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EXECUTIVE SUMMARY

This report summarizes the current knowledge on potential effects of the special properties of ice as old as 1.5 Myr at the bottom of the Antarctic ice sheet (strong thinning, old age, relative high in situ temperatures of -5 to -10°C) on the climate record to be retrieved from a 1.5 Myr old ice core.

The most important effect is the likely occurrence of signal damping due to diffusion and migration processes in the ice not encountered to this extent in previous, much younger ice core records. In contrast, in situ production effects will likely not be different from the existing ice core records from Antarctica. Diffusion/migration may lead to the loss of the climate information at higher frequencies in a few tracers, however for most of the tracers investigated (for example greenhouse gases, water isotopes, soluble and particulate impurities) a total obliteration of orbital variations is unlikely. Moreover, using improved data on diffusion lengths for the individual tracers, a signal inversion of the true amplitude is possible for most species.

Another point of concern is the potential occurrence of stratigraphic anomalies in this bottom-most ice, such as folds. The risk for the occurrence of such effects is becoming greater the closer to the bedrock the 1.5 Myr old ice will be found and the larger the lateral flow of the ice was over the last 1.5 Myr before it reached the drill hole. Careful site selection for the drill location at Little Dome C will minimize these risks, however, the final proof whether stratigraphic disturbances occurred will become only available with the retrieval of the ice core at the site. Using new and improved multi-parameter dating techniques as outlined in this report as well as the stratigraphic information embedded in the physical and chemical properties of the ice will allow us to recognize stratigraphic disturbances. Moreover, using the marine sediment dust template we will be likely able to correct for them if they appear.

In contrast to the significant effects of this old and warm ice on the climate information stored in the ice, the character of ice as old as 1.5Myr has little impact on drilling technology and ice core handling. Previous experience with gas loss in ice cores makes storage of at least part of the ice at -50°C necessary and affords suitable logistics measures. The strong thinning of this ice has a significant impact on the availability of sufficient ice for all the tracers to be studied on the core. Using new analytical techniques with higher precision, higher resolution, and less sample consumption, the most important climate information can be retrieved from the core. Using replicate drilling, additional sample material for large sample analyses will become available.

1. Introduction

The overarching objective of the Coordination and Support Action (CSA) "Beyond EPICA: Oldest Ice (BE-OI)" and of the currently planned Research and Innovation Action (RIA) "Beyond EPICA: Oldest Ice Core (BE-OIC)" is to drill an ice core in Antarctica that provides a continuous, stratigraphically ordered climate sequence covering the last 1.5 Myr. Such an ice core will cover for the first time the enigmatic Mid Pleistocene Transition (MPT), characterized by a shift of the glacial/interglacial cyclicity, from 40,000 years earlier than 1.2 Myr before present, to the well-known 100,000 yr cycles found over the last 800,000 yr. The reason for this transition is still unknown and only the direct atmospheric record stored in an Antarctic ice core covering this time interval (including its information on greenhouse gases, molecular oxygen and nitrogen, noble gases, gaseous erosion proxies, Antarctic and Circum-Antarctic climate and ice sheet conditions,…) can provide the crucial climate information needed to understand the nature of this shift.

While the age of the Antarctic ice sheet is in principle much larger than 1.5 Myr, glacier flow and subglacial melting under the ice sheet lead to a permanent removal of the very old ice. In fact, the oldest ice core record to date (the EPICA Dome C ice core), covers "only" 800,000 yr as deformation and basal melting removed older ice at that site[1]. One dimensional flow modelling as well as 3D ice sheet modelling (Fischer et al., 2013; van Liefferinge and Pattyn, 2013; Passalacqua et al., 2018) shows that older ice can be found in Antarctica at sites with similar climate conditions (snow accumulation, temperature) and similar geothermal heat flux at the ice/bedrock interface as at Dome C but exhibiting a significantly lower ice thickness of 2600-2800 m to avoid basal melting. Moreover, the location of such a drill site should be close to a permanent dome structure to avoid extended horizontal ice flow/large bottom drag, which is conducive to stratigraphic folding of the ice. In reality, the potential areas exhibiting optimum boundary conditions for a 1.5 Mr yr ice core are very limited and constrained to a few high plateau regions of the East Antarctic Ice Sheet. One most promising drill site at Little Dome C has been identified within BE-OI in the vicinity of Concordia Station, i.e., only 40 km away from the EPICA Dome C drill site. Using a 1D model constrained by new radar isochrone information it is predicted to find 1.5 Myr old ice about 150 m above bedrock at this site (Parrenin et al., 2017).

However, even if retrieval of a 1.5 Myr old ice core can be achieved at that site, the strong glacial thinning of the ice causes the ice sequence older than 700 kyr to be compressed in a depth interval of only 200-300 m, providing ice of a character previously not encountered in any other polar deep ice core drilling[2]. The strong thinning, the relatively warm in situ temperatures of this ice and its old age may alter the climate information stored in the various ice core proxies and gas species investigated through diffusion, chemical alteration or crystallographic changes. Moreover, the strong thinning requires substantially improved resolution and precision of the measured ice core parameters to reconstruct the original climate signal. State-of-the-art ice core drilling and ice handling techniques are mandatory to obtain the best quality ice core material required for the novel ice core analyses to be performed on the core and dedicated measures for transport, storage and curating of the core are needed to preserve the climate signal in the best possible way.

Workshop 4.1 on

"Special glaciological conditions of Oldest Ice and implications on the Beyond EPICA science plan"

and workshop 4.2 on

"Special glaciological conditions of Oldest Ice and implications of ice core drilling and handling"[3]

(i) compiled and discussed the current knowledge on these issues,

[1] Note, however, that underneath the climate sequence of the last 800,000 yr in the Dome C ice core there is a 60 m layer of meteoric ice of unknown origin which is characterized by typical meteoric ice properties but not showing any glacial/interglacial variations.

[2] 1D-modelling shows that a 40,000 yr cycle in the climate record can be compressed into 1 m of ice at an age of 1.5 Myr.

[3] 1-day workshop organized before the POLAR2018 conference in Davos, Switzerland, on the 16th of June 2018 including oral presentations, 1 page written summaries and extended discussion sessions on individual topics.

(ii) devised strategies for ice core analyses and handling for such highly thinned ice to provide the best climate record and

(iii) made recommendations for dedicated research to be carried out in the coming years before the climate sequence of ice older than the EPICA Dome C ice core becomes available to better quantify potential alterations processes in the ice.

The outcome of the two workshops with respect to points (i) - (iii) are summarized in this report.

2. Results and Discussion

The unprecedented age of the ice and the warm in situ temperatures between -5 and -10°C that the ice experienced for many hundred thousands of years combined with the extraordinary thinning leading to large vertical gradients in ice core parameters can lead to significant alteration processes affecting the ice core tracers. Such effects comprise:

1. In situ diffusion/relocation of water isotopes, dissolved chemical tracers and gases
2. Potential in situ formation compromising the ice core record
3. Stratigraphic disturbances: Folding and abnormal flow

Moreover, the special character of this unique ice makes special efforts mandatory to obtain and preserve the best ice core quality in order to get the best climate information. This pertains to

4. Dating the ice using complementary methods
5. Avoiding post-coring alterations of the ice core material
6. Drilling and handling of the bottom-most ice

In the following the existing knowledge on these issues will be presented and the potential reverberations for a BE-OIC 1.5 Myr old ice core and its science plan will be discussed.

2.1 In situ diffusion/relocation of water isotopes, dissolved chemical tracers and gases

Diffusion processes of water stable isotopes were already shown to be very strong in the bottom part of the EDC ice core (Pol et al., 2010). Analysing relatively high resolution (11 cm) samples, the authors showed a loss of δD signals for periodicities shorter than 1600 years in the ice corresponding to interglacial Marine Isotope Stage (MIS) 19. These authors concluded that an enhanced isotopic diffusion occurred with an estimated diffusion length reaching about 40 cm, a value which is twice the modelled one based on known self-diffusion rates of water isotopes in monocrystalline ice. The authors estimated that the ice layers, corresponding to MIS19, spent around 200 kyr at a temperature higher that -10°C enhancing the isotopic diffusion. Conservatively assuming ice twice the age as at Dome C and stored at the same in situ temperatures, such ice would exhibit a stable water isotope diffusion length of about 60 cm as diffusion length increases with the square root of the age. The excess diffusion above that expected in single crystals might be due to the possible presence of water-veins at grain junctions. These processes must be considered and possibly corrected for before reconstructing the climatic signals from water stable isotopes in order to reconstruct the full amplitude of orbital changes. As diffusion is a well understood physical process, such a signal inversion can be achieved mathematically if centimetre to decimetre resolution and especially high-precision analysis (0.01‰ for $\delta^{18}O$ and 0.1‰ for δD) of discrete samples can be achieved for all the ice > 700 kyr and the temperature history of ice at a certain depth is calculated using ice flow modelling. Moreover, more dedicated studies to better constrain the diffusion length of this excess diffusion are needed on existing old ice core material

Soluble ionic compounds (mainly marine and biogenic compounds) can undergo post-depositional process mainly connected with the presence of liquid water. In particular in warm bottom-most ice (Rempel et al., 2001) hypothesized a net migration of impurities along the temperature gradient due to the increasing presence of liquid water in the deepest ice. Although theoretical considerations by the authors suggest that a downward migration may take place, it has so far not been observed in existing ice cores (for example at Dome C), where similar temperature gradients are encountered as expected for an Oldest Ice drill site. Independent whether this net downward movement occurs, bidirectional diffusion of compounds (such as sulphate and chloride) has been observed from volcanic horizons (Barnes et al., 2003). Extrapolating, this diffusion process to ages >700 kyr, the detection of volcanic acid horizons is highly unlikely.

Another process that might cause re-allocation/migration of the soluble ionic compounds is the formation of larger ice crystals at the bottom. The formation of such crystals might cause an expulsion of the soluble ionic compounds in between the ice crystal causing an enrichment at the interface and in the ice veins. Long-term post-depositional processes were indeed observed in the Dome C ice core for ice layers deeper than 2800 m (Traversi et al., 2009). They likely involve a rearrangement of impurities via migration in the vein network rich with sulfuric acid, and can lead to the formation of particles of magnesium sulfate salts, soluble at warmer temperatures near the bed. Similar and enhanced chemical processes due to recrystallization at high temperature were detected as frequent occurrences of $CaCO_3$ and $CaSO_4$ particles within visible aggregates in the bottom EDC basal ice (3248-3252 m) (Tison et al., 2015; de Angelis et al., 2013). Interestingly, high spikes have also been observed in the ^{10}Be record in old ice (Raisbeck et al., 2006), which are not atmospheric in nature and may be related to this precipitation/relocation effect. Further studies of these processes in deep EDC ice are required to assess how best to correct for such effects.

Particulate dust should not migrate in the ice by itself; however due to the slow and temperature dependent ice recrystallization process, ice grain boundaries may move relative to particulate dust particles and aggregation of dust at grain boundaries has been observed (Tison et al., 2015). These processes may change locally the dust and ionic concentrations on depth scales of grain sizes and also lead to spikes in the records that are not atmospheric in nature. As the relocation processes are conservative in nature (i.e., they do not produce or destroy impurities or dust particles in the ice) appropriate averaging or time series analytical pretreatment of tracer records should allow us to overcome this problem, and use the dust record, for example, to compare with the marine sediment dust template for dating purposes. However, while the total dust content should not be affected by this effect, determining dust size variations from such ice may be hindered by the aggregation effect, if we cannot separate the dust particles without changing their initial dust size distribution.

Finally, modeling studies for gas diffusion in ice suggests, that the high permeation rate of O_2 in ice does not strongly affect precessional cycles in the 800 kyr record in the EPICA Dome C ice core, but may lead to a complete loss of precessional signals in O_2/N_2 (Bereiter et al., 2014) in the bottom-most ice of a 1.5 Myr ice core depending on the value of O_2 diffusion within ice matrix (note that the current estimate has a large uncertainty). Due to its much lower permeation rate, CO_2 variations are likely to survive but may experience a damping by up to 30% in 1.5 Myr old ice. As diffusion is a well understood physical phenomenon, this damping can be reversed using signal inversion, while if the O_2/N_2 signal is fully smoothed it is unlikely that any signal can be recovered. Accordingly, a robust estimate of O_2 diffusion in the ice matrix should be provided and other means of information are needed to aid dating of the core by orbital tuning. In this respect, the Total Air Content (TAC) appears of crucial importance, as it also shows an obliquity variation of a few percent (Raynaud et al., 2007) and should be less influenced by diffusion. Most importantly, particulate dust and dissolved dust components will likely represent the most important tuning parameters as quantitative dust deposition records exist from Southern Ocean marine sediments.

2.2 Potential in situ formation compromising the ice core record

The success of ice core research is to a large part based on the fact that ice core gas records represent the true past atmospheric composition. While there were examples where artifacts led to erroneous results (e.g. CO_2 in Greenland glacial ice (Smith et al., 1997)), these problems could be quickly resolved mostly with the help of other ice cores spanning the same time interval. For all of the 3 greenhouse gases

(CO_2, CH_4, N_2O) artifacts have been documented in ice from either Greenland and/or Antarctica. Depending on the parameter, several strategies have been developed to identify these artifacts:

a) comparison of records from different ice cores with different impurity content or delta age characteristics.

b) high temporal resolution measurements that allow detection of non-climatic variability, i.e. jumps faster than possible from the species' atmospheric lifetime, from known release processes or from the low-pass filtering through the bubble entrapment process in the firn.

c) isotopic signatures indicative of production using a different pathway or source material (e.g. N_2O (Sowers, 2001)).

For the future BE-OIC record, where no other ice cores exist to compare with and where resolution is limited due to the highly thinned nature of the ice, we are mostly left with strategy c). Key in this respect are long time series of other parameters measured on the same ice sample and ideally a process understanding of how these are causally related to in situ formation. For example, measurements of short-chain alkanes (methane, ethane, propane) in ice samples from glacial Greenland ice revealed an artifact during the wet extraction of CH_4 analyses which challenges some previously derived CH_4 records (Bock et al., 2010; Baumgartner et al., 2012). This effect can be minimized using fast Continuous Flow CH_4 analysis, which is now standard in ice core research. For the in situ production of N_2O in Antarctica a characteristic isotopic fingerprint was currently found within the BE-OI consortium in both the $\delta^{15}N$ and $\delta^{18}O$ signature that helps to identify production of N_2O in the ice without relying on a dust threshold or scatter criterion. However, while in situ N_2O production can be in principle well identified using stable isotopes, these measurements are currently slow and need relatively large samples, which is prohibitive for establishing continuous records. Accordingly, fast (potentially less precise) online methods should be explored to identify the strong in situ signal in N_2O isotopes. For CO_2 small offsets (of a few ppm) have been also observed between individual Antarctic ice cores (Bereiter et al., 2012). Their origin is still a matter of debate, but they could potentially be related to small in situ production. Note that currently available ice core results show offsets of a few to up to 10 ppm during the Holocene, which however do not increase further with age, suggesting that any effect is still expected to be only a few ppm at most. In any case, stable CO_2 isotopes represent an efficient means to detect such in situ production and should be performed if at all possible on the BE-OIC ice core, for example using latest laser spectroscopic techniques currently developed within the BE-OI consortium. Further, 17D of O2 varies to first order with CO_2 (Blunier et al., 2012) and can potentially be used to verify the CO2 record.

2.3 Stratigraphic disturbances: folding and abnormal flow

Despite theoretical glaciological conditions to find old ice being well known (see Introduction) even well selected drill sites are subject to significant shear stresses in the lower part of the ice column, when the ice is frozen to the bed. Under these conditions the strong crystal-orientation anisotropy of the ice at lower depth is causing small-scale disturbances in the stratigraphy due to localization of deformation, ranging from centimeter to decimeter scale (Jansen et al., 2016). Such disturbances have been observed in the visual stratigraphy record of deep ice cores (Svensson et al., 2005). Note that the climate record averaged over longer depth scales than affected by this localized deformation effect was not affected. In any case, minimizing the basal shear stress during site selection appears to be an important selection criterion. How far the occurrence of such small-scale disturbances may compromise the BE-OIC climate record on orbital time scales strongly depends on the thinning of the ice. A selection of a drill site where 40,000 yr cycles are found in more than 1 m of ice (such as at Little Dome C) appears to be safe to reconstruct the orbital climate record. It should be noted, however, that this localized deformation effect may more strongly affect the climate record in ice even more strongly thinned and may represent a natural limit for ice core reconstructions back in time.

Disturbances of the ice stratigraphy on a much larger depth scale may occur due to folding with hinges perpendicular to the flow direction. Such folds are likely to occur in case of varying basal conditions in upstream flow direction of the ice, where the ice is either frozen to the ground or going over slippery patches, (Wolovick Michael et al., 2015; NEEM community members, 2013). Selecting small horizontal travel distances, a permanently frozen bedrock also upstream of the drill site and finding the climate section of interest (the time interval 0.7-1.5 Myr) well above bedrock during the site selection will minimize the risk of folding and large-scale stratigraphic disturbances.

Even in the absence of folding, glacial flow may compromise the climate record in ice close to the bedrock. In the case of the Dome C ice core, another example of anomalous ice flow has been found where underneath the climate sequence covering the last 800 kyr there is a 60 m layer of meteoric ice which does not show any glacial/interglacial cycles. One explanation for this ice could be anomalous thinning/flow within the bedrock depression underlying the Dome C location (Tison et al., 2015) which may lead to lateral horizontal compression of the ice and therefore anomalously (reduced) vertical thinning. Longitudinal valley over-deepening and basal melting along flow could also have contributed to the local relative vertical thickening. Again, the most efficient way to avoid such complications is to use a drill site where the 1.5 Myr isochrone is well above bedrock and to pick a drill site located over a bedrock plateau, not a depression. Both criteria are fulfilled for the envisaged Little Dome C drill site.

As ice penetrating radar studies were so far unable to unambiguously resolve the stratigraphy of the bottom ~10% of the ice (Young et al., 2017), a final proof of the stratigraphic integrity of the ice between 0.7 and 1.5 Myr at Little Dome C will only be possible after the core has been drilled. Accordingly, high-resolution visual stratigraphy in addition to grain size, orientation and c-axes measurements represent an important part of the BE-OIC science plan as well as the application of precise dating techniques as described in the next section.

2.4 Dating the ice using complementary methods

Due to the potential risk of stratigraphic disturbances and the chance for a reduced amplitude (or in the case of O_2/N_2 even absence) of glacial/interglacial variations in ice core climate parameters for ice as old as 1.5 Myr (see 2.1 and 2.3 above), the dating strategy for the ice core section between 0.7 - 1.5 Myr is of greatest importance. Here we advise for a complementary dating strategy using:

1) Glacial/interglacial variations in climate parameters (after correction for diffusion effects) that can be compared to other existing climate archives, in particular marine sediments or orbital parameters. Of special importance in this respect will be the particulate dust and Fe record in the BE-OIC ice core which - after correcting for aggregation effects on the millimeter to centimeter depth scale - can be directly correlated to existing mineral dust tracers fluxes from the Southern Ocean (Martinez-Garcia et al., 2011). As both dust deposition in the Southern Ocean as well as in Antarctica are derived from the same Patagonian dust source, relative changes in both dust archives must be the same in amplitude and occur simultaneously (no phase lag). This marine sediment template can also be used to identify potential hiatus in the ice core record due to folding. If indications for the latter are found, the physical property information on visual stratigraphy, grain properties and c-axes distribution can be used to confirm or refute potential stratigraphic inconsistencies. Other parameters that can be used for orbital tuning are the variations in O_2/N_2 and $\delta^{18}O_2$ (if they survived to a sufficient degree to allow for signal inversion) and the Total Air Content.

2) Absolute dating techniques using radioisotopes or geochemical tracers that exhibit an internal clock. The most important examples for the prior are cosmogenic isotopes such as aerosol-borne ^{10}Be, ^{36}Cl or ^{26}Al (where the large samples of Antarctic ice core material required for ^{26}Al dating of about 5 kg (Auer et al., 2009) is currently prohibitive) and gaseous ^{81}Kr. Current sample sizes for ^{81}Kr analyses using Atom Trap Trace Analysis (ATTA) are still a minimum of 5 kg for Antarctic ice core material of an age of 1 Myr, but technological process may allow for smaller samples in the future. Currently, ^{10}Be and ^{36}Cl measurement are feasible on samples of a few hundred grams. The $^{36}Cl/^{10}Be$ ratio with an effective half-life of about 384 kyr is especially promising to date 1.5 Myr old ice as this tracer also corrects for transport effects of the cosmogenic isotopes from their stratospheric source to the ice sheet. However, Cl loss through HCl emanation from acidic Antarctic snow has been reported in several studies in particular from low accumulation sites in central East Antarctica which can alter the ^{36}Cl content (Delmas et al., 2004) Cl loss is not found in glacial ice with high dust content (Wolff et al., 2010). Thus accurate $^{36}Cl/^{10}Be$ dating should be at least possible for glacial ice. An example for the use

of a stable isotope with an inherent clock is the $^{40}Ar/^{36}Ar$ ratio in the atmosphere which slowly increases due to the ^{40}Ar formation by ^{40}K decay in the crust and the mantle (Bender et al., 2008). High precision measurements of ^{40}Ar, ^{38}Ar and ^{36}Ar have been established within the BE-OI consortium in recent years using ice core samples of only a few hundred grams and this technique will be applied in BE-OIC. Anomalously elevated ^{40}Ar values were observed at the bottom of Greenland ice cores (Yau et al., 2016) likely due to mixing in of silty ice containing crustal material. This effect is unlikely to occur for 1.5 Myr old ice sufficiently high above bedrock as to be encountered at Little Dome C. Finally, the size of clathrates in the ice exhibit a time scale of growth (Salamatin et al., 2003) which can also be used to date the ice. All these methods allow for absolute dating of the ice, however the precision of each of these techniques is only on the order of ± 100 kyr for ice of an age of 1.5Myr. Thus, it will provide absolute ages to test the BE-OIC chronology but the age constraints are insufficient to establish a precise age scale on their own.

3) In order to combine both orbital tuning constraints from 1) and absolute ages from 2) with our knowledge of plastic ice flow at an ice sheet dome location, the recently established Bayesian optimization dating tool ICECHRONO (Parrenin et al., 2015) can be used which allows us to derive an age scale which is consistent with the dating uncertainties of all the employed methods and the rheology of the ice.

2.5 Avoiding post-coring alterations of the ice core material

Due to the uniqueness of the ice with an age of 1.5 Myr, special care has to be taken also after the drilling to preserve the climate information embedded in the ice. This is especially important for gaseous species in the ice as gas loss has long been observed in ice cores and affects especially the smallest molecules, i.e. O_2 and Ar preferentially to N_2 (Bender et al., 1995). During storage of clathrate ice at relatively high temperature (-20°C), $\delta O_2/N_2$ was shown to decrease steadily with time (Kawamura et al., 2007) and decreases from -10‰ to -40‰ on average for ice stored 10 years. This process also affects $\delta^{18}O$ of O_2 as illustrated by a slope of -0.01 ($\delta^{18}O$ of O_2 vs. $\delta O_2/N_2$) (Landais et al., 2003). Similar, gas loss effects for ice that got warmer than -20°C were reported for noble gases from the Greenland NEEM site. More recently, the effect of gas loss on $\Delta^{17}O$ of O_2 has been quantified for old clathrate ice within the BE-OIC consortium: a maximum effect of 10 ppm has been found. $\delta^{15}N$ of N_2 does not seem to be affected by such gas loss. No strong $\delta^{40}Ar$ effect linked to post coring gas loss has been observed in bubble ice (Kobashi et al., 2008) but this effect should be checked for clathrate ice.

The effect of postcoring gas loss is most pronounced at high storage temperature. While storage temperature at -25°C for a few weeks may still be acceptable, short-term warming of the ice to for example -10°C already compromises the results of the gas species mentioned above. Postcoring gas loss can be minimzed at storage temperatures of -50°C. Accordingly, a closed refrigeration chain of ice used for analyses of tracers sensitive to gas loss has to be established. This entails special reefer containers run at -50°C for ship transport of part of the ice back from Antarctica to Europe and permanent storage of such ice at a -50°C cold storage facility in Europe. For permanent safeguarding a smaller part of the ice should be stored at Dome C, where mean annual temperature is -54°C. To this end, an extended storage capacity has to be established at Concordia Station.

Apart from avoiding gas loss to the best possible extent, further studies on gas loss processes are needed, which encompass the full suite of gas tracers studied on ice cores. Establishing a firm quantitative understanding which gas species are affected by gas laoss and to what extent will allow us to correct for any gas loss effects observed.

2.6 Drilling and handling of the bottom-most ice

Drilling a 2600-2800 m long ice core in central Antarctica is a well-established technique. Several even deeper ice cores have been retrieved from similar conditions as encountered at Little Dome C for example at Dome C itself, at Vostok, and at Dome F. So, in principle standard ice core drilling technology can be used also for the BE-OIC ice core. The same holds true for the handling of the core at the surface, although the strong thinning of this ice will require a much denser sampling for discrete samples and the application of the highest resolution continuous flow methods wherever possible. Most of these techniques are already in use within the BE-OI consortium, however, additional improvements of analytical systems in terms of precision and resolution and in terms of sample consumption have to be carried out (see also 2.1 and comment on replicate drilling below).

The experience during these deep ice core drillings characterized by high hydrostatic pressure and high temperatures close to the pressure melting point for the bottom-most ice was that ice warmer than -5°C is hard to retrieve and penetration of the drill is insufficient. In the past, this could be remedied by adding some ethanol water-slush to the bottom of the drill hole, however on the cost of the quality of the ice material. Compromising the ice core material is not acceptable for the BE-OIC drilling, where the climate record of interest is only found in the bottom 200-300 m.

The specific glaciological boundary conditions required to find 1.5 Myr old ice play into our hands as the ice of interest will be significantly colder (between -5 and -10°C). Moreover, the use of a new drill fluid (Estisol 140) promises efficient chip transport also at higher temperature and pressure, thus improved ice penetration. In summary, no unknown effects are expected for drilling 1.5 Myr old ice in East Antarctica, however, additional drill tests with the new drill fluid should be performed in the coming years before drilling of the deepest and warmest ice at Little Dome C commences.

Moreover, as the climate record of interest is highly thinned in any ice core covering the last 1.5 Myr, the availability of ice material is strongly limited and a single ice core provides not enough ice to apply the full suite of the state-of-the-art analytical techniques developed within the BE-OI consortium. Accordingly, replicate drilling of the bottom 200-300 m must be one of the highest priorities of BE-OIC to make full use of the ice core climate information covering the MPT.

3. Recommendations for Future Research

In order to improve quantification of the above-mentioned processes that lead to signal loss, to enable us to perform signal reconstruction of affected parameters, or to avoid it, the following research and action items have been identified which should be tackled in the coming 4-5 years before ice older than 700 kyr becomes available from an BE-OIC ice core.

- Determine diffusion lengths/diffusion rates of water isotopes, chemical tracers and gases using ice from existing ice cores (such as EPICA Dome C, EPICA Dronning Maud Land, and Talos Dome)
- Quantify gas loss processes including bubble enclosure gas loss and post-coring gas loss in bubble and especially clathrate ice. The prior may require a dedicated firn pumping experiment in the Dome C region in the coming years.
- Explore (using existing ice core material) how dust aggregates, chemical precipitates and chemistry spikes are formed, distributed and how these should be treated in time series analysis to obtain an unbiased climate record
- Improve our understanding of signal formation at the ice sheet surface (snow/atmosphere exchange, post-depositional loss signal of tracers (such as ^{36}Cl) and bubble entrapping processes in lowest accumulation rate areas
- Quantify in situ /in extractu production of trace gases using stable isotope signatures on existing ice and explore analytical options to quantify these effects on ice > 700 kyr
- Establish improved analytical techniques with high resolution and in particular very high measurement precision to perform signal inversion of diffused signals
- Analytical improvement for experimental dating methods (gases, clathrates, cosmogenic isotopes, radioisotopes)

- Analytical improvement of LA-ICPMS based techniques for high resolution/non-destructive elemental analyses of the bottom part of the ice.
- Perform transient modeling of the temperature history of ice at a certain depth to quantify the diffusion history
- Improve our theoretical understanding of the relationship between Dielectric Profiling (DEP) signals and climate state so that the DEP carried out in the field can be used to predict the climate phase in deep ice.
- Better understanding of large scale folding and small-scale mixing imprints on respectively radio echo sounding records and multi-parametric ice properties of existing ice cores
- Develop a visual line scanner for half cores (to avoid unnecessary cuts) and add a dust logger
- Establish unbroken transport and storage capacity at -50°C for the part of the ice which is used for analyses of post-coring gas loss sensitive species including dedicated ice core insulation boxes and -50°C reefer containers.
- Test potential effects of the new drill fluid (Estisol 140) on any measurements
- Establish a strategy how to handle/subsample ice from different zones (stratified ice/non-stratified (folded) ice, mixed ice, …)

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5. Acronyms

EPICA: European Project for Ice Coring in Antarctica
TALDICE: Talos Dome Ice Core Drilling
BE-OI: Beyond EPICA – Oldest Ice
BE-OIC: Beyond EPICA – Oldest Ice Core
DEP: Dielectric Profiling

6. Annexes

Agenda of workshops 4.1 and 4.2

9:00-9:10 Opening and layout of the workshop (H. Fischer, UBERN): The joint workshops have the following goals:

- Identify issues with signal preservation in the bottom-most ice (the bottom 200-300 m)

- Identify required test measurements with already existing ice and analytical development needs

- Come up with a strategy how to best handle the bottom 200-300 m of ice most ice during drilling and core handling

9:10-9:30 Effects in water isotopes (B. Stenni, Ca' Foscari University of Venice)) (15 min presentation + 5 min discussion and identification of action items)

9:30-9:50 Effects in dissolved and particulate aerosol compounds (E. Wolff, UCAM)

9:50-10:10 Effects in gases I - signal preservation (A. Landais, CNRS)

10:10-10.30 Effects in Gases II - in situ production (J. Schmitt, UBERN)

10:30-11:00 coffee

11:00-11:20 Effects in cosmogenic isotopes (R. Muscheler, Lund University)

11:20-11:40 Effects in Physical Properties (D. Jansen, AWI)

11:40-12:00 Bottom/weird ice (J.-L. Tison, ULB)

12:00-12:30 discussion (M. Hansson, SU)

12:30-14:00 lunch

14:00-14:20 special considerations for drilling the bottom 200-300 m of ice (F. Wilhelms, AWI)

14:20-14:40 special considerations for core handling and cutting scheme of the bottom the bottom 200-300 m of ice (D. Dahl-Jensen, UCPH)

14:40-15:00 special considerations for modeling/dating (C. Ritz, CNRS)

15:0-15:30 discussion (C. Barbante, ENEA (University of Venice))

15:30-16:00 coffee

16:00-18:00 Summary discussion (H. Fischer, M. Hansson, E. Wolff, C. Barbante).

Summary, plans for tests on EDC and other ice cores, required new technical developments, identify report writing team, AOB