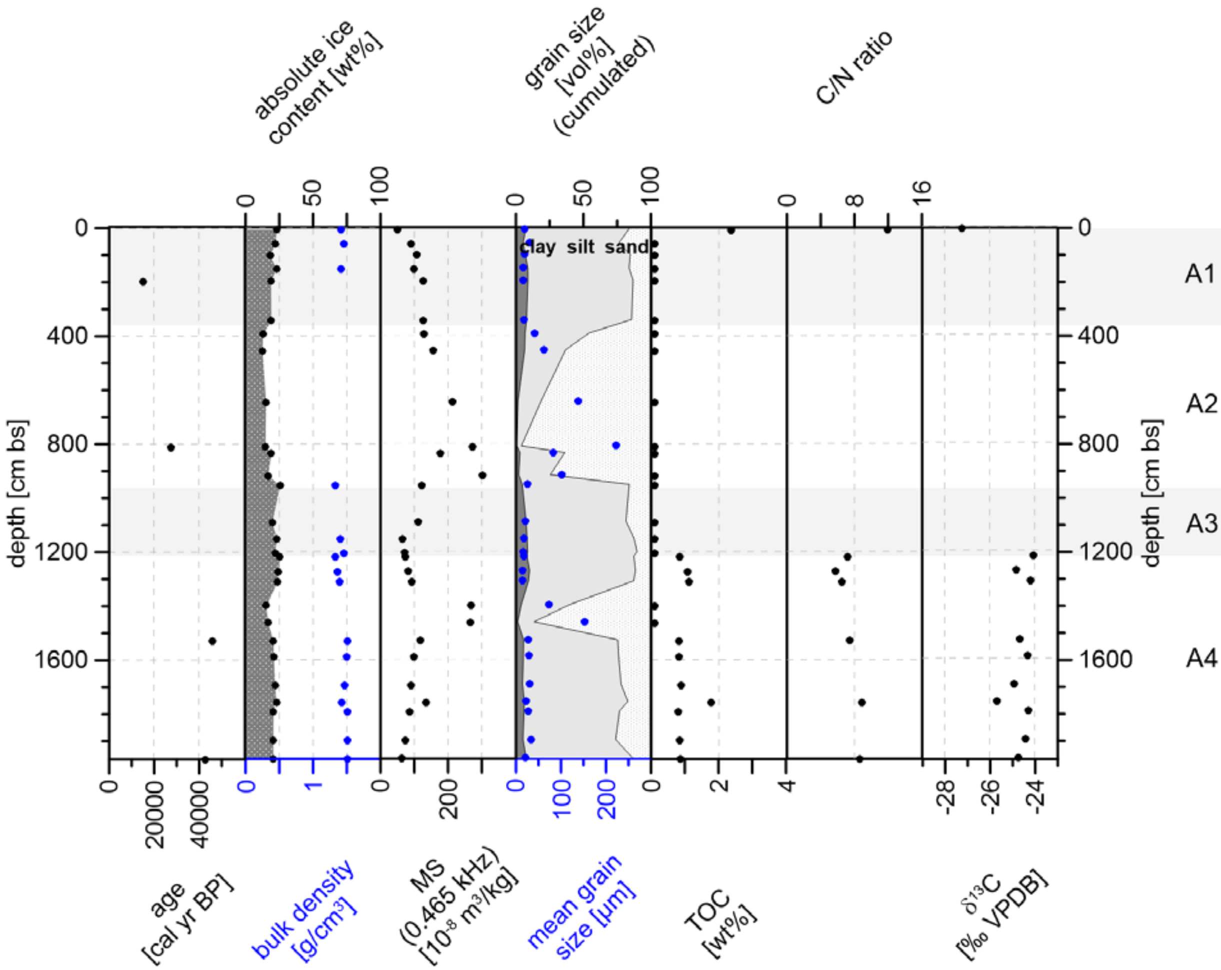


Figure 5 – a: overview of the Alas1 core; depth given in cm bs; state after core retrieval is given by colors: blue = frozen, red = unfrozen; light brown marks silty material, yellow marks sandy material, dark brown marks silty material containing more organic material; b: detailed pictures of the Alas1 core; (1) ~~828–840~~88–64 cm bs, picture of A1 showing the silty grey

matrix including dark organic structures; (2) 840–828 cm bs, picture of the sandy A2 unit; (2) 3) 1169–1148 cm bs, picture of A3 showing a silty grey matrix with some darker organic dots; (4) 1781–1767–1781 cm bs picture of the fine-grained silt-dominated A4 unit including black organic-rich inclusions.


absolute ice content [wt%]
grain size [vol%] (cumulated)
C/N ratio
clay silt sand
depth [cm bs]
A1
A2
A3
A4
age [cal yr BP]
bulk density [g/cm³]
MS (0.465 kHz) [10⁻⁸ m³/kg]
mean grain size [µm]
TOC [wt%]
δ¹³C [‰ VPDB]

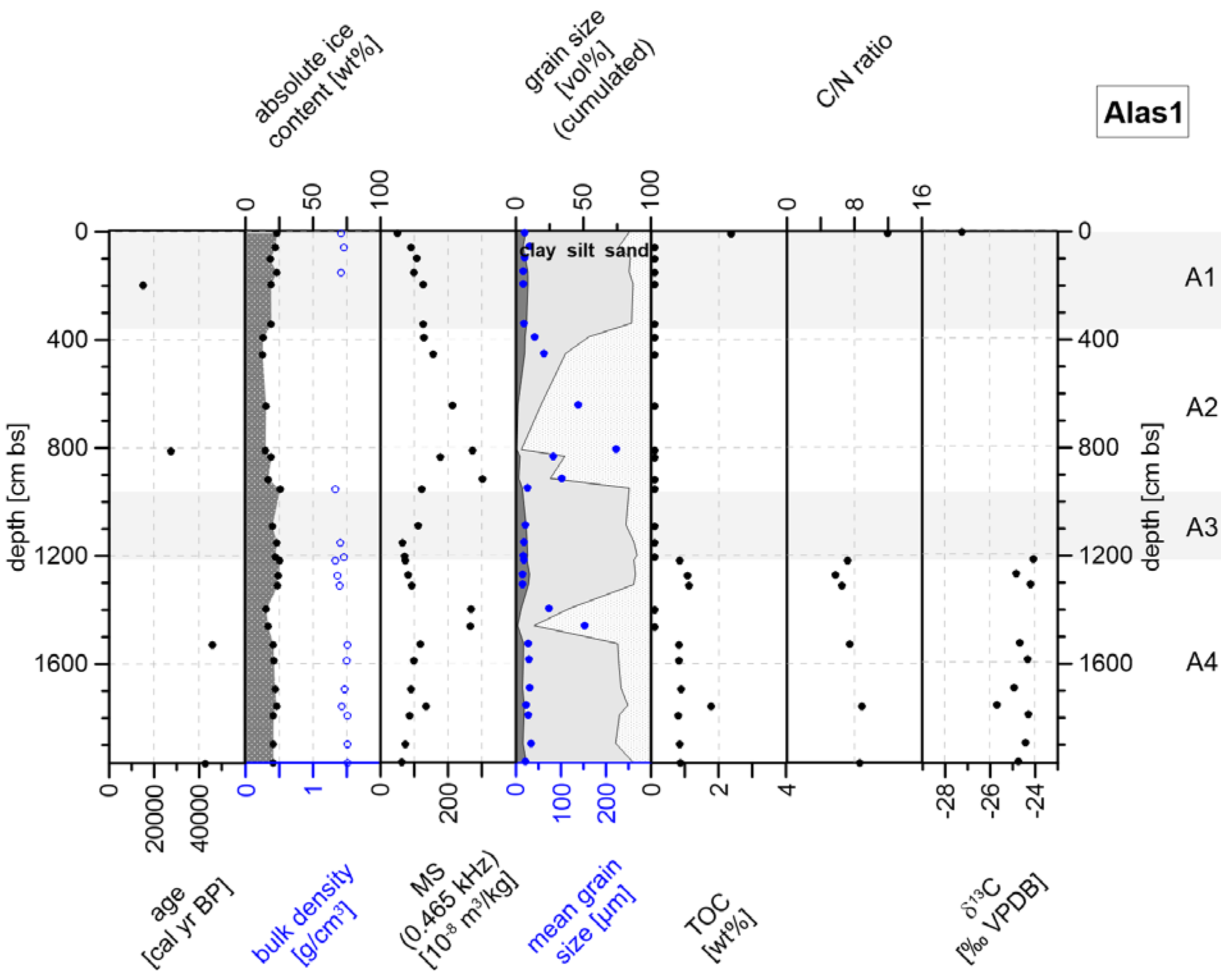
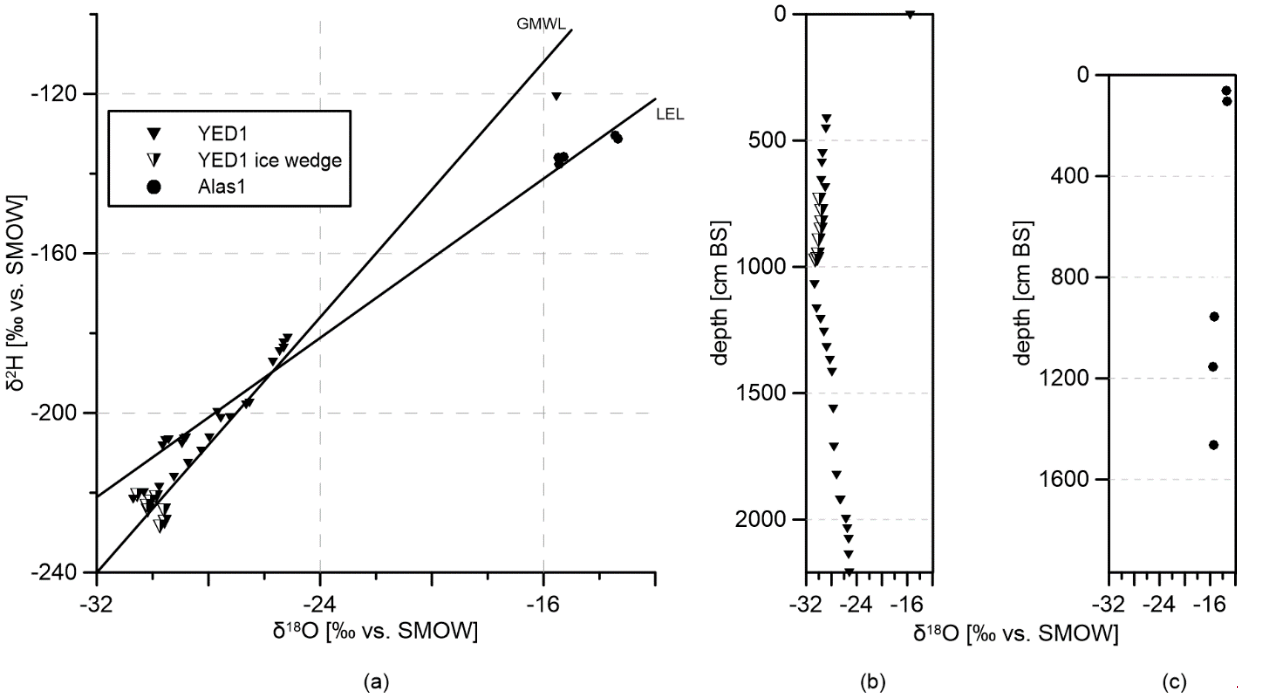


Figure 6 -– Characteristics of the Alas1 core: radiocarbon age, absolute ice content, bulk density, magnetic susceptibility (MS,), grain size composition, mean grain size, total organic carbon (TOC,) content, carbon-nitrogen (C/N) ratio, and stable carbon isotope ($\delta^{13}C$) ratio; grey/white areas mark the different stratigraphic units (A1 to A4).


GMWL
LEL
YED1
YED1 ice wedge
Alas1
-120
-160
-200
-240
δ²H [‰ vs. SMOW]
-32
-24
-16
δ¹⁸O [‰ vs. SMOW]
(a)
0
500
1000
1500
2000
depth [cm BS]
-32
-24
-16
(b)
0
400
800
1200
1600
depth [cm BS]
-32
-24
-16
δ¹⁸O [‰ vs. SMOW]
(c)

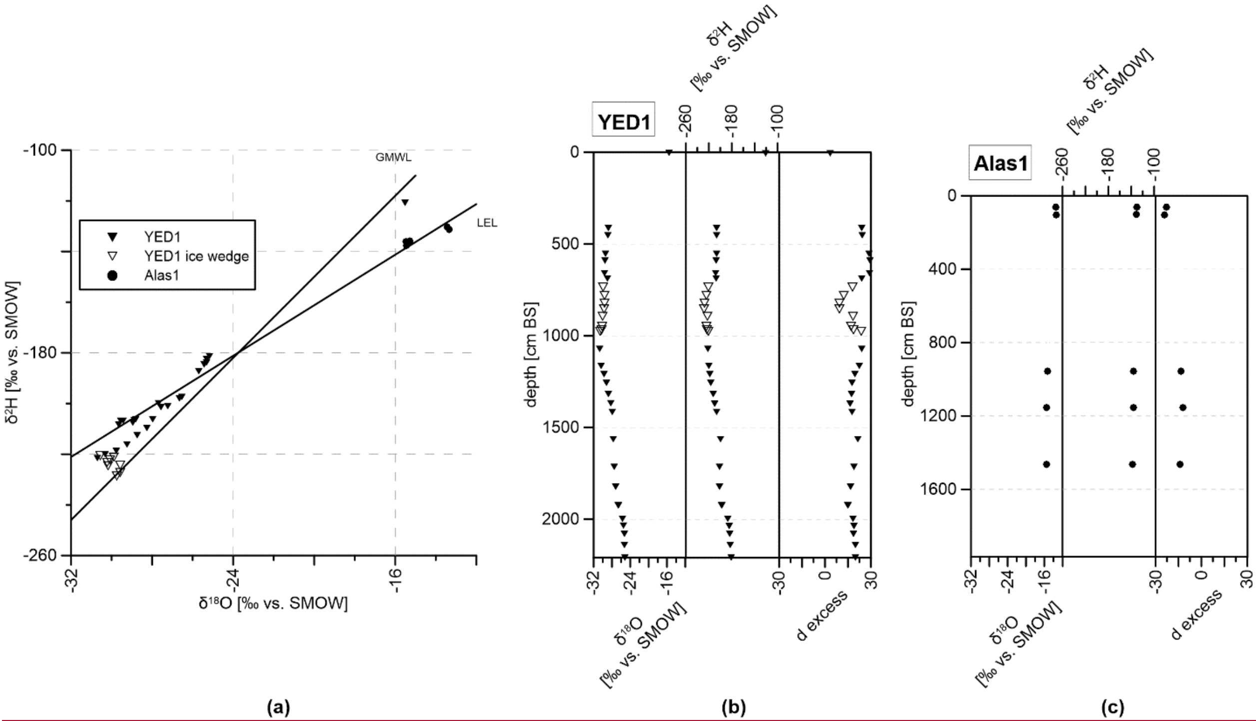


Figure 7 – The characteristics of water stable isotopes in the studied sediment cores; a: stable hydrogen (δ^2H) and oxygen ($\delta^{18}O$) isotope ratios of YED1 pore ice (black triangles), YED1 ice wedge ice (~~semi-~~hollow triangles), and Alas1 pore ice and pore water (black dots) [‰ vs. SMOW]; global meteoric water line GMWL: ~~y=8x~~$\delta^2H=8*\delta^{18}O+10$; local evaporation line LEL of Central Yakutia (based on data compiled until 2005 after Wetterich et al., 2008); b: oxygen isotopes, hydrogen isotopes and d excess values of YED1 plotted over depth; c: oxygen isotopes~~ of YED1 (b)~~, hydrogen isotopes and d excess values of Alas1~~ (c)~~ plotted over depth.