Ice wedges as archives of winter palaeoclimate: A review

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Abstract

Ice wedges are a characteristic feature of northern permafrost landscapes and grow mainly by snowmelt that refreezes in thermal contraction cracks that open in winter. In high latitudes the stable-isotope composition of precipitation ($\delta^{18}O$ and δD) is sensitive to air temperature. Hence, the integrated climate information of winter precipitation is transferred to individual ice veins and can be preserved over millennia, allowing ice wedges to be used to reconstruct past winter climate. Recent studies indicate a promising potential of ice-wedge-based palaeoclimate reconstructions for more comprehensive reconstructions of Arctic past climate evolution. We briefly highlight the potential and review the current state of ice-wedge palaeoclimatology. Existing knowledge gaps and challenges are outlined and priorities for future ice-wedge research suggested. The major research topics are (1) frost cracking and infilling dynamics, (2) formation and preservation of the stable-isotope information, (3) ice-wedge dating, (4) age-model development, and (5) interpretation of stable-isotope time series. Progress in each

of these topics will help to exploit the palaeoclimatic potential of ice wedges, particularly in view of their unique cold-season information, which is not adequately covered by other terrestrial climate archives.

1.   INTRODUCTION

Reconstruction of Holocene climate history of high northern latitudes is mainly based on biological climate proxies that record summer or growing season air temperatures and Greenland and Canadian Arctic ice-core records. About two thirds of the temperature-sensitive records included in the Arctic2k v1.1 database[1], the Arctic Holocene Transitions database[2], and the most recent PAGES2k temperature database[3]—which share high standards regarding record length, dating and temporal resolution—represent temperatures of the summer or growing season, whereas annual temperatures and, in particular winter temperatures are underrepresented. Moreover, the proxies are unevenly distributed spatially, with few records from Russian high latitudes. This seasonal and spatial bias may explain the reconstructed trends of summer and annual cooling in the Northern Hemisphere and Arctic from the Holocene Optimum until the Little Ice Age, reversed only by the ongoing warming e.g. [4,5-8]. Such mid to late Holocene cooling is commonly attributed to decreasing summer insolation in the Northern Hemisphere. In contrast, transient climate model simulations indicate increasing annual air temperatures over the Holocene due to rising greenhouse gas concentrations and retreating ice sheets[9]. This model–data mismatch has been attributed to biases in the climate sensitivity of climate models and in the seasonality of climate proxy reconstructions. The latter underlines the need to reconstruct winter climate, especially for polar regions, where winter conditions prevail for most of the year.

Winter climate reconstructions from ice wedges in the northeast Siberian permafrost region have recently identified warming trends during the mid to late Holocene and pronounced modern warming that may be explained, respectively, by seasonal solar insolation and greenhouse gas forcing[10,11]. These trends are

supported by a recent study of speleothems in continental Eurasia[12] that emphasized the importance of winter climate dynamics for Holocene temperature evolution there. Overall, attempts to reconstruct winter temperatures from biological proxies (such as pollen[13] and beetles[14]) have had little success. Recently, though, a study by Biskaborn et al.[15] revealed the potential of using diatoms (*Fragilaria spp.*) of the spring bloom as a winter/spring climate proxy, which also confirmed the ice-wedge-based Holocene winter warming trend[10].

In addition to other climate archives, ice wedges may therefore help to bridge the gap between other proxy data and climate models[10], but remain to be evaluated systematically. Here we highlight the palaeoclimatic value of ice wedges as unique archives of winter palaeoclimate in permafrost regions and review the current state of such research. In particular, we focus on the potentials and challenges of ice-wedge palaeoclimatology, and outline priorities for future research to improve the understanding of ice wedges as climate archive as well as ice-wedge based reconstructions of past climate. The isotope geochemistry of ice wedges is reviewed by Lacelle and Vasil'chuk[16] and their dynamics, structure and palaeoenvironmental significance by Christiansen et al.[17].

2. ICE-WEDGE GROWTH

Ice wedges hold the largest potential for palaeoclimate reconstructions from analysis of ground ice because their infill derives from atmospheric moisture, they may grow over centennial to millennial timescales and they are widely distributed in permafrost environments. Ice wedges grow in polygonal patterns owing to thermal contraction (frost) cracking of the frozen ground in winter and filling of cracks mostly by snowmelt in spring[18]. Minor contributions of snow and/or depth hoar[19,20] as well as of mineral particles and organic material may occur, the latter allowing for direct dating. The melt water refreezes immediately due to the sub-zero ground temperatures and forms a vertical ice vein[21]. Ice wedges widen by repeated frost cracking, snow-melt filling and refreezing, and, therefore, may be identified by their

vertical to subvertical foliation (Figure 1). If the wedges crack in their centres and grow symmetrically, then the youngest ice veins constitute the central part of a wedge and the ice veins become progressively older towards its margins. However, such a textbook-like growth pattern has seldom been observed because ice-wedge growth is often more complex and interrupted by periods of inactivity, thaw or frost cracking that is not limited to wedge centres.

In general, ice-wedge growth may take place (1) after the formation of permafrost (epigenetic ice wedges that grow mostly wider), (2) during the formation of new permafrost due to a rise of the permafrost table following deposition of sediment on the ground surface (syngenetic ice wedges that grow both wider and higher) or (3) during ground-surface lowering by net removal of active layer material by erosion or mass wasting (anti-syngenetic ice wedges that grow downwards)[22]. Growth can be complex in geometry and extend for centuries or millennia (Figure 1). Syngenetic permafrost development and ice-wedge growth over several thousands of years may lead to ice-rich formations such as the Late Pleistocene Yedoma Ice Complex in northeast Siberia, characterized by huge ice wedges more than 20 m high and more than 5 m wide (Figure 1).

Ice wedges likely include some of the oldest ice preserved in the Arctic. Ages of about 200,000 years from Bol'shoy Lyakhovsky Island in the eastern Siberian Arctic[23] and more than 700,000 years from Yukon, Canada,[24] have been reported. Ice wedges from the last glacial period are abundant in permafrost sequences across the Arctic, in particular in northern Siberia, Alaska, and Canada.

3. ICE WEDGES AS PALAEOCLIMATE ARCHIVES

At high latitudes, the stable-isotope ratios of oxygen and hydrogen ($\delta^{18}O$ and δD) in precipitation are sensitive to local air temperatures[25]. Ice wedges in Siberia, Canada, Alaska, Svalbard, and China have been studied as they preserve $\delta^{18}O$ and δD values over centennial to millennial timescales[10,11,17,23,26-41], which additionally allow calculation of the second-order parameter deuterium excess d ($d=\delta D-8*\delta^{18}O$)[25]. In

spring, frost cracks may fill mostly with melt water from the last winter's snow pack, whose integrated isotopic signal is transferred into a single ice vein without additional isotopic fractionation due to rapid freezing in the frozen ground[21]. Hence, ice wedges are considered as climate archives for the cold period, i.e. when precipitation falls as snow. Meyer et al.[10] defined the climate recording season as meteorological winter and spring, i.e. December to May, hereafter referred to as winter. Based on stable isotope data of modern ice wedges and precipitation, Vasil'chuk[42], Nikolayev and Mikhalev[43], Konyakhin[44], Konishchev et al.[45], and Streletskaya et al.[38]suggested regression equations (with large errors) to calibrate ice-wedge stable isotopes to winter air temperatures in northern Eurasia (Table 1). Porter et al.[41] used regionally derived regression lines between temperature and precipitation isotopes based on the GNIP (Global Network for Isotopes in Precipitation) dataset[46]. However, as these approaches are based on only a limited amount of data and may be oversimplified (section 4.2.1), they have not been generally accepted and applied quantitatively; instead, variations in $\delta^{18}O$ and δD are often interpreted as *relative* changes of winter temperatures. The interpretation of ice wedge *d* is complex and local processes have to be taken into account[29]. Nevertheless, long-term changes in *d* have been interpreted as varying evaporation conditions in the moisture source and/or shifting moisture sources due to changing atmospheric circulation[28-30].

Previous palaeoclimate studies of ice wedges have covered different timescales of the late Quaternary. Due to syngenetic ice-wedge growth—often over tens of thousands of years—and limited dating methods, the temporal resolution of ice-wedge paleoclimate studies is often very low and corresponds to specific stratigraphic units of the Late Pleistocene and the Holocene, depending on the dating techniques applied[23,28,29,47].

Recently, detailed studies have significantly improved the temporal resolution of ice-wedge records. Sub-millennial to centennial-scale stacked $\delta^{18}O$ records have been generated for Lateglacial and Holocene time

periods by combining radiocarbon ages of organic inclusions from horizontal sampling profiles across ice wedges with the stable-isotope values of the same samples[10,11,30]. In particular, the wedge-ice $\delta^{18}O$ records obtained by Meyer et al.[10] and Opel et al.[11] from the northeast Siberian Arctic—with high temporal resolution and replicable trends consistent with climate model-based and independent proxy-based winter-climate records of recent millennia—highlight the great potential of ice wedges as archives of winter climate.

However, compared to other well-established climate archives such as ice cores or speleothems, ice wedges are relatively understudied and ice-wedge palaeoclimatology faces several open questions, challenges and limitations (see chapter 4). Ice wedges cannot compete with ice cores or tree rings in terms of temporal resolution, but they can contribute valuable time-averaged information on past climate development, in particular for regions that lack other climate archives and/or research questions that concern past winter climate.

4.   RESEARCH TOPICS – STATE OF THE ART AND FUTURE RESEARCH PRIORITIES

The following interrelated research topics need to be addressed in order to evaluate more fully the strengths and weaknesses of ice wedges as a palaeoclimate archive and to improve the quality and temporal resolution of ice-wedge based palaeoclimate reconstructions: (1) modern ice-wedge cracking and infilling dynamics; (2) formation and preservation of the stable-isotope information stored in ice veins; (3) improvement of ice-wedge dating; (4) development of ice-wedge age/growth models and stable-isotope time series; and (5) generation of new ice-wedge stable-isotope records and improved interpretation.

4.1 Frost cracking and infilling dynamics

The dynamics of frost cracking and crack infilling significantly affect the use of ice wedges as climate archives. They determine which climate signal is incorporated into the ice veins (e.g. fresh snow, melt

water, or depth hoar, each with different climate–isotope relationships). Furthermore, they influence the recorded season, and the resolution and chronology of the climate record. An ice-wedge record can be continuous or discontinuous, depending on the timing, frequency and position of frost cracking and infilling.

4.1.1 State of the art

Monitoring studies of ice-wedge growth[48] are rare. Most studies of frost cracking cover only short time periods (one to five years)[49-51]. Longer-term observations (20 years) on Garry Island in the Canadian Arctic revealed that frost cracking does not necessarily occur every year but may vary considerably over time and space[52]. Per year between 8 and 75% of the 91 ice wedges observed by J.R. Mackay at two study sites cracked during the 1967 to 1987 period. Some wedges cracked in most years, but one did not crack at all. Such high variability within and between study sites indicates a major role of local effects (e.g., snow cover thickness), whereas only a poor correlation of cracking to air temperatures was found. Although the exact position of cracking may vary, ice wedges tend to crack preferentially near their centre and often year after year at nearly the same place[53]. According to observations in Arctic Canada, ice-wedge cracking occurs between November and April, but mostly between mid of January and late March[54]. Frost-crack depths of 2 to 3 m have been reported[48]. Cracks may narrow before infilling or close without infilling because of thermal expansion of ground in summer or plugging with ice or sediment[55].

Frost-crack filling and ice-vein formation have not been studied systematically over several years. Snowmelt water is assumed to be the major source for crack infilling of modern ice wedges, even though hoar crystals may grow in ice-wedge cracks[26]. Gasanov[56] reported crack infilling by desublimation in the upper part of the crack. Black[51] found that the amount of hoar frost added to cracks near Barrow, north Alaska, generally ranged from ~ 25 to 75% of the void volume, and that the amount of spring meltwater added to cracks was negligible in some and substantial in others. The width of annual ice infillings at the

top of permafrost was 0.4–6.0 mm at different study sites, with average increments of 1–3 mm, decreasing with depth.

Climate and site-specific environmental conditions play an important role for infilling of ice-wedge cracks. St-Jean et al.[19] suggested that ice wedges from colder-than-modern periods (e.g. Late Pleistocene) in Yukon and Alaska may have formed by snow densification or hoarfrost accretion in frost cracks, whereas late Holocene ice wedges predominantly formed by freezing of liquid water. Boereboom et al.[20] inferred a variable water–snow mix as a source for crack infilling of Pleistocene and Holocene ice wedges at Cape Mamontov Klyk in the Siberian Laptev Sea region, with meltwater contributing relatively more during the warmer Holocene.

The source material of the crack infill may strongly determine the isotopic signature of the wedge ice. For example, the isotopic composition of depth hoar in the lower part of the snowpack (Figure 2) may vary from that of the upper snowpack and also of snow melt due to fractionation processes involved. If depth hoar is a significant component of ice veins, this may explain why significant offsets have been observed between the isotope composition of winter snow and modern ice veins [29,32]. It is unclear whether these offsets can be primarily attributed to (a) later stages of snowmelt, with enriched isotope values compared to the earlier stages due to progressive isotope fractionation[57]; or (b) changes (i.e. enrichment) of the snowpack's isotopic composition during winter due to seasonality of precipitation, sublimation, isotopic exchange between snow and atmospheric water vapour, snow drift and depth-hoar formation e.g. [45,58-60]. It is likely that the timing of crack infilling plays a major role and the material that is available at this specific moment constitutes the ice vein. Early filling would exclude the later stages of winter precipitation, whereas late filling may integrate the remaining snow cover of the preceding winter. However, precipitation that has been falling closer to the infill date might predominate over earlier stages of winter precipitation, which are likely more affected by post-depositional processes such as redistribution due to

wind drift, sublimation and recrystallization during depth-hoar formation. A significant contribution from the active layer is assumed to be very unlikely due to its frozen state.

4.1.2 Future research priorities

Improved understanding of frost cracking and crack infilling requires an approach based on observations and instrumentation, ideally over at least several years. This could be supported by field manipulation experiments such as installing appropriate sampling devices in artificial cracks in order to collect samples of newly-formed ice veins at different depths and at different times of crack infilling. Monitoring of frost-crack timing using shock loggers (accelerometers)[61,62] or breaking cables e.g.[50,63] should be combined with measurements of air and ground temperatures as well as snow thickness, even though breaking cables do not provide information on subsequent events such as crack widening or secondary cracking. This would help to detect the threshold conditions for frost cracking at specific sites and to assess seasonal patterns as well as the temporal frequency of precipitation, frost cracking and infilling events. The characteristics of the frost cracks (spatial patterns, depth, width, potential plugs, and closure) as well as the crack infilling (time, filling material) of a representative number of polygons should be studied during repeat surveys until the end of melt season in spring. The use of computed tomography (CT) scans[64] (Figure 3) and thin sections of newly formed wedge ice for analysis of air bubbles and ice crystals may provide an additional source of information on ice-vein formation, in particular on filling material and characteristics of refreezing.

Promising sites to systematically study modern ice-wedge growth dynamics include recently drained thermokarst lake basins such as Illisarvik[48] in the Western Canadian Arctic (with well-known boundary conditions of freshly aggrading permafrost) or study sites near meteorological or research stations such as Longyearbyen on Svalbard or Samoylov Island in the Lena Delta (with good logistical support for winter observations).

4.2 Formation and preservation of the stable-isotope information stored in ice veins

The stable-isotope composition of precipitation at high latitudes relates to air temperatures[25], a relation widely used in ice-core studies. A precondition for quantitative interpretation of stable isotopes in wedge ice is to determine the extent to which this temperature–isotope relation remains constant or changes during formation of ice veins (snow-cover development, melting and refreezing in the frost crack) and the preservation of the isotopic signal within ice wedges over thousands of years.

4.2.1 State of the art

Existing $\delta^{18}O$–temperature relations for ice wedges (Table 1) are based on a spatial comparison of stable-isotope data of modern ice veins and modern syngenetic ice wedges (i.e. those formed during the last 60 to 100 years[37]) and respective mean air temperatures from nearby meteorological stations. Streletskaya et al.[38] used only study sites with meteorological stations within 100 km and referred to 1961–1990 as the reference period. The studies suggest a strong correlation of ice-wedge $\delta^{18}O$ values to January, meteorological winter, and cold-season temperatures, respectively. These regressions are based on the assumptions that the ice veins originate only from snow melt and that the isotopic composition has not changed significantly during snow cover formation, melt and refreezing in the frost cracks. Both assumptions may be questioned. Hence, Konishchev et al.[45] corrected Vasil'chuk's equation[42] for sublimation effects at the snow surface. However, the regressions rely only on a limited number of study sites and samples (Table 1) with an uneven spatial distribution, and sampling protocols, sample properties, dating details, and temperature data handling are not well documented. As only $\delta^{18}O$ values have been reported, potential isotopic exchange processes between ice veins, ice wedges, and host sediments (detectable by excursions of *d*) cannot be excluded. The calculated relationships are suggested to be valid for at least large parts of northern Russia and therefore do not consider regional to local peculiarities. Furthermore, it is unlikely that the isotope–temperature relations are constant throughout space and time

(e.g. glacial–interglacial timescales) due to changing climate, moisture source and ice-vein formation dynamics.

The preservation of the isotopic signal is also important. The outermost several cm of ice wedges can show increased ion contents as well as less depleted δ^{18}O and δD and lower d values[28,32,65], similar to the pore and segregated ice of host sediments. This indicates exchange processes at the interface of wedge ice and host sediments, presumably driven by migration of bound water[28]. Meyer et al.[65] estimated that these exchange processes may affect 10 to 15 cm of ice and sediment, respectively, per 10,000 years. This raises the question whether the isotope signature of narrow and/or very old ice wedges or composite wedges still contains the original climate signal or not. Moreover, whether isotopic diffusion affects the stable-isotope composition of ice wedges remains to be studied, though Pleistocene ice wedges tend to have smoother isotope profiles (i.e. less variability in horizontal profiles) than Holocene ice wedges.

4.2.2 Future research priorities

For quantitative reconstructions of past winter temperatures the existing isotope–temperature relations need to be validated by means of modern analytical devices and a significantly larger well-documented dataset. All isotopic fractionation processes during ice-vein formation (from snow-cover development until freezing in the frost crack) must be evaluated.

Following the hypothesis that snowmelt is the main source for newly formed ice veins, the following steps should be considered to elucidate the stable-isotope history of ice veins and to constrain the δ^{18}O–temperature relations of ice wedges. Analyses should include hydrogen isotopes, which allow the derivation of δ^{18}O–δD co-isotope relationships and d data. Hence, both isotopes should be analysed in a similar manner to better understand the significance of fractionation processes in ice-wedge formation. This is also needed to interpret ice-wedge d data in terms of climate.

Local air temperatures and stable isotopes in precipitation must be evaluated on an event basis to calibrate the isotopes on a local to regional scale and derive a corresponding "isotope thermometer" for different periods of the cold season.

The modern spatial relationship of observed air temperatures and ice-wedge stable isotopes allows an independent calibration under the common assumption that spatial and temporal relationships are related. Comparison of temporal trends in ice-wedge isotopes in recent decades and the warming trend of instrumental temperatures provides a further constraint on isotope–temperature relationships. Finally, isotope-enabled climate model simulations e.g.[66] allow estimates of the local relationship of air temperature and the stable-isotope composition of snow.

The period of time between the onset of snow-cover and the infilling of frost cracks, with associated changes of the snow cover stable-isotope composition, needs to be studied in detail, ideally at the same ice-wedge polygons studied for the frost-crack dynamics (section 4.1.2) and near the precipitation monitoring site. Repeated snow surveys (thickness, stratigraphy, proportion of depth hoar, Figure 2) are needed and repeated sampling of snow profiles, including final snowmelt (for stable-isotope analysis) to trace the transformation of the stable-isotope composition of the snowpack due to snow drift and redistribution, sublimation, compaction, recrystallization, melting and refreezing. The focus should be on the snow cover on polygonal rims (i.e. near the ice-wedge troughs) as new ice veins may develop specifically from this snow and its melt. The snow-cover and snowmelt isotope data need to be compared with those of the new ice veins. Finally, the new ice veins should be sampled in very high resolution (sub-mm scale) for stable-isotope analysis. This allows evaluating whether the freezing within the frost crack is rapid enough to limit isotopic fractionation due to non-equilibrium conditions, as suggested by Michel[21].

High-resolution studies of ice wedges of different ages (e.g. Holocene and Late Pleistocene) are essential to investigate the preservation of stable-isotope signals. A focus on isotope variability of the ice wedge is

needed to detect potential diffusion effects. Detailed high-resolution sampling (e.g. 1 cm resolution or even less) across the interface of wedge ice and intrasedimental ice in host sediments may help to determine modifications due to exchange processes. However, one should exclude the outermost (oldest) samples of an ice wedge-profile (usually some cm) which show increasing (decreasing) $\delta^{18}O$ (d) values from climate interpretation.

High-resolution mapping of the spatial variability of stable isotopes and statistical comparisons of the temporal variability recorded by the ice wedges and the driving climate signal, similar to studies performed for ice-cores[67,68], should provide insight into the signal formation and preservation. Both questions could be supported by numerically modelling signal formation[67,69]. Very low d values may indicate that the original climate signal has been overprinted due to disequilibrium fractionation, limiting the palaeoclimatic significance.

4.3 Improvement of ice-wedge dating

As with other climate archives, age determination is crucial for a meaningful interpretation of ice-wedge data and generation of high-quality palaeoclimate information.

4.3.1 State of the art

Currently, the ages of ice wedges are determined either indirectly by dating of host sediments or by direct dating of the wedges themselves. The indirect approach attributes ice wedges to stratigraphic units and dates the host sediments using radiocarbon [70,71], radioisotope disequilibrium[47], luminescence[23], or fission-track dating of tephra[24]. However, the temporal relation of ice wedges to dated host sediments is complex and variable. At a given altitude wedge ice is younger than the host sediments due to the downward directed frost cracking and ice-vein formation. Age offsets may amount to several thousands of years[28]. Moreover, complex landscape development with a variety of periglacial processes that may occur

simultaneously in space and time needs to be considered while interpreting late Quaternary permafrost stratigraphies. Hence, this approach cannot be used for high-quality palaeoclimate records, but may provide rough age estimates for the studied ice wedges. It remains nonetheless a valuable approach, especially to ice wedges beyond the limit of radiocarbon dating.

Direct dating of ice wedges based on the cosmogenic nuclide chlorine-36 (^{36}Cl) to chloride (Cl^-) ratio ($^{36}Cl/Cl^-$) in wedge ice[72] has been applied to Middle to Late Pleistocene ground ice[73]. It has yielded local chronologies, which are in general concordance with geological expectations and other chronological methods, but only for ice wedges older than 40,000 years. As the $^{36}Cl/Cl^-$ dynamics during ice-wedge formation are not yet fully understood, this approach cannot be applied for high-quality palaeoclimate records and needs methodological refinement.

Uranium isotopes and modelling of uranium evolution in ice offer another direct dating approach[74]. For dating permafrost cores in Alaska which contained mostly segregated but also wedge ice, this approach yielded chronologies up to ~200 ky BP but with substantial age uncertainties of up to one order of magnitude. In combination with other dating methods model parameters may be refined to yield more precise results.

So far, accelerator mass spectrometry (AMS) radiocarbon dating of organic carbon of different size incorporated in wedge ice has provided the majority of direct ages of such ice e.g. [75,76]. Preferentially, plant macro-remains such as roots, leaves or twigs have been used[10,30], but also lemming droppings[11,30,32]. Pollen[36] and fine-dispersed organic material[32,35] in ice-wedge samples are other sources of radiocarbon-based age information, but may lead to age overestimation as they might be reworked. The use of dissolved organic carbon (DOC) and CO_2 from air bubbles for dating of wedge ice is in its infancy. The DOC is assumed to originate from leaching of surface organic matter[77] and also from the active layer during thaw[35]. A study of Late Pleistocene wedge ice from interior Alaska by Lachniet et al.[35] suggests that dating

of DOC and CO_2 may provide significantly younger and geologically more reasonable ages for ice-wedge growth compared with ages inferred from AMS-dated fine-dispersed organic material and plant macro-remains.

4.3.2 Future research priorities

Three interrelated research topics should be prioritized to improve ice-wedge dating. Further systematic radiocarbon dating of different carbon fractions (i.e. macro-remains, DOC, bubble CO_2) incorporated in ice wedges is required to validate the results of Lachniet et al.[35]. This should be done at several study sites and involve ice wedges of different ages to test for fraction-specific characteristics such as (dis)-similarities in age distributions. Such testing may help to identify the "ideal" carbon fraction for ice-wedge radiocarbon dating that addresses research questions and possible temporal resolution as well as field and laboratory requirements. Replicate radiocarbon dating might allow for detecting and statistically correcting outlier ages caused by reworked materials, as these will always lead to age estimates that are too old.

To date old ice wedges beyond the radiocarbon range, the direct approaches of Blinov et al.[73] ($^{36}Cl/Cl^-$) and Ewing et al.[74] (uranium isotopes) remain to be evaluated systematically. Ideally, samples for both approaches will be taken from the same ice wedges at study sites where different pre-Marine Isotope Stage (MIS) 3 ice wedges are exposed, as on Bol'hoy Lyakhovsky Island[47,78] or at the Batagai megaslump[79,80] in northeast Siberia. Complementary sediment dating should be used to validate the ice-wedge ages and to test for syngenetic ice-wedge growth.

The temporal relation between growth of ice wedges and deposition of host sediments needs to be assessed in order to better compare ice-wedge palaeoclimate signals and palaeoenvironmental datasets of host sediments (such as pollen, plant macro-remains and beetles). The main questions are: how much younger is syngenetic wedge ice than host sediments at the same sampling height; and whether there are

site-specific or regional age offsets? These questions can be addressed by carefully reassessing existing samples, datasets and stratigraphic observations or by systematic dating of host sediments and ice-wedge samples. The most promising sedimentary units are widespread Late Pleistocene (i.e. MIS3 and 2) Ice Complex deposits in long-term accumulation zones and Holocene thermokarst basin or river terrace deposits.

4.4 Development of ice-wedge age/growth models and stable-isotope time series

High-resolution stable-isotope records from ice wedges are vital to infer past climate variability and to relate changes in climate forcing to reconstructed climate changes. These would also facilitate the comparison of ice-wedge archives with other Arctic climate archives such as glacier ice cores and strongly enhance the usability of the winter palaeoclimatic information preserved in ice wedges.

4.4.1 State of the art

So far, two types of time-series of ice-wedge stable-isotope data have been developed: age interpolation between radiocarbon-dated samples in Alaska[30] and stacking of stable-isotope data of radiocarbon-dated samples of several ice wedges per study site in Siberia[10,11]. These approaches have led to Lateglacial and Holocene time series of sub-millennial to centennial resolution, whereby the stacking approach leads to relatively few data points per record. Age-modelling approaches similar to the methods used for sedimentary climate archives[81] might allow construction of high-resolution isotopic records, but have not been applied to ice wedges yet.

However, ice-wedge samples only rarely contain enough plant macro-remains for AMS radiocarbon dating, especially in ice wedges from MIS 2 and 3. Age inversions in horizontal ice-wedge profiles due to irregular cracking or redistribution of older organic material into frost cracks as well as uncertainties of radiocarbon dating (e.g. the ^{14}C plateau during the Little Ice Age) hamper the straightforward

development of radiocarbon-based age models. Moreover, ice wedges in the MIS3 Yedoma Ice Complex are sometimes at the temporal (i.e. analytical) limit of radiocarbon dating[71].

4.4.2 Future research priorities

A major focus of future research should be to overcome the rather simplistic approach of stacking paired age–isotope data in order to compile high-resolution time series (i.e. sub-centennial for Holocene ice wedges). Similar to age-modelling approaches used for sedimentary climate archives, the use of statistical modelling of the age–distance relationship in between radiocarbon ages should be investigated. The age modelling has to account for the specific conditions of ice wedges, such as non-regular growth due to varying frost-cracking frequencies and positions. To develop and test this approach high-resolution (~1–2 cm) horizontal (i.e. along the time axis of ice wedges) sampling profiles with numerous radiocarbon ages (minimum of 20 per ice-wedge profile) are needed. Ideally, several horizontal profiles should be sampled from the same ice wedge (e.g. at different depths) or from different ice wedges of the same polygonal network to assess the representativity of both the chronology and the stable-isotope profiles and the influence of site-specific conditions. Numerous radiocarbon ages allow for statistically assessing and removing outliers due to reworked organic material or spatially irregular cracking. In the ideal case of a symmetric growth, comparing the derived profiles on both sides of the centre allows further constraint of the uncertainty of the age model and the derived isotopic time series. The application of state-of-the art MICADAS AMS devices[82] that can date samples of less then 50µg carbon may be the best way to deal with the usually limited amount of organic carbon available in individual ice-wedge samples. Ideally, ages can be derived for single ice veins, which may be feasible in young and relatively wide ice veins like those identified at Lake Illisarvik[48].

We see the highest potential for a successful time-series development for large syngenetic Holocene ice wedges from thermokarst basin deposits. In such "reset landscapes", ice-wedge growth dynamics are

independent from those of a palaeo relief. In contrast, Holocene ice-wedge growth on top of the Yedoma Ice Complex is likely influenced by the polygonal ice-wedge networks of the latter. However, wide syngenetic ice wedges of the Late Pleistocene Ice Complex likely enable the reconstruction of centennial-scale time series if sufficient datable material is available.

4.5 Generation of new ice-wedge stable-isotope records and improved interpretation

To take advantage of ice wedges as distinct winter palaeoclimate archives, the few existing ice-wedge palaeoclimate reconstructions need to be validated, new records generated and interpretations improved.

4.5.1 State of the art

To date, relatively high-resolution ice-wedge records are very limited in number and spatial distribution. Only three well-dated $\delta^{18}O$ time series exist for two study sites in the Siberian Arctic[10,11] and one site in Alaska[30], and only one d record has been published so far[30]. Furthermore, stable-isotope records of pre-Holocene ice wedges are generally scarce, often discontinuous and have low temporal resolution and dating accuracy due to the radiocarbon dating limitations. But they are strongly needed to elucidate interstadial and stadial winter climate conditions. The best record known is from Bykovsky Peninsula, northern Siberia, with ca. 50,000 years of continuous accumulation in MIS3 and 2 and associated ice-wedge growth[28].

4.5.2 Future research priorities

New Holocene ice-wedge time series are needed from a circum-Arctic array along spatial and temporal gradients (i.e. from Greenland, Svalbard, West and Central Siberia, Alaska and Canada) to validate whether the Holocene winter warming trend detected in two East Siberian $\delta^{18}O$ time series is a regional

pattern or an Arctic-wide phenomenon. Replicate records from nearby sites and ice wedges would allow validation and testing of the ability of ice wedges to record regional scale climate signals.

New ice-wedge records should be derived along spatial climate gradients such as a west–east transect across the Arctic, ideally connected to monitoring of frost cracking and snow cover dynamics, as outlined above. The new time series ought to be based on systematic dating of ice wedges and improved understanding of the isotope signal. All (new) ice-wedge stable isotope data should be made publicly available, e.g. in a freely available database analogously to the PAGES2k temperature database[3].

New ice-wedge stable isotope time series need to be analysed together with other regional and Arctic palaeoclimate records for a seasonal assessment of past climate change. A particular focus should lie on the interpretation of the ice-wedge *d* signal, considering potentially varying moisture sources and transport pathways. Furthermore, palaeoclimate simulations, such as from the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3)[83], and simulations of water-isotope-enabled climate models such as ECHAM5-wiso/MPI-OM[66,84] need to be considered for the evaluation and interpretation of ice-wedge derived records and a refinement of the explicit season recorded by ice wedges.

5.   CONCLUSIONS

During recent years, ice wedges have been increasingly and successfully employed as archives for past winter climate conditions. The stable-isotope ratios ($\delta^{18}O$ and δD) from wedge ice provide temperature proxies with the potential to contribute to closing existing seasonal and spatial gaps of Arctic palaeoclimate reconstructions. To fully exploit this potential, it is necessary to improve the understanding of processes involved in ice-wedge growth and the formation and preservation of winter-precipitation stable isotopes in wedge ice. Further progress is needed in ice-wedge dating and in developing age models, taking into account the specific characteristics of ice-wedge growth. As strictly related to the cold season, new high-resolution ice-wedge stable-isotope records would both spatially and temporally
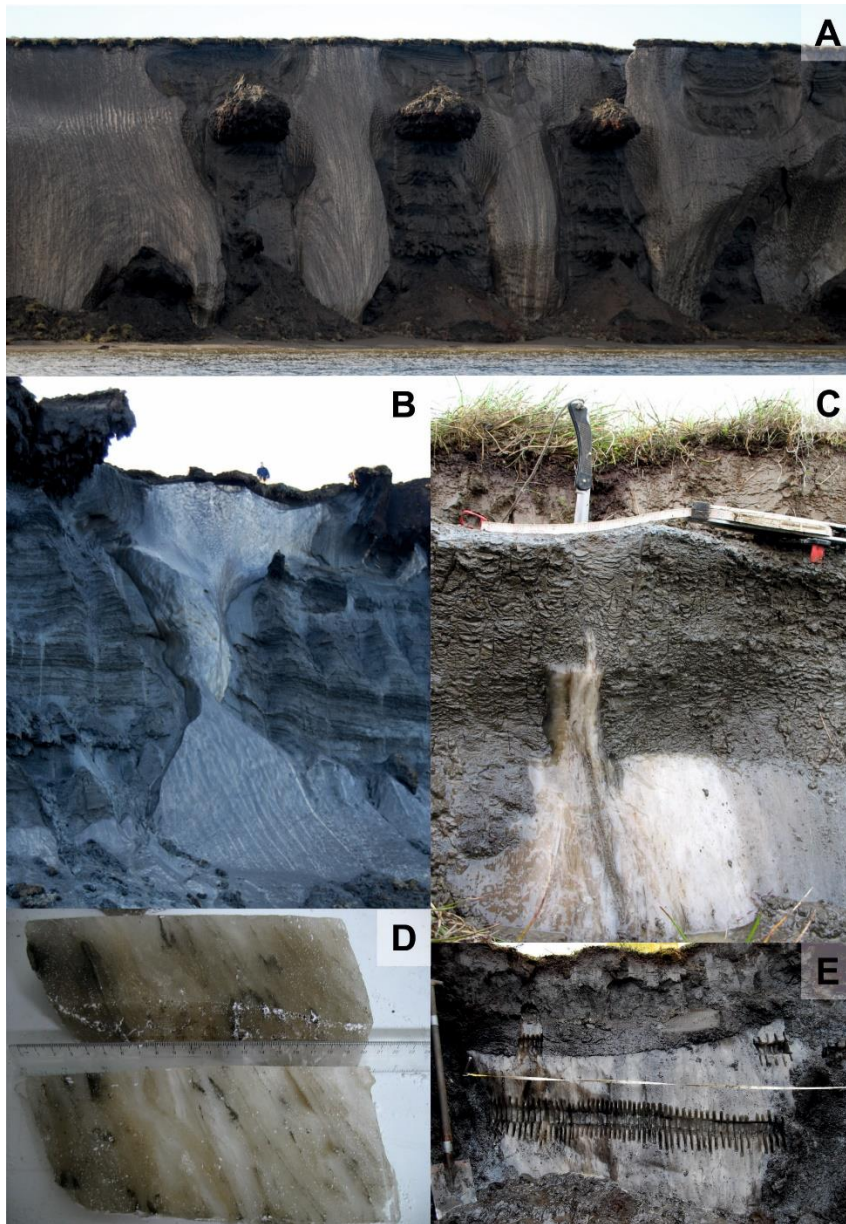
complement the existing paleoclimate archives. By doing so, ice wedges in concert with other palaeoclimate archives will significantly contribute to a more comprehensive characterization of Arctic climate evolution on seasonal scales and of the sensitivity of Arctic past and present climate change to external and internal forcing.

FIGURE 1 Selected photographs of ice wedges and wedge ice. A: About 25 m high river cliff in the Lena River Delta (Siberian Arctic) consisting of Late Pleistocene Yedoma Ice Complex with typical wide and high ice wedges and several peaty horizons. B: Complex geometry of Late Pleistocene and Holocene ice wedges at Muostakh Island (Siberian Arctic), person on top for scale. C: Holocene ice wedge with two rejuvenation stages at the Oyogos Yar coast (Siberian Arctic), the youngest ice wedge parts show the typical white ice with numerous small air bubbles. D: Typial foliation of Holocene wedge ice (horizontal cut) representing ice veins with sedimentary and organic inclusions (Oyogos Yar coast, Siberian Arctic). E: Holocene ice wedge with non-central rejuvenation stage and suggested high-resolution horizontal sampling profile (Muostakh Island, Siberian Arctic)
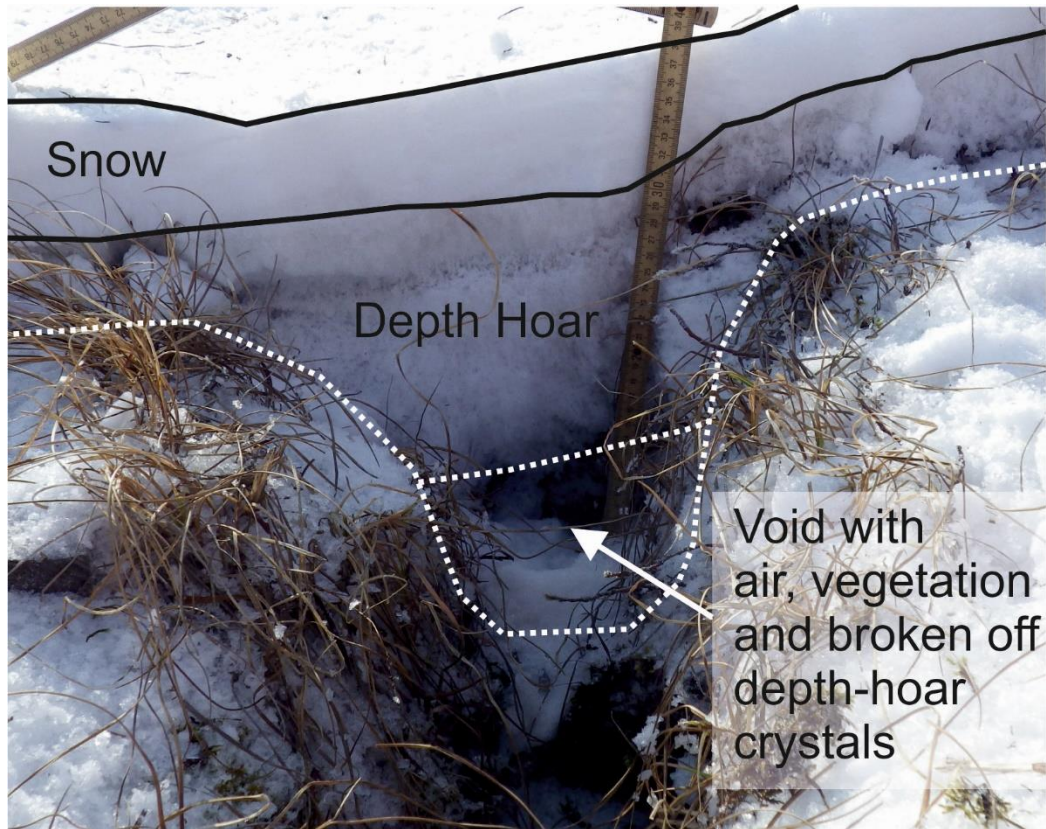
FIGURE 2 Photograph of a snow-filled ice-wedge trough (~ 25 cm deep, 10–15 cm wide) taken at Samoylov Island (Lena Delta) on 22 April 2013. Snow-cover thickness is 37 cm, 32–37 cm from bottom: snow, 15–32 cm: depth hoar, 0–15 cm: void filled with air, vegetation and some broken off depth-hoar crystals. Below the trough a frost crack 1–1.5 cm wide and at least 1.3 m deep was observed (not visible)
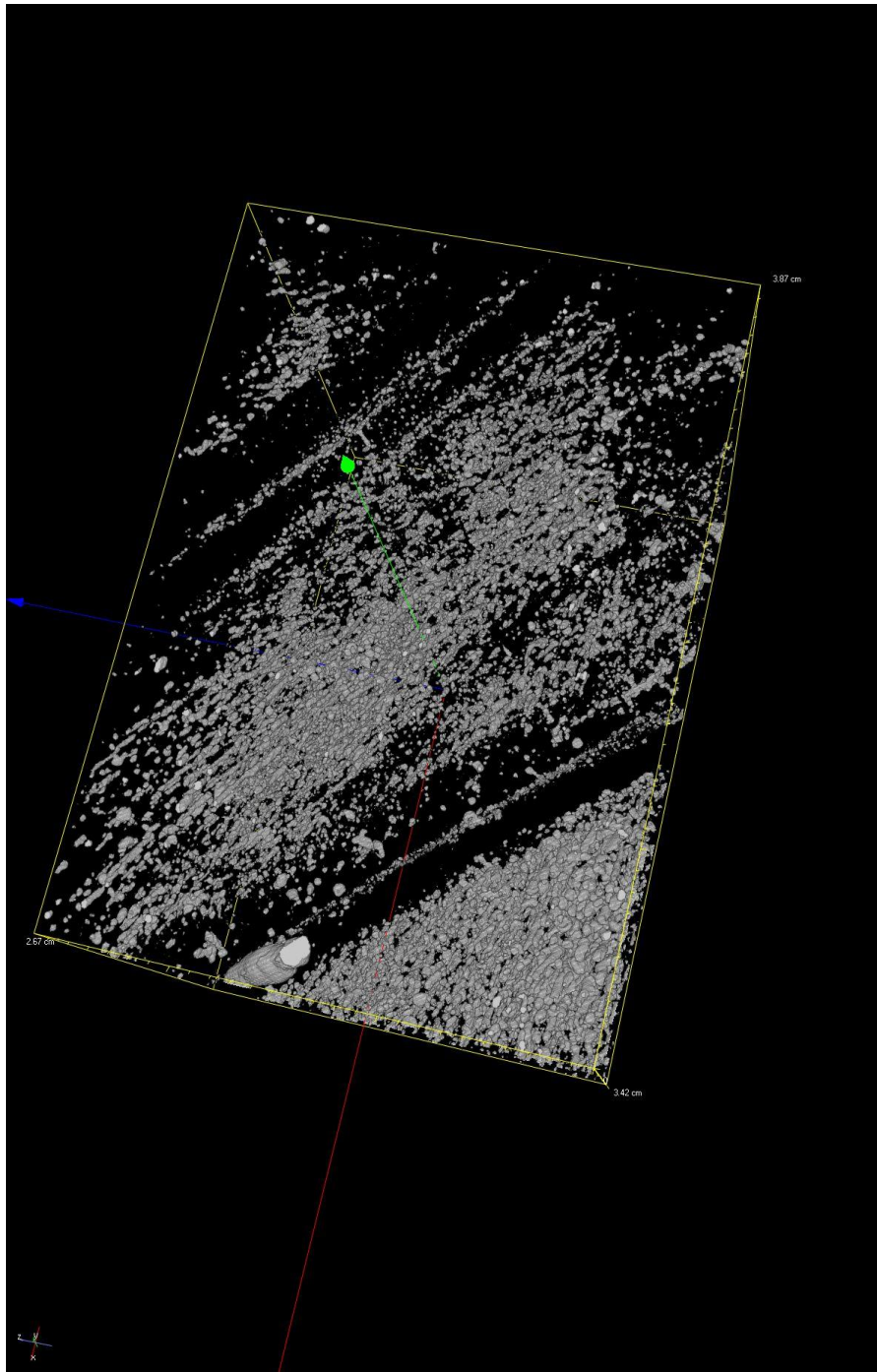
FIGURE 3 CT scan of Holocene wedge ice (sample size 3.87x2.67x3.42 cm) from Muostakh Island (northeast Siberian Arctic) showing air bubbles in white (total bubble volume ~1%). Note the clearly detectable ice vein in the lower right and upper left characterized by very small bubbles within bubble-free ice. The CT scan was performed by means of the AWI-ICE-CT at 140kV in 56μm pixel resolution. Technical details are given in Freitag et al.[64].

TABLE 1 Existing temperature-ice wedge $\delta^{18}O$ relations for northern Eurasia

Study / reference period	January	Winter (December to February)	Cold period (October to May)
Vasil'chuk, 1992[42] (34 study sites, 34 samples)	$T = 1.5\ \delta^{18}O \pm 3$	$T = \delta^{18}O \pm 2$	n/a
Nikolaev and Mikhalev, 1995[43] (35 study sites)	$\delta^{18}O = (0.53\pm0.06)\ T - (5.39\pm0.38)$ ($r^2=0.796$)	$\delta^{18}O = (0.59\pm0.07)\ T - (4.15\pm0.37)$ ($r^2=0.819$)	$\delta^{18}O = (0.86\pm0.10)\ T - (3.88\pm0.36)$ ($r^2=0.830$)
Nikolaev and Mikhalev, 1995[43] (Northern Yakutia, 15 study sites)	$\delta^{18}O = (0.48\pm0.04)\ T - (9.02\pm0.14)$ ($r^2=0.90$)	$\delta^{18}O = (0.56\pm0.05)\ T - (6.90\pm0.13)$ ($r^2=0.91$)	$\delta^{18}O = (0.83\pm0.12)\ T - (6.14\pm0.20)$ ($r^2=0.78$)
Konyakhin, 1996[44] (27 study sites, 94 samples)	n/a	$T = 1.2\ \delta^{18}O$	n/a
Konishchev et al., 2003[45]	n/a	$\delta^{18}O = 1.25\ T + 4.0$	n/a
Streletskaya et al., 2015[38] (20 study sites, 140 samples)	$T = 1.12\ \delta^{18}O - 6.43$ ($R^2 = 0.745$, $\sigma = 2.6$)	$T = 1.15\ \delta^{18}O - 4.6$ ($R^2 = 0.754$, $\sigma = 2.7$)	$T = 0.885\ \delta^{18}O - 2.55$ ($R^2 = 0.674$, $\sigma = 2.7$)

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