Towards BEYOND EPICA

Summary table of persons involved in the project:

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (person.month) throughout the project's total duration
IGE	PARRENIN	Frédéric	Senior Scientist	Main Coordinator IGE's scientific leader Coordinator WP3 Ice dynamics and age modelling	24 p.month
	MARTINERIE	Patricia	Senior Scientist	Gas signal preservation	3 p.month
	SAVARINO	Joël	Senior Scientist	Ice core chemistry	4 p.month
	GINOT	Patrick	Research Engineer	PANDA-CFA measurements	6 p.month
	CAILLON	Nicolas	Research Engineer	PANDA-CFA measurements	2 p.month
	TESTE	Gregory	Engineer	CO_2 and TAC measurements	6 p.month
	CAPRON	Emilie	Junior Scientist	CO_2 and TAC interpretation	3 p.month
	GRILLI	Roberto	Junior Scientist	Laser CO_2 measurements	3 p.month
	FAIN	Xavier	Junior Scientist	CH_4 CFA measurements	2 p.month
	RITZ	Catherine	Emeritus	Ice dynamics	Expert
	QUIQUET	Aurélien	Post-doc	Ice dynamics	3 p.month
	CHUNG	Ailsa	PhD	Age numerical modeling	12 p.month
	PhD IGE		PhD	Signal preservation	36 p.month
	PD IGE		Post-doc	Ice dynamics	12 p.month
			Master Trainee	CO_2 and TAC measurements	6 p.month
			Master Trainee	CFA measurements	6 p.month
LSCE	LANDAIS	Amaëlle	Senior Scientist	LSCE's scientific leader Coordinator WP2	6 p.month
	FOURRE	Elise	Scientist	Noble gases analyses and interpretation for dating ; CFA analyses and interpretation	8 p.month
	CASADO	Mathieu	Junior Scientist	Water isotopes diffusion modeling	8 p.month
	DUMAS	Christophe	Research Engineer	Ice sheet mdelling	6. p.month
	MINSTER	Bénédicte	Technician	water isotopes measurements (CFA and discrete)	8 p.month
	PRIE	Frédéric	Technician	Discrete analyses of gas	8 p.month
	ORSI	Anaïs	Junior Scientist	^{40}Ar dating method	2 p.month
	JOSSOUD	Olivier	Engineer	Data Treatment	6 p.month
	PhD LSCE		PhD	Study of the signal preservation / diffusion of water isotopes and gases in the bottom part of the EDC ice core using data acquisition and models of diffusion / ice permeation	36 p.month
			Master trainee	Water isotopis measurements and diffusion study	6 p.month
			Master trainee	Dating of the bottom part of EDC ice core using ^{40}Ar and ^{81}Kr measurements	6 p.month
CEREGE	BARONI	Mélanie	Senior Lecturer	CEREGE's scientific leader Coordinator WP2 ^{10}Be, ^{36}Cl sample preparation and interpretation.	10 p.month
	BARD	Edouard	Professor	^{10}Be, ^{36}Cl interpretation	4.8 p.month
	ZAIDI	Fawzi	Engineer	^{10}Be, ^{36}Cl measurements	4.8 p.month
	AUMAITRE	Georges	Engineer	^{10}Be, ^{36}Cl measurements	4 8 p.month
	KEDDADOUCHE	Karim	Research Engineer	^{10}Be, ^{36}Cl measurements	4.8 p.month

	PD CEREGE		*Post-doc*	*Study of the $^{36}Cl/^{10}Be$ ratio as a dating tool, ^{10}Be, ^{36}Cl sample preparation and interpretation.*	*15 p.month*
CRPG-Nancy	*BLARD*	*Pierre-Henri*	*Senior Scientist*	*CRPG's scientific leader – Coordinator WP4* *Sample preparation and selection* *Supervision of mineralogical and geochemical analysis* *Data interpretation*	*10 p.month*
	PD CRPG		*Post-doc*	*Sample preparation, SEM analysis of grain shapes and textures, geochemical analysis in silicates, dating with in situ cosmogenic ^{10}Be, ^{26}Al,^{21}Ne*	*15 p.month*
	SCHUMACHER	*Aymeric*	*Engineer*	*In situ ^{10}Be, ^{26}Al : preparation of samples*	*6 p.month*
	ZIMMERMANN	*Laurent*	*Engineer*	*^{21}Ne analysis*	*6 p.month*
	TIBARI	*Bouchaïb*	*Engineer*	*^{21}Ne analysis*	*6 p.month*
	ZIMMERMAN	*Catherine*	*Engineer*	*In situ ^{10}Be, ^{26}Al : preparation of samples*	*6 p.month*

Any changes that have been made in the full proposal compared to the pre-proposal

The only significant change is that we decide not to include the analysis of the bottom part of the Vostok ice core. Indeed, this work relies on a collaboration with our Russian colleagues which we cannot guarantee at this stage because of the general political situation. This part was however not a central part of our project.

I. Proposal's context, positioning and objective(s)

a. Objectives and research hypothesis

In the context of the current continuing greenhouse gas emissions in the atmosphere, it is essential to turn to the past to understand how the climate system behaves. A particularly interesting problem is the shift in Earth's climate response to orbital forcing during the 'Mid-Pleistocene Transition' (MPT), around 1 Myr ago, when the dominant glacial/interglacial cyclicity changed from 40 kyr to 100 kyr. Only polar ice cores contain direct and quantitative information about past climate forcing and atmospheric responses. However, the longest ice core record available to date is EPICA Dome C (EDC) and covers only the last 800 kyr. It is why the European H2020 project *Beyond EPICA* (2019-2026), with a strong participation of the French ice core community, aims at drilling a 1.5 Myr ice core in the vicinity of Dome C in Antarctica (https://www.beyondepica.eu/en/).

The aim of the current *ToBE* project is to develop new methods (both analytical and numerical) and to acquire new knowldege, which will be used for the interpretation of the European H2020 *Beyond EPICA* drilling project. The research hypothesis can be expressed as follow:

- *Is it possible to reconstruct climatic and environmental variations from the very old ice which exists at the base of the Antarctic ice sheet, despite of the ice alteration?*
- *Is it possible to date this very old ice, whose stratigraphic integrity is not guaranteed?*
- *Was this region of central East Antarctica stable in terms of ice flow, in particular the position of Dome C and the ice flow lines?*
- *Is it possible to determine the nature of the subglacial bedrock from inclusions present in the basal ice, as well as the timing when this bedrock was last uncovered by ice?*

Therefore, the objectives of this project will be:

- To derive high resolution records of water isotope, CH_4, CO_2, impurities used for climatic and environmental reconstructions as well as gas orbital tracers used for ice core dating (O_2/N_2, $\delta^{18}O_{atm}$ and Total Air Content, noted TAC) for the old sections of the EDC ice cores and to analyze how they are altered with respect to more recent periods.
- To develop absolute dating techniques on smallest possible ice samples based on ^{40}Ar, ^{81}Kr and on the $^{36}Cl/^{10}Be$ ratio and test them on the ice from the EDC and Byrd cores.
- To develop a large scale modeling of the East Antarctic ice sheet during the last climatic cycles and determine the position and movements of the dome and flow lines in the Dome C region.

- To develop a methodology to determine the nature of the sub-glacial bedrock and the timing of its last glaciation, by analyzing the in situ cosmogenic nuclides contents ($^{26}Al/^{10}Be/^{21}Ne$) of the debris present in the basal ice of the Antarctic Byrd ice core.

b. Position of the project as it relates to the state of the art

The H2020 *Beyond EPICA* project will drill the first ever ice core record from basal ice covering the MPT. This will extend our knowledge on climate and atmospheric greenhouse gas concentration forcing to 1.5 Myr, where glacial/interglacial cycles changed from a 40,000 to a 100,000 yr cyclicity. This is an important aim for the international ice core community (federated in the IPICS project, International Partnership in Ice Core Science), and is eagerly awaited by the entire palaeoclimate discipline and the wider climate community. But, the *Beyond EPICA* project primarily funds the drilling, and only a small fraction of the budget is dedicated to the science, which hence, relies on the national funding of the European partners.
It is why we submit this *ToBE* proposal to the ANR. French scientists play an important role in the *Beyond EPICA* project, with key leaderships in signal preservation, dating, ice dynamics and geology consortia. They are at the fore-front of these themes and the current proposal is of primary importance to *Beyond EPICA* so that they are able to advance these questions. Among the 12 nations involved in the Beyond EPICA project, the community of French glaciologists is also the only one to gather expertise covering all the ice core analysis and dating techniques required for an optimal exploitation of the new ice core.

<u>Signal preservation</u>

One of the major questions for the analysis of the Beyond EPICA ice core is to know how the signal is preserved in the bottom part, i.e. the most interesting part since it contains the oldest ice (the lowest 300 m should record the period between 1.5 Ma and 800 ka). Because of warm temperature close to melting point and huge thinning of the ice at that depth as well as the age of the deep ice, diffusion, extreme grain growth and migration of chemical species within the grain (e.g. Tison et al., 2015) are expected which can affect the preservation of the climatic and environmental signal as well as the proxies records used for ice core dating. Previous studies on deep and old ice cores have already documented the strong effects of diffusion. A diffusion length of 50 cm within the ice has been estimated at the bottom of the EPICA Dome C ice core which prevents documentation of climatic signal from water isotopes for period lower than 300 years (Pol et al., 2010). As for gas records in air bubbles, Bereiter et al. (2014) studied the diffusive exchange of the trapped gases O_2, N_2 and CO_2 using estimate of permeation coefficients within the ice matrix, and suggested that the O_2/N_2 orbital signal, usually used as a key constraint for all deep ice core chronologies, may be significantly damped for ice older than 1 million year. The effect is expected to be less important for CO_2 at orbital scale but the recorded variability at the millennial scale may be affected. Similarly, diffusion exchange may affect CH_4 record, especially over centennial variability characterizing the CH_4 glacial variability. The chemical composition of the ice (major ions) may also play a role on the CH_4 record (Fourteau et al., 2019). Finally, $\delta^{13}C$ of CO_2 is a very useful tracer of the carbon cycle (Bauska et al., 2016) but the signal preservation of this proxy has still not being studied because current measurements only cover the last 150 ka (Schneider et al., 2013). Despite multi-proxy measurements in several deep ice cores, there are still large uncertainties in the diffusive effects on the recorded signals. This is mainly due to the fact that deep ice cores have not been analyzed with a sufficiently high resolution for such highly thinned ice. The current difficulty to recover a signal should be compensated by increasing the resolution of the measurements and by increasing the precision which will allow the reconstruction of the signal originally recorded by inversion techniques of the diffusion process.

<u>Dating</u>

Deep ice core dating relies on several tools. First, some absolute dating methods are promising for old ice such as measurement of the increase of ^{40}Ar concentration in the atmosphere through radioactive decay of ^{40}K outgassing from the crust and mantle (Bender et al., 2008) or ^{81}Kr radiometric dating (Buizert et al., 2014). However, the uncertainty associated with these measurements is still very high (e.g. 180 ka for $\delta^{40}Ar$ method, 20-150 ka for the ^{81}Kr method) and the quantity of ice needed for such measurements is large (e.g. 500 g for the $\delta^{40}Ar$, 6 kg for the ^{81}Kr method).

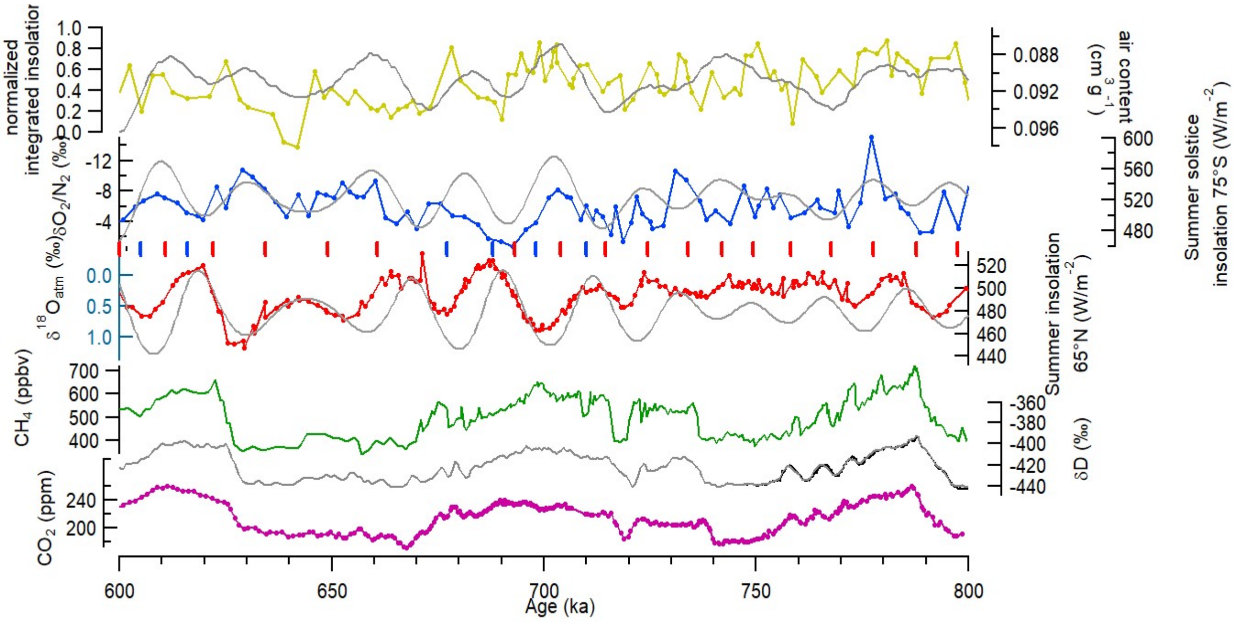

Figure 1: Records of three orbital proxies (TAC, $\delta O_2/N_2$ and $\delta^{18}O_{atm}$, with their insolation targets; the small vertical bars indicate the inferred dating constraints for $\delta O_2/N_2$ in blue and $\delta^{18}O_{atm}$ in red), two greenhouse gases (CH_4 and CO_2) and one temperature proxy (δD) for the oldest 200 kyr of the EDC ice core. The visual consistency between the orbital tracer and their targets become too unclear between 700 and 800 ka (600 - 800 ka for TAC) to be used for dating purposes. This is likely due to a too low resolution of the measurements and the bad quality of ice used for the analyzes. The $\delta^{18}O_{atm}$ variations are of very small amplitude between 700 - 800 ka which complicates also the use of this tracer for orbital dating purposes.

At LSCE with a recent mass spectrometer acquisition (end of 2018) and through the ICORDA ERC project (2019-2024), we are working on new developments in mass spectrometry enabling the use of amplifiers with 10^{13} Ohms resistors to increase precision and decrease sample size (100 g) to further explore gas loss and crustal influence. Because of very small abundance of this radioactive element, ^{81}Kr relies on individual atom counting in a magneto-optical trap (Buizert et al. 2014), a very heavy and expensive method available in only two places in the world, such as in Hefei University (China). Through a pilot study performed in collaboration with Hefei University in 2017-2018 and using loaned pieces of equipment for extraction, we obtained first dates of old Antarctic ice (TALDICE ice core) with an age uncertainty of 5% on 6 kg samples (Crotti et al., 2021). Developments are ongoing to further reduce the mass of ice needed for ^{81}Kr measurements. In *ToBE*, we want to develop combined measurements of ^{81}Kr and $\delta^{40}Ar$ in deep ice cores for dating applications. WP2 will hence provide the means to extract air for both ^{81}Kr and $\delta^{40}Ar$ on the same samples at LSCE to (a) provide absolute dating of old ice in a maximum number of ice cores and (b) document the conditions for biased $\delta^{40}Ar$ dating. This development is strongly needed since ice transportation to Hefei University and processing of ice core there is not possible.

Second, orbital dating tools are used to provide periodic tie points along deep ice cores. The classical orbital dating tools developed for ice core dating are $\delta^{18}O_{atm}$, $\delta O_2/N_2$ and total air content (TAC) in air bubbles. A strong link has been evidenced between insolation at 65°N in June and $\delta^{18}O_{atm}$variations over the last climatic cycles (Bender et al., 1994). $\delta^{18}O_{atm}$ is thus used to provide orbital dating points for Antarctic ice cores taking into account a delay of 6 ka between orbital target and $\delta^{18}O_{atm}$ as observed over the last deglaciation (Dreyfus et al., 2007). Still, $\delta^{18}O_{atm}$ is a complex tracer resulting from fluxes of oxygen (photosynthesis and oxygen uptake) and associated fractionations and a better understanding of this signal suggested that the $\delta^{18}O_{atm}$ dynamic at both orbital- and millennial-scale timescales should be taken into account which significantly decreases the uncertainty of ice core chronology (Extier et al., 2018). On the other hand, $\delta O_2/N_2$ and TAC are affected by the processes of air trapping at about 50-120 m depth under the ice sheet surface when porous snow (designed as firn in the following) is sufficiently compacted to reach the density of the ice. These trapping processes leading to $\delta O_2/N_2$ and TAC variations have been linked to the local insolation in summer (Bender, 2002; Raynaud et al., 2007; Eicher et al., 2016). They have thus been further used for ice core dating (Kawamura et al., 2007; Bazin et al., 2013). These 3 orbital dating tools are key to date the deep ice cores and will be essential for the dating of the Beyond EPICA ice core. Still, available records from the deep ice cores such as EPICA Dome C and TALDICE are difficult to use because of their too low resolution (impossible to capture the millennial scale variations of $\delta^{18}O_{atm}$ and difficult to clearly record the orbital variations) and relatively large scattering. The large scattering observed at the bottom of the EPICA Dome C ice core (Figure 1) and difficulty to capture a clear orbital signal may be due to the quality of deep and warm ice, diffusion effect or simply the fact that the orbital forcing is of weak amplitude at 800 ka.

Another method for absolute dating relies on the use of the chlorine-36 (^{36}Cl)/beryllium-10 (^{10}Be) ratio by applying the principle of radioactive decay. The ^{10}Be and ^{36}Cl half-lives are 1.387±0.012 Ma (Chmeleff et al., 2010; Korschinek et al., 2010) and 301 ka, respectively. Most of the ^{10}Be and ^{36}Cl produced, in the atmosphere, by galactic cosmic rays (GCR), originates from spallation reactions on oxygen and nitrogen atoms for the former, and on argon for the latter. The theoretical production $^{36}Cl/^{10}Be$ ratio in the atmosphere is 0.09 (Poluianov et al., 2016). However, processes not related to the radioactive decay, can affect each nuclide individually and modify the $^{36}Cl/^{10}Be$ ratio. A first profile of ^{10}Be was obtained on the bottom part of the EDC ice core enabling to identify the signature of the Bruhnes-Matuyama geomagnetic reversal (Raisbeck et al., 2006) which is a key event for the dating of deep ice cores. However, the record of this ^{10}Be excursion is affected by frequent spikes not observed in the upper part of the EDC ice core. A possible explanation for these spikes also observed in other species such as dust and calcium is the increasing number of solid inclusion aggregates at deep depth of the EDC ice core (Tison et al., 2015). This effect is observed in other deep ice cores (Baccolo et al., 2021) and will also probably affect the Beyond EPICA ice core. ^{36}Cl data of bottom ice are also very scarce in particular for low accumulation sites probably because of the study conducted by Delmas et al. (2004), who showed that anthropogenic ^{36}Cl produced through the capture by the ^{35}Cl from the sea salt (as sodium chloride NaCl) of thermal neutrons emitted during the marine nuclear tests (e.g. Heikkila et al., 2009; Elmore et al., 1982) from the 1950s to the 1970s, was moving toward the surface in the Vostok snowpack (a low accumulation site in Antarctica). Approximately 80 kg of anthropogenic ^{36}Cl were injected into the stratosphere, resulting in a ^{36}Cl flux, 100 to 1,000 times higher than the natural ^{36}Cl fluxes related to the natural atmospheric production caused by galactic cosmic rays (e.g. Heikkila et al., 2009). A study conducted at CEREGE on a snow pit dug 10 years after that of Delmas et al. (2004), showed that pre-bomb ^{36}Cl level was still not recovered in 2008, at Vostok (Pivot et al., 2019). This was explained by the mobility of ^{36}Cl in its gaseous form ($H^{36}Cl$), in the firn, at this low accumulation site which is not observed at high accumulation sites such as Dye 3 and NGRIP sites, in Greenland, Berkner Island and Talos Dome, in Antarctica, where ^{36}Cl deposited as gaseous $H^{36}Cl$ and particulate $Na^{36}Cl$, are both well preserved (Heikkila et al., 2009, Pivot et al., 2019). Low accumulation sites, in Antarctica, are chosen for their ancient ice. For instance, the site chosen in the frame of the European project Beyond-EPICA Oldest Ice is a few tens of km away from the French-Italian station, Concordia. Preliminary results indicate the accumulation is lower than the Dome C one, i.e. lower than 2.5 cm we.yr^{-1}. Consequently, the ^{36}Cl content can be altered, it results in low values of $^{36}Cl/^{10}Be$ ratio as observed over the last centuries, at Dome C, i.e. 0.03 (Baroni et al., unpublished data). A value of 0.03 corresponds to an age of 600 ka, if the initial global production $^{36}Cl/^{10}Be$ ratio is 0.09. This method has been used to date the deep part of the GRIP ice core (Greenland), and an age of 950 ± 44 ka has been found (Willerslev et al., 2007). It has been calculated from an initial $^{36}Cl/^{10}Be$ value of 0.25 which prevailed during the last glacial period at GRIP and not from the Holocene value of 0.17. Surprisingly, at GRIP, the $^{36}Cl/^{10}Be$ ratio during the last glacial period is higher than that of the Holocene, while radioactive decay would predict the reverse. Starting the calculation of radioactive decay with the Holocene value of 0.17 would lead to an age of 750 ka in the deeper part of the GRIP ice core, ~200 ka younger than the value calculated in Willerslev et al. (2007). The age difference of 200 ka is much higher than the uncertainty of 44 ka found from propagating errors on the $^{36}Cl/^{10}Be$ ratio. It shows that the choice of the initial value of the $^{10}Be/^{36}Cl$ ratio is crucial for dating ancient ice. In *ToBE*, we aim at improving our understanding of the ^{36}Cl deposition and behavior at low accumulation sites in order to better use the ^{36}Cl/^{10}Be ratio for dating ancient ice.

Ice dynamics

Understanding how ice flows in East Antarctica is of uppermost importance to determine the age vs depth relationship and ice particles trajectories for deep ice cores in this region. The first application is of course to produce the depth vs age relationship, hence the first age model, for the *Beyond EPICA* ice core. This study has also numerous other applications since other deep drilling are projected in the Dome C area with the aim to retrieve old ice under the IPICS umbrella. Another important application of this study is to reconstruct the surface mass balance history in the Dome C area. Information on ice flow comes either from observations or from numerical modeling. Observations are composed of isochrones reconstructed by Radio Echo Sounding (RES) measurements (e.g., Cavitte et al., 2021) or from ice cores measurements (e.g., Bazin et al., 2013; Veres et al., 2013). Numerical modeling was performed either with local 1D models with prescribed geometries (e.g., Parrenin et al., 2007) or from large scale 3D models with free geometry (e.g., Sutter et al., 2019), albeit with lower spatial and temporal resolutions. It is therefore clear that the best we can do is to combine observations and numerical modeling with a Bayesian framework. This has been done in the Dome C region with a simple 1D model (Parrenin et al., 2017), which allowed to define the drilling site for the future *Beyond EPICA* ice core project.

Ice-bedrocks interactions and chronology of the last deglaciation

Over the last decade, a new line of research has emerged to constrain the long term waxing and waning of paleo-ice sheets. This was done measuring radioactive in situ cosmogenic nuclides (^{26}Al, ^{10}Be, ^{21}Ne) in debris material located in the most bottom sections of the basal ice. These isotopes are necessarily produced in the absence of ice, and their concentrations permit to constrain the duration of previous glacial episodes. Moreover, measuring radioactive cosmogenic nuclides with different half-lives, and knowing the age of the basal ice, it is possible to constrain the duration of the ice readvance. This approach was successfully applied to Greenland ice cores (Christ et al., 2021; Schaefer et al., 2016), showing that the last near complete disappearence of the Greenland ice sheet was 1 Ma, while a partial melting probably occurred 400 ka, during MIS11 (Christ et al., 2021). Although the volume of water stored in the Antarctic Ice Sheet is much larger than the one of Greenland (60 m and 7 m of sea-level equivalent, respectively), little is known about the long term fluctuations of the volume of the Antarctic Ice Sheet, that is supposed to have formed about 34 Ma (Wilson et al, 2012). In preparation of the future recovery of basal material from Beyond Epica (Eastern Antarctic Ice Sheet) we have the opportunity to apply in situ cosmogenic nuclides on the Byrd core (Western Antarctic Ice Sheet), the only ice core that bear basal silicate debris (Gow et al., 1979). This Byrd material is available at the NBI Copenhagen, and tight link between our group, ULB and NBI permit to secure the accessibility to this material. This pilot study will permit to assess whether the paleo-exposure signal in the Antarctic basal material is detectable with the detection limit of our system (CRPG preparation lab, ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios measured at CEREGE ASTER AMS).

c. Methodology and risk management

The *ToBE* proposal will be composed of five different work packages (WP).

<u>WP0 - Management</u> (PI: F. Parrenin)

The management tasks will be supervised by the PI of the project (F. Parrenin), as well as by a Executive Committee composed of the PI of the different partners (A. Landais, M. Baroni and P.H. Blard).

Task 0.1: Meeting organization (PI: F. Parrenin, participants: A. Landais, M. Baroni, P.H. Blard)

The *ToBE* project will organize an internal meeting every year to discuss the scientific outcomes and foster the interactions. These meetings will give a large expression to the post-docs, PhD and trainees hired for the project. They will serve also as a preparation for the meetings within the European DEEPICE and *Beyond EPICA* projects, which also meet annually and which provide networking opportunities within the European community. The presentations done at the internal meetings will be made available to all participants.

Taks 0.2: Reporting and communication (PI: F. Parrenin, participants: A. Landais, M. Baroni, P.H. Blard)

Following the ANR policy, an annual report will be written every year. Communication actions will be conducted regularly (see Impacts section). A web site will be launched, which will contain in particular the annual reports, the list of publications and the list of communication actions.

Task 0.3: Synergies and synthesis (PI: A. Landais, participants: F. Parrenin, M. Baroni, P.H. Blard, P. Martinerie, E. Capron, M. Casado, PhD LSCE)

Strong synergies exist between the WPs of this projects: for example, our understanding of the signal preservation (WP1) will provide key results for the realization of the dating (WP2). The oldest ice ages (obtained in WP2) will allow to model the signal alteration (WP1) and will permit to reduce the number of possible scenarii of paleo-exposure previous glaciation from in situ cosmogenic nuclides (WP4). At least one (probably 2) publications will be written at the end of the project to summarize all the outcome of the *ToBE* project, including the synergies of the different WPs. These publications could contain: 1) a new dating and improved records for the bottom part of the EDC ice core, 2) possible past deglaciation/glaciation scenarios of the Western Antarctic Ice Sheet (Byrd core) derived from the geological debris, 3) an estimation of record alteration in the *Beyond EPICA* ice core at different timing (e.g., 1, 1.2 and 1.5 Myr), 4) and improved dating and ice flow scenarios for the *Beyond EPICA* ice core site.

<u>WP1 - Signal preservation</u> (PI: Amaëlle Landais)

Task 1.1: Continuous measurements over the deeper climatic section of the EDC ice core (PI: P. Ginot; participants: PhD1, P. Martinerie, G. Teste, E. Fourré)

New high resolution records of impurities (dust, ICPMS, conductivity, anions, cations), water isotopes and CH_4 will be obtained on the depth interval 3150-3215 m from the EDC ice core, covering the time period 750-800 ka as well as on some basal ice whose age is not clearly determined. This will be done using a new Continuous Flow Analysis (CFA) system developed in the frame of the french PANDA ice core analytical platform (https://panda.osug.fr/).

Task 1.2: High precision discrete measurements of water isotope composition over the deeper climatic section of the EDC ice core (PI: M. Casado; participants: E. Fourré, B. Minster, A. Landais, M. Horhold, B. Stenni)

Due to the impact of archival noises and isotopic diffusion, the minimum time scale at which a meaningful climatic signal can be retrieved from a single ice core record is dominated by the measurement noise (Casado et al, 2020). Because of strong thinning and diffusion in the bottom of the EPICA Dome C ice core (Grisart et al., CPD, to appear), it can be calculated that a precision of 0.01‰ for $\delta^{18}O$ is necessary to be able to reconstruct the climatic signal at a centennial timescale, while only millennial timescale is available with a precision of 0.1‰ (calculation extended from Casado et al., 2020 with relevant ice thinning and diffusion length). We will thus perform discrete measurements using high precision IRMS and optical spectroscopy techniques over the depth range 3150-3190 m. We are now able to reach a precision of 0.01 ‰ (1 sigma) for $\delta^{18}O$ on IRMS and 0.1‰ (1 sigma) on δD on some series. We will further improve this method taking advantage of a new IRMS to be acquired within the Paris-Saclay PANOPLY and PANDA French analytical platforms.

Task 1.3: Quantification of diffusive effect in deep ice cores for CH_4 and water isotopes (PI: P. Martinerie &M. Casado; participant: PhD LSCE, T. Laepple - expert)

A comparison will be done with records from more recent periods to quantify the signal variability and the level of signal smoothing, especially for the water isotopes and CH_4 records (e.g. period 760 - 770 ka on Figure 1). This comparison will be used to adjust a model for inferring the diffusive effects for water isotopes (based on approaches proposed by Johnsen et al., 2000 and Gkinis et al., 2021) and for CH_4 (extending the work of Fourteau et al., 2020). This adjustment is essential in order to then use this diffusion approach for the Beyond EPICA ice core.

Task 1.4: CO_2 and $\delta^{13}C$ acquisition over the 600 - 800 ka period (PI: R. Grilli; participants: PhD IGE, E. Capron, G. Teste)

New CO_2 measurements will be done on the 600 - 800 ka section of the EDC ice cores using a new system based on optical spectroscopy (developed within the on-going ISOCARB project) and enabling to get CO_2 and $\delta^{13}C$ of CO_2 on samples smaller than 20 g instead of the classical 50 g samples. This time period has been chosen because uncertainties exist on the exact CO_2 levels during glacial periods within 600-800 ka (Bereiter et al., 2015). Moreover, we plan to obtain sub-millennial records especially at the onset of the warm period MIS 19 (~780 ka) where an overshoot in CO_2 concentrations is expected by analogy with MIS 5 (~125 ka) or MIS 11 (420 ka) (Nehrbass et al., 2020). This record of millennial variability will be compared to the record of millennial variability at shallower depth (i.e. the high resolution record of the last interglacial, Silva et al., manuscript in preparation) in order to estimate the effect of diffusion on CO_2 record at deep depth and compare this estimate to the predictions of Bereiter et al. (2014). .

Task 1.5: Measurements and diffusion study of proxies for orbital dating (PI: A. Landais; participants: E. Capron, F. Prié, G. Teste, F. Parrenin)

New high resolution (1000 years) measurements of gas orbital tracers (O_2/N_2, $\delta^{18}O_{atm}$ and TAC) will be performed on well preserved ice from the old section of the EDC ice core (700-800 kyr BP) making a special effort on selecting samples stored at -50°C at the Concordia station which are not affected by any cracks. This is essential to prevent that gas loss or pollution affect the measured values of the different gas tracers. By avoiding such possible bias, it will be possible to focus on signal preservation in relation with permeation within the ice and to refine the estimates of Bereiter et al. (2014) performed without direct data constraints. In particular, we should be able to infer if the $\delta O_2/N_2$, TAC and $\delta^{18}O_{atm}$ will be preserved in a 1.5 Myr ice core. This result will permit to build the dating strategy of the *Beyond EPICA* ice core together with results from WP2. In addition, the new series will be used to better constraint the dating of the bottom part of the EDC ice core and especially Marine Isotopic Stage 19 whose full interglacial period (~790 to 775 ka) is the best analogue of our present interglacial based on orbital configuration.

<u>WP2 - New Dating Methods:</u> (PI: M. Baroni)

Task 2.1 : improvement of the ^{40}Ar and ^{81}Kr analysis (PI: E. Fourré; participants: A. Orsi, A. Landais, F. Prié)

The method to date ice with ^{40}Ar on 100 g samples will be improved, in particular to better quantify and hence correct the fractionation due to gas loss. We will develop a method using getter for purifying gas at LSCE from extracted air on 1 to 6 kg of ice to perform measurements of ^{40}Ar (at LSCE) and ^{81}Kr (collaboration with Hefei University performing the analyzes of ^{81}Kr by magneto-optic trap, Crotti et al., 2021).

Task 2.2 : New measurements of ^{40}Ar and ^{81}Kr to date the old ice of the EDC ice cores below the climatic signal (800 ka) (PI: E. Fourré; Participants: A. Orsi, F. Prié, A. Landais, F. Ritterburg and Wei Jiang)

Using the current set-up at LSCE and collaboration with Hefei University, a preliminary result have been obtained on 6 kg of ice at 3220 m depth of the EDC ice core, i.e. 20 m deeper than the lowest end of the ice corresponding to the climatic signal and dated at 800 ka. This 3220 m ice has been dated with ^{81}Kr at an age of 903±50 ka (Figure 3). We thus suspect that oldest ice can also be found lower in the EDC ice core, i.e. on the stagnant ice section covering the depth range 3220 - 3260 m. To answer this question, we propose to perform measurements of ^{40}Ar and ^{81}Kr over this depth range. The extraction and purification of the samples will be done at LSCE as well as $\delta^{40}Ar$ measurements and ^{81}Kr measurements, hopefully on 1 kg ice, will be performed at Hefei University by our collaborators.

Task 2.3 : New dating technique based on the $^{36}Cl/^{10}Be$ ratio (PI : M. Baroni; participants : PD CEREGE, E. Bard, K. Keddadouche, G. Aumaître, F. Zaïdi)

Low accumulation sites (<4 cm water equivalent (we)/year) are affected by a significant loss of chlorine during interglacial periods, up to 60% at Dome C (Röthlisberger at al., 2003). This loss is calculated from the deviation from the chlorine to sodium (Cl^-/Na^+) ratio in sea-salts (e.g. Legrand et al., 2017). This chlorine loss also affects ^{36}Cl (Pivot et al., 2019). One could think the initial ^{36}Cl of a sample could be calculated simply by taking into account the loss of Cl^-, however many other parameters have to be taken into account such as diffusion and/or advection in the snowpack (Delmas et al., 2004; Pivot et al., 2019). The study of Pivot et al. (2019) conducted at CEREGE, was the first to highlight the need to take chlorine into account when interpreting ^{36}Cl data. Glacial periods are better for the chlorine preservation (Röthlisberger et al., 2003) because a high dust content but there is no existing data on ^{36}Cl.

In *ToBE*, we propose to measure ^{36}Cl and ^{10}Be samples from different glacial and interglacial periods in the EPICA Dome C ice core in order to improve our understanding of the ^{36}Cl behavior at low accumulation sites and better constrain the $^{36}Cl/^{10}Be$ ratio for dating ancient ice. With an expected age of 1 Ma in the very last meters of the BE-OI ice core, most of the ^{36}Cl would have significantly decayed (half-life = 301 ka) and samples of 500g will be necessary implying a possible sampling of both glacial and interglacial periods. The chlorine preservation will be evaluated from the Cl^-/Na^+ ratio obtained from the task 1.1. Because of its long half-life, ^{10}Be could still be measured on small samples (40-50g) and provide a time resolution good enough to replicate the detection of the Bruhnes-Matuyama geomagnetic reversal used as a dating point (Raisbeck et al., 2006).

^{10}Be and ^{36}Cl sample extraction from ice cores are operational and run routinely at CEREGE (Baroni et al., 2011, 2019, Pivot et al., 2019). ^{36}Cl ice core sample preparation developed at CEREGE is unique because it is based on the use of an ^{35}Cl enriched-spike (one of the two chlorine stable isotopes) allowing to calculate the chloride (Cl^-) concentration from isotopic dilution at a level of a few tens of ppb (Braucher et al., 2018, Pivot et al., 2019). These high quality ^{36}Cl and ^{10}Be sample preparations and measurements on the accelerator mass spectrometer, ASTERisques, a French national facility installed at CEREGE, will be applied to the EPICA Dome C and the Byrd ice core samples.

In parallel to the EPICA Dome C and Byrd samples dedicated to the ^{10}Be and ^{36}Cl analysis, tests will also be conducted on the melt water taken after the ^{40}Ar and ^{81}Kr gas analysis (Task 2.2). Some preliminary results conducted in collaboration between the LSCE and the CEREGE, indicate it is possible to optimize the use of these precious samples. This would be important for future sample request of the BE-OI ice core.

Task 2.4: Use of the orbital tracers records over the 600 - 800 ka period to refine the chronology of the EDC ice core (responsible: A. Landais; Participants: PhD IGE, PhD LSCE, E. Capron)

The measurements of $\delta^{18}O_{atm}$, $\delta O_2/N_2$ and TAC presented above (WP1) will be gathered here to provide a refined timescale of the 600 - 800 ka section of the EDC ice core. We will use the classical method approach of matching $\delta O_2/N_2$ and TAC to their respective orbital targets (solstice or integrated summer insolation) and match $\delta^{18}O_{atm}$ to the summer insolation at 65°N following Extier et al. (2018). This timescale will be largely improved compare to the previous one which only relied on δ^{18}Oatm measurements with a large data scattering. Using 3 proxies for orbital tuning should enable us to decrease by a factor of two the current uncertainties of the EDC timescale over this period.

<u>WP3 - ice dynamics:</u> (PI: F. Parrenin)

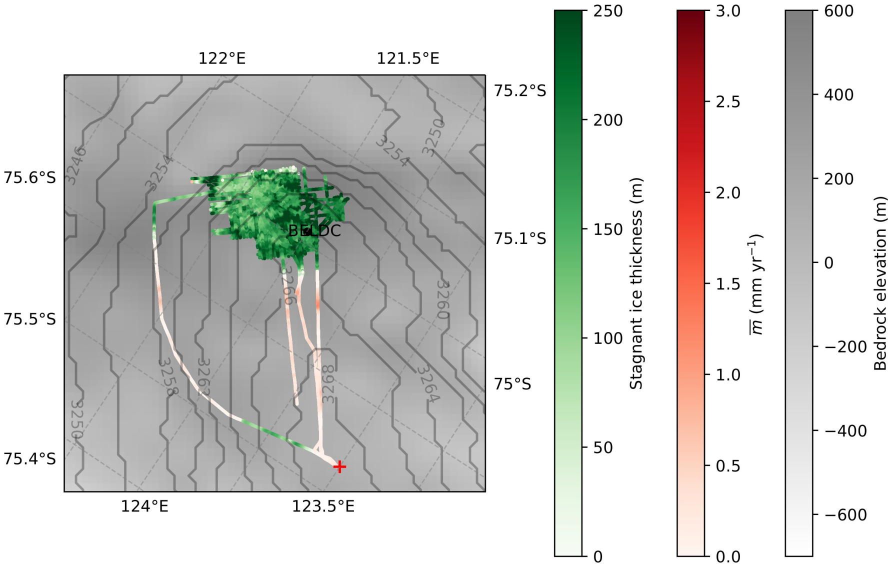

Figure 2: Preliminary result of a 1D dating model fitted on isochronal information. The model reconstructs either a layer of stagnant ice (green color) or a basal melting (red color). The EDC location is marked by the red cross, the future BELDC (Beyond EPICA Little Dome C) drilling site is also indicated.

Task 3.1: Local 3D numerical age model with prescribed geometry (PI: F. Parrenin, participants: Ailsa Chung, Catherine Ritz)

A 3D numerical model of ice age will be applied in the vicinity of Dome C in Antarctica, assuming a steady geometry of the ice sheet. It will use an innovative numerical scheme, adapted to the age equation which is a purely advective problem. Based on the agreement with isochronal layers observed by RES, it will invert three quantities: the surface accumulation rate, an exponent related to the vertical profile of velocity and an effective ice thickness (Figure 2). If the effective ice thickness is smaller than the observed ice thickness, it will mean that there is a layer of stagnant ice at the bottom of the ice sheet (Lilien et al., 2021). If it is larger, a basal melting at the ice-bedrock interface will be calculated. We will therefore get scenarios of ice particles trajectories, surface accumulation rate, stagnant basal layer thickness and ice age in the Dome C area. The degree of agreement of the numerical model with isochronal horizons will also inform us on the stability of the ice flow in the past.

Task 3.2: Large scale 3D model of Antarctica with free geometry (PI: C. Dumas, participants: PD IGE, A Quiquet, C. Ritz)

Dome positions and flow lines may have been affected by the evolution of the Antarctic ice sheet over glacial interglacial cycles. Here we will use the GRISLI ice sheet model (Quiquet et al., 2018) to study possible dome migrations in the past and their impact on ice flow lines and ice sheet stratigraphy. GRISLI is a 3D thermomechanical ice sheet model which allows for long (i.e. several glacial-interglacial cycles) transient ice sheet simulations in response to atmospheric, oceanic and sea level forcings. First, we will make use of the existing ensemble of simulations of the last 400 kyr from Quiquet et al. (2018) to assess the occurrence of dome migrations in the past. This ensemble of simulations covers the uncertainty in terms of mechanical parameters in the model for a given climate and sea level forcing. Second, as a complement to these simulations, we will explore the sensitivity of dome positions to past climate uncertainties. While Quiquet et al. (2018) used homogeneous atmospheric and oceanic perturbations in the past, we will test here spatially heterogeneous climatic perturbations. All new simulations will make use of the passive tracer transport model of Clarke and Marshall (2002) embedded in GRISLI (Lhomme et al., 2005) which will provide the modeled ice sheet stratigraphy (age-depth relationship). The coarse spatial resolution of the model (40 km) will not allow us to perform direct data-model comparisons but in turn we will be able to quantify the effect of regional ice sheet geometry changes (e.g. elevation changes and grounding line migration) on ice sheet stratigraphy and ice flow in the vicinity of the domes.

WP4 - geology: (PI: P.-H. Blard)

***Task 4.1: Characterization of rock debris in the basal ice of Byrd** (PI: PH Blard; participants: PD CRPG and Engineers)*

The nature of the bedrock material retrieved from the Byrd drilling in Antarctica (see Figure 3) will be characterized in term of lithology and mineralogy, but also using geochemical source tracers, analysing the grain shape and their alteration history (SEM analysis). Debris embedded in the basal ice of Byrd will be collected a posteriori from samples treated for gas analyses. The debris will be collected after gas extraction and filtered on 0.20 µm Millipore®filters. Collected dry residues will be weighted and their content expressed as weight percentage of the ice plus debris weight. Aliquots will be dedicated to granulometry, geochemistry, mineralogy. Granulometry will be measured using a laser granulometer. We will determine the petrological, the mineralogical and the geochemical nature, the provenance, the crystallization age and the thermal history of these sub-ice rock debris and bedrocks: major and trace elements chemistry, Sr and Nd isotopes, $^{207}Pb/^{206}Pb$, U/Pb, (U-Th)/^{4}He thermochronometry (collaboration with Imperial College, UK, for cross measurements and data interpretation). We will determine the post-erosion surficial process through the measurement of adsorbed meteoric ^{10}Be (~50 samples), clay mineralogy and using Scanning Electrons Microscopy analyses of sands/silts (Mahaney, 2002). This approach consists in describing their morphology, shape, surficial features and weathering states, focusing on the chronological succession of these features (thereby placing relative chronological control on waxing and waning of the GrIS) (Protin, Blard et al., Submitted 2022).

***Task 4.2: Dating and duration of the last deglaciation** (PI: PH Blard; participants: PD CRPG and Engineers)*

In situ cosmogenic nuclides (^{26}Al, ^{10}Be, ^{21}Ne in quartz and possibly ^{36}Cl in plagioclases) will be measured in basal sediment samples of Byrd. Chemical preparation will be performed at the new CRPG preparation clean lab, while the measurements of the $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios will be done on the ASTER AMS (CEREGE). The CRPG preparation lab yields $^{10}Be/^{9}Be$ blank ratios of ca 10^{-15}, with a special homemade carrier at $3x10^{-16}$, permitting the detection of <10^{5} at of ^{10}Be and ^{26}Al (Mariotti et al., 2021; Puchol et al., 2017), which is among the lowest worldwide detection limit (Corbett et al., 2016; Merchel et al., 2021). In this project, we will make efforts to further reduce these backgrounds, through 1) - A new clean lab procedure at the new CRPG facility, 2) – Developing a new phenakite carrier having a $^{10}Be/^{9}Be$ ratio of 10^{-16} (Merchel et al., 2021). Moreover, the ASTER AMS is now equipped with a Gas Filled Magnet (Second machine worldwide, after the Purdue AMS), that ensures an optimal ^{26}Al detection limit. All these innovations will permit the analysis of <10 g sized quartz samples given the expected concentrations.

Finally, we will combine all the information on the age of the Byrd basal clear ice with the paleo-exposure constraints from in situ cosmogenic nuclides measured in these bottom debris. This will permit to reduce the number of paleoexposure scenarii and compute both the duration of the last deglaciation and the age of the last Antarctic Ice Sheet readvance. When possible, we will perform statistical Bayesian modelling, integrating the stratigraphical relationships between the different dated units (basal ice and underlying sediments), thus reducing the analytical uncertainties and obtaining a synthetic geochronological framework (Blard et al., 2013; Martin et al., 2020).

The *ToBE* project therefore gathers national scientists experts on various analytical methods (applied to the ice, air bubbles or bedrock material) with ice flow modelers, to make an optimal use of the precious old ice which will be drilled at the *Beyond EPICA* site in Antarctica. Being part of the EPICA community, the consortium has access to the EDC ice core to perform analyzes, although a formal request to the EPICA steering committee will be needed once the project is accepted. CRPG-Nancy also has access to the Byrd basal material through collaborations.

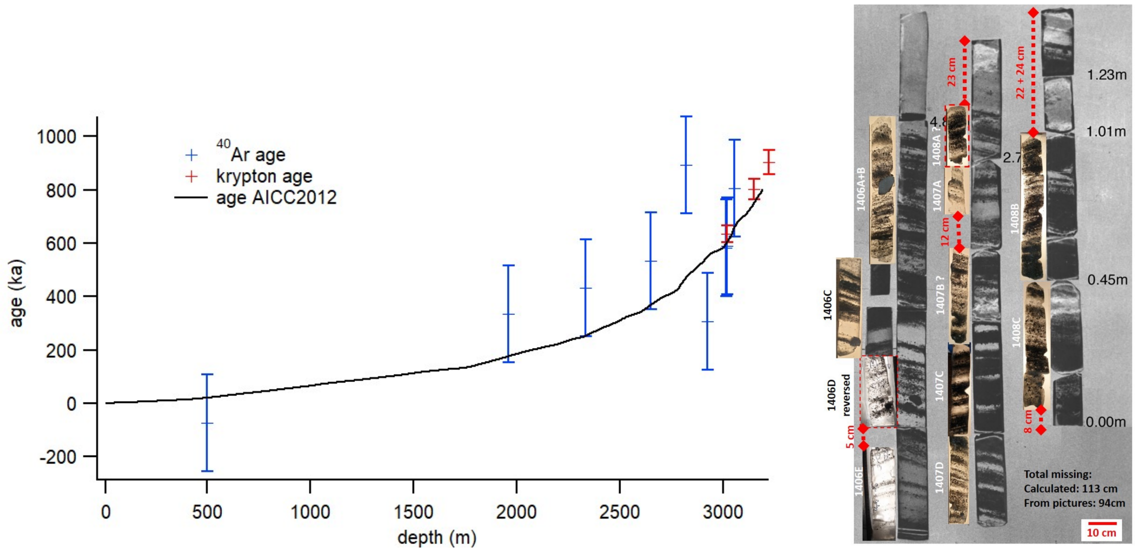

Figure 3: (Left) Preliminary results of ^{40}Ar and ^{81}Kr ages for the EDC ice core compared with the AICC2012 chronology. (Right) Picture of the bottom section of the Byrd ice core containing bedrock material which is available for analysis.

The *ToBE* project is innovative because it is the first time we study so deeply the problems of signal preservation, dating, ice dynamics and geology for old ice present at the base of the Antarctic ice sheet. Such thorough work is mandatory to interpret the 1.5 Myr old ice which will be retrieved in the frame of various drilling projects, in particular the European *Beyond EPICA* project. This project is also innovative in the methodology used for the analysis (e.g., new study of diffusive effect, new dating methods, new ice flow simulations, new CO_2 measurement method).

II. Organisation and implementation of the project

This paragraph refers to the evaluation criteria "Organisation and implementation of the project"

a. Scientific coordinator and its consortium / its team

Implication of the scientific coordinator and partner's scientific leader in on-going project(s)

Name of the researcher	Person.month	Call, funding agency, grant allocated	Project's title	Name of the scientific coordinator	Start - End
Frédéric PARRENIN	6 p.month	Europe H2020	Beyond EPICA	Carlo BARBANTE	2019-2026
Frédéric PARRENIN	2.5 p.month	CNRS/INSU	Ice Archives	Frédéric PARRENIN	2020-2024
Frédéric PARRENIN	6 p.month	CNRS/INSU/LEFE	PROXYNNOV	Patricia MARTINERIE	2022-2024
Amaëlle LANDAIS	1.8 p.month	Europe H2020	Beyond EPICA	Carlo BARBANTE	2019-2026

Amaëlle Landais	14 p.month	Europe H2020	ERC ICORDA	Amaëlle Landais	2019-2024
Amaëlle LANDAIS	6 p.month	CNRS/INSU/LEFE	PROXYNNOV	Patricia MARTINERIE	2022-2024
Mélanie BARONI	1.8 p.month	Europe H2020	Beyond EPICA	Carlo BARBANTE	2019-2026
Mélanie BARONI	7.5 p.month	CNRS/INSU/LEFE	PROXYNNOV	Patricia MARTINERIE	2022-2024
Pierre-Henri BLARD	15 p.month	ANR	PANTERA	Julien Charreau	2022-2026
Pierre-Henri BLARD	2 p.month	Europe H2020	Beyond EPICA	Carlo BARBANTE	2019-2026

Coordinator : Dr Frédéric Parrenin, senior scientist at IGE (Grenoble, France)

Dr Frédéric Parrenin is a renowned senior ice core scientist, specialized in problems related to the age of the ice archive (both in the ice matrix and the air bubbles). He authored or co-authored 75 peer-reviewed articles (H-index of 38). He was awarded the bronze medal of CNRS in 2008 for his work on the dating of ice cores. He is among the highly cited researchers in his field since 2014 (Thomson-Reuters ranking). He obtained 10 funding during the course of his career. See https://www.ige-grenoble.fr/Frederic-Parrenin for more information.

Dr Frédéric Parrenin will manage the current *ToBE* project. He will also lead WP0 and WP3 in which he will take an active part, since he will work on modeling the age of ice in the vicinity of the future Beyond EPICA drilling site and he will supervise the large scale modeling of the ice flow in East Antarctica.

Consortium: IGE (Grenoble), LSCE (Saclay), CEREGE (Aix-en-Provence) and CRPG (Nancy)

The consortium is composed of the four main french labs working on the interpretation of ice core records in Antarctica. These four labs are strongly interacting which each others in the frame of the "*Carottes de glace France*" (CGF) working group, which has a formal meeting every year and many informal interactions during the course of the year.

IGE has a strong expertise on ice dynamics (Frédéric Parrenin, Catherine Ritz), firn densification and gas signal preservation (Patricia Martinerie), age modeling (Frédéric Parrenin), CFA chemistry measurements (Patrick Ginot) and interpretation (Joël Savarino), stable isotope measurements (Nicolas Caillon), CO_2 measurements (Gregory Teste, Roberto Grilli) and interpretation (Emilie Capron), CH_4 measurements (Gregory Teste, Xavier Fain) and interpretation (Xavier Fain), TAC measurements and interpretation (Emilie Capron, Dominique Raynaud).

LSCE has a strong expertise on orbital tuning tracers (Amaëlle Landais), on absolute dating of ice through ^{40}Ar and ^{81}Kr measurements (Elise Fourre, Anaïs Orsi, Amaëlle Landais), on water stable isotope measurements (Bénédicte Minster, Frédéric Prié) and interpretation (Amaëlle Landais, Elise Fourré, Mathieu Casado).

CEREGE has a long standing expertise in geochemistry and paleoclimatology that is internationaly recognized. The use of cosmogenic isotopes (^{10}Be and ^{36}Cl in ice cores and ^{14}C in tree rings, corals, forams,...) is also one of CEREGE's specialities, both for reconstructing past solar activity and for dating (Mélanie Baroni, Edouard Bard). A laboratory is entirely dedicated to the ^{10}Be and ^{36}Cl extraction from ice cores (cold room, clean conditions). The ^{10}Be and ^{36}Cl sample preparation is operational (Baroni et al., 2011, 2019, Pivot et al., 2019). All the samples will be measured at CEREGE, on the accelerator mass spectrometer, ASTERisques, a French national facility (Karim Keddadouche, Georges Aumaître, Fawzi Zaidi).

CRPG-Nancy is specialized in the measurement (Aymeric Schumacher, Laurent Zimmermann, Bouchaïb Tibari, Catherine Zimmermann) and interpretation (Pierre-Henri Blard) of cosmogenic isotopes in rock samples, including those retrieved at the bottom of ice cores. CRPG is notably a world recognized lab for the measurement of cosmogenic noble gases (^{3}He and ^{21}Ne) and also host since 2022 a new low background clean-preparation lab (2.2 M€ project from CNRS and Université de Lorraine funding) for the preparation of ^{10}Be and ^{26}Al samples, before the analysis of their $^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ ratios at CEREGE, on the accelerator mass spectrometer, ASTERisques, a French national facility. Moreover, CRPG is a recognized lab for measurements in the field of petrology, geochemistry and geochronology, equipped with modern facilities devoted to solid Earth analysis (SEM, EPMA, SIMS, ICPMS, TIMS, IRMS).

Synergies between the partners: The four partners have a long track record of collaboration with tens of joint publications. Their research interests and activities are complementary. They belong to the CGF group (Carottes de Glace France), which is a structure that supervises the drilling operations and ice core research in France, with a formal meeting every year and with many informal interactions during the course of the year. The four partners are also part of the European H2020 *Beyond EPICA* project. The project will take advantage of new analytical techniques, notably the national ice core analysis plateform PANDA (https://panda.osug.fr/).

b. Implemented and requested resources to reach the objectives

Partner 1: IGE

Staff expenses

- 3 years PhD on signal preservation - 120,000€
- 1 year Post-Doc on 3D modelling of Antarctica (2-7 yr experience)- 73,771€
- Two 6-months Master internships - 7,600€

Instruments and material costs

- Use of CFA measurement system - 642€/m*60m=38,500€
- Consumables for 100 Air Content measurements - 100x47=4,700€
- Consumables for 63 CO_2 measurements - 63x83=5,229€
- 2 personal computing stations for the PhD and Post-doc - 4,000€

Outsourcing / subcontracting

3 Publications - 4,500€

General and administrative costs & other operating expenses

- 4 international missions to present results at conferences (e.g., EGU, AGU) : 6,000€
- Conferences and workshops organisation : 4,000€

Partner 2: LSCE

Staff expenses

- 3 years of PhD - 120,000€
- Two 6-months Master Internships - 7,600€

Instruments and material costs

- Adaptation of the line for air extraction and purification (^{81}Kr + ^{40}Ar)
    - Pump and compressor for ^{81}Kr line : 3,000€
    - Connecting parts and tubes : 2,000€
    - Oven and getter for purification: 2,000€
    - Small pressure gauges : 1,000€

  - Flasks to store the extracted air: 1,000€ x 5
- Measurements of ^{40}Ar: 95 euros per samples - 10 samples -> 950€
- Measurements of $\delta O_2/N_2$ and $\delta^{18}O_{atm}$: 68 euros per samples - 200 samples -> 13,600€
- Measurements of water isotopes (4 euros / sample - 2000 samples) -> 8,000€
- 1 personal computing station for the PhD - 2,000€

Outsourcing / subcontracting

- 2 publications - 3,000€

General and administrative costs & other operating expenses

- 3 international missions to present results at conferences (e.g., EGU, AGU) - 4,500€

Partner 3: CEREGE

Staff expenses

- 15 months Post-Doc (<2 yr experience) - 64,497€
- One 6-months Master Internship - 3,800€

Instruments and material costs

- Consumables for the water purification system, saws, plastic and glass containers for the samples-5,000€
- 40 analysis for ^{10}Be and ^{36}Cl cosmogenic nuclides (from atmospheric production) - 15,000€
- 1 personal computing station - 2,000€

Outsourcing / subcontracting

- 1 publication - 1,500€

General and administrative costs & other operating expenses

- 2 missions for international conferences (EGU) - 2,000€

Partner 4: CRPG-Nancy

Staff expenses

- 15 months Post-Doc (<2 yr experience) - 64,497€

Instruments and material costs

- 10-days analyzes at MEB - 2,000€
- 12 analyzes for in-situ cosmogenic radionuclides $^{10}Be/^{26}Al/^{21}Ne$ - 8,000€
- 12 geochemical analysis: Nd, Sr isotopes, U/Pb, (U-Th)/He - 3,000€
- Buying of a diamond saw for cutting subglacial diamictons - 2,000€

Outsourcing / subcontracting

- 1 publication - 1,500€

General and administrative costs & other operating expenses

- Missions to ULB and CEREGE - 1,000€
- 2 missions to international conferences - 2,500€

Requested means by item of expenditure and by partner*

	Partner *IGE*	**Partner** *LSCE*	**Partner** *CEREGE*	**Partner** *CRPG-Nancy*
Staff expenses	201,371€	127,600€	68,297€	64,497€
Instruments and material costs (including the scientific consumables)	52,429€	37,550€	22,000€	15,000€
Building and ground costs				
Outsourcing / subcontracting	4,500€	3,000€	1,500€	1,500€
General and administrative costs & other operating expenses	10,000€	4,500€	2,000€	3,500€
Administrative management & structure costs**	34,879€	22,445€	12,194€	10,985€
Sub-total	**303,179€**	**195,094€**	**105,991€**	**95,482€**
Requested funding				**699,746€**

* The amounts indicated here must be strictly identical to those entered on the website. If both information are not consistent, if they were badly filled in or lacking, the information entered online will prevail on those reported in the submission form / scientific document.

** For marginal cost beneficiaries, these costs will be a package of 13% of the eligible expenses. For full cost beneficiaries, these costs will be a sum of max. 68% of staff expenses and max. 7% of other expenses.

III. Impact and benefits of the project

Expected Impacts

This project has several impacts, first for the comprehension of the past climate system and interactions with carbon cycle, second for the link between climate and Antarctic ice-sheet dynamics on orbital timescales and third for the preparation of the interpretation of the *Beyond EPICA* ice core which is the major European challenge in the ice core community.

The first impact on quantifying the links between change in the carbon cycle (in particular atmospheric concentrations of CO_2 and CH_4) and climate is at the heart of the societal challenge to mitigate and adapt to climate change. It should be noted that ice cores provide the only means to directly probe the palaeo-atmosphere of the Earth. In this perspective, our study will have a high impact by providing unique high resolution reconstruction of climate and greenhouse gases concentration on MIS-19 which is the best analogue to our current interglacial. This period is key to decipher the natural and anthropic variability of climate and hence improve future climate projections. The results obtained with *ToBE* will be of paramount importance for future Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) and to the Climate Action objective (#13) of the Sustainable Development Goals of the United Nations.

The second impact relates to the past evolution of the Antarctic ice sheet. Within WP3, we will be able to evaluate if the position of Dome C has been steady in the past, and if not, what has been its movements. This is not only important for the interpretation of the ice cores archives in this region, but also to understand the past contribution of the Antarctic ice sheet to sea level variations. On longer time scales, WP4 will inform us on the inception of the Antarctic ice sheet by deciphering the last time the Antarctic continent was ice-free.

Finally, *ToBE* is essentially a preparation for the interpretation of the *Beyond EPICA* ice core, which will make a substantial contribution to an improved understanding of the key processes controlling the climate-Earth system and lead to reduced uncertainty in climate projections. Indeed, the *Beyond EPICA* ice core to be drilled will take the climate record (including that of greenhouse gases) back in time out of the familiar 100 kyr cycling world of the last 800 kyr, into a period of 40 kyr climate cycles.

With the extended range of climate conditions encountered in the less glaciated 40 kyr world (which partly provides templates of our planet in future warmer conditions after an increased GHG forcing sustained over several millennia), it will also provide benchmark data to assess the occurrence of irreversible tipping points in the climate system and of rapid climate changes in the future. Among others these templates will allow us to quantify the Earth System Sensitivity under an extended set of climate boundary conditions and to assess long-term feedbacks in ice sheets, sea level and biogeochemical cycles (Fischer et al., 2018). It has been agreed within the European ice core community that the BE-OI ice core should be dated with a strong effort of the French ice core community both on data acquisition (orbital tracers, cosmogenic nuclides measurements, ^{40}Ar and ^{81}Kr analyses; F. Parrenin is co-chair of the dating consortium). Similarly, the water isotopes and signal preservation consortium are co-chaired by French researchers (A. Landais, P. Martinerie) so that the results of *ToBE* are strongly awaited to adapt the strategy of measurements and interpretation of the coming *Beyond EPICA* ice core.

At a broader scale, results from *ToBE* and *Beyond EPICA* will lead to new information for EU policy and decision makers for future improved mitigation and adaptation actions. Such an oldest ice record is also a key priority for the international ice core community, as articulated by its planning body IPICS (International Partnerships in Ice Core Sciences). It is also much anticipated by other palaeoclimate scientists, as was affirmed at the recent 2017 PAGES (PAst Global changES) Open Science meeting.

Dissemination strategy

There will be five main measures to disseminate the results from this *ToBE* project:

1. Results will be presented at annual workshops organized jointly with the Beyond EPICA project at which the key stakeholders listed above will be whenever present to ensure full dissemination and valorization of the *ToBE* results.
2. The results will also be presented before and after publication at the main disciplinary and interdisciplinary conferences (e.g. EGU, AGU, PAGES), where they will attract the international and wider discipline stakeholders.
3. Main results will be published in peer-reviewed high impact journals. All such publications will be open access (OA).
4. All datasets will be archived at the best used international data centers in the field of palaeosciences, generally PANGAEA (https://www.pangaea.de) and/or the NOAA - National Center for Environmental Information - palaeoclimatology data centre (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets).
5. General public conferences will be given on the Oldest-Ice projects.

Education

New ice core scientists will be educated through the PhDs and Post-docs proposed in the *ToBE* project, in a strong European context. They will work in partnership with the PhDs and Post-docs of the ITN DEEPICE (15 phD students recruited in fall 2021 working on ice core related research in link with the BE-OI project, https://deepice.cnrs.fr/) and H2020 *Beyond EPICA* European projects.

Communication

The *ToBE* consortium is strongly involved in scientific communication. The ToBE project and its results will be promoted through the *ToBE* website, as well as websites and social medias of the laboratories and associated project (e.g. https://www.ige-grenoble.fr/-ICE3-, https://panda.osug.fr/, https://www.beyondepica.eu/en/, https://twitter.com/OldestIce, https://deepice.cnrs.fr/, https://iceclimiso.cnrs.fr/, https://twitter.com/climate_cerege)... We will benefit from the strong communication network as well as twitter account developed within the DEEPICE and *Beyond EPICA* projects to broadly promote our results.

IV. References related to the project

Baccolo, G. *et al.* Deep ice as a geochemical reactor: insights from iron speciation and mineralogy of dust in the Talos Dome ice core (East Antarctica). *The Cryosphere* **15**, 4807–4822 (2021).

Baroni, M., Bard, E., Petit, J.-R., Magand, O. & Bourlès, D. Volcanic and solar activity, and atmospheric circulation influences on cosmogenic 10Be fallout at Vostok and Concordia (Antarctica) over the last 60years. *Geochimica et Cosmochimica Acta* **75**, 7132–7145 (2011).

Baroni, M., Bard, E., Petit, J.-R., Viseur, S. & Team, A. Persistent Draining of the Stratospheric 10Be Reservoir After the Samalas Volcanic Eruption (1257 CE). *Journal of Geophysical Research: Atmospheres* **124**, 7082–7097 (2019).

Bauska, T. K. *et al.* Carbon isotopes characterize rapid changes in atmospheric carbon dioxide during the last deglaciation. *Proceedings of the National Academy of Sciences* **113**, 3465–3470 (2016).

Bazin, L. *et al.* An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120–800 ka. *Clim. Past* **9**, 1715–1731 (2013).

Bender, M., Sowers, T. & Labeyrie, L. The Dole Effect and its variations during the last 130,000 years as measured in the Vostok Ice Core. *Global Biogeochemical Cycles* **8**, 363–376 (1994).

Bender, M. L. Orbital tuning chronology for the Vostok climate record supported by trapped gas composition. *Earth and Planetary Science Letters* **204**, 275–289 (2002).

Bender, M. L., Barnett, B., Dreyfus, G., Jouzel, J. & Porcelli, D. The contemporary degassing rate of ^{40}Ar from the solid Earth. *PNAS* **105**, 8232–8237 (2008).

Bereiter, B., Fischer, H., Schwander, J. & Stocker, T. F. Diffusive equilibration of N_2, O_2 and CO_2 mixing ratios in a 1.5-million-years-old ice core. *The Cryosphere* **8**, 245–256 (2014).

Bereiter, B. *et al.* Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present. *Geophysical Research Letters* **42**, 542–549 (2015).

Blard, P.-H. *et al.* Cosmogenic ^{3}He production rate in the high tropical Andes (3800 m, 20°S): Implications for the local last glacial maximum. *Earth and Planetary Science Letters* **377–378**, 260–275 (2013).

Braucher, R. *et al.* Chlorine measurements at the 5MV French AMS national facility ASTER: Associated external uncertainties and comparability with the 6MV DREAMS facility. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **420**, 40–45 (2018).

Buizert, C. *et al.* Radiometric ^{81}Kr dating identifies 120,000-year-old ice at Taylor Glacier, Antarctica. *Proceedings of the National Academy of Sciences* **111**, 6876–6881 (2014).

Buizert, C. *et al.* Antarctic surface temperature and elevation during the Last Glacial Maximum. *Science* **372**, 1097–1101 (2021).

Casado, M., Münch, T. & Laepple, T. Climatic information archived in ice cores: impact of intermittency and diffusion on the recorded isotopic signal in Antarctica. *Climate of the Past* **16**, 1581–1598 (2020).

Cavitte, M. G. P. *et al.* A detailed radiostratigraphic data set for the central East Antarctic Plateau spanning from the Holocene to the mid-Pleistocene. *Earth System Science Data* **13**, 4759–4777 (2021).

Chmeleff, J., von Blanckenburg, F., Kossert, K. & Jakob, D. Determination of the 10Be half-life by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **268**, 192–199 (2010).

Christ, A. J. *et al.* A multimillion-year-old record of Greenland vegetation and glacial history preserved in sediment beneath 1.4 km of ice at Camp Century. *Proceedings of the National Academy of Sciences* **118**, e2021442118 (2021).

Clarke, G. K. C. & Marshall, S. J. Isotopic balance of the Greenland Ice Sheet: modelled concentrations of water isotopes from 30,000 BP to present. *Quaternary Science Reviews* **21**, 419–430 (2002).

Corbett, L. B., Bierman, P. R. & Rood, D. H. An approach for optimizing in situ cosmogenic ^{10}Be sample preparation. *Quaternary Geochronology* **33**, 24–34 (2016).

Crotti, I. *et al.* An extension of the TALDICE ice core age scale reaching back to MIS 10.1. *Quaternary Science Reviews* **266**, 107078 (2021).

Delmas, R. J. *et al.* Bomb-test ^{36}Cl measurements in Vostok snow (Antarctica) and the use of ^{36}Cl as a dating tool for deep ice cores. *Tellus B: Chemical and Physical Meteorology* **56**, 492–498 (2004).

Dreyfus, G. B. *et al.* Anomalous flow below 2700 m in the EPICA Dome C ice core detected using δ^{18}O of atmospheric oxygen measurements. *Climate of the Past* **3**, 341–353 (2007).

Eicher, O. *et al.* Climatic and insolation control on the high-resolution total air content in the NGRIP ice core. *Climate of the Past* **12**, 1979–1993 (2016).

Elmore, D. *et al.* ^{36}Cl bomb pulse measured in a shallow ice core from Dye 3, Greenland. *Nature* **300**, 735–737 (1982).

Extier, T. *et al.* On the use of $\delta^{18}O_{atm}$ for ice core dating. *Quaternary Science Reviews* **185**, 244–257 (2018).

Fischer, H. *et al.* Palaeoclimate constraints on the impact of 2 °C anthropogenic warming and beyond. *Nature Geosci* **11**, 474–485 (2018).

Fourteau, K. *et al.* Multi-tracer study of gas trapping in an East Antarctic ice core. *The Cryosphere* **13**, 3383–3403 (2019).

Fourteau, K. *et al.* Estimation of gas record alteration in very low-accumulation ice cores. *Climate of the Past* **16**, 503–522 (2020).

Gkinis, V. *et al.* Numerical experiments on firn isotope diffusion with the Community Firn Model. *Journal of Glaciology* **67**, 450–472 (2021).

Gow, A. J., Epstein, S. & Sheehy, W. On the Origin of Stratified Debris in Ice Cores from the Bottom of the Antarctic Ice Sheet. *Journal of Glaciology* **23**, 185–192 (1979).

Heikkilä, U. *et al.* ^{36}Cl bomb peak: comparison of modeled and measured data. *Atmospheric Chemistry and Physics* **9**, 4145–4156 (2009).

Johnsen, S. J. *et al.* Diffusion of stable isotopes in polar firn and ice: the isotope effect in firn diffusion. in *Physics of ice core records* 121–140 (Hokkaido University Press, 2000).

Jouzel, J. *et al.* Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years. *Science* **317**, 793–796 (2007).

Kawamura, K. *et al.* Northern Hemisphere forcing of climatic cycles in Antarctica over the past 360,000 years. *Nature* **448**, 912–916 (2007).

Korschinek, G. *et al.* A new value for the half-life of ^{10}Be by Heavy-Ion Elastic Recoil Detection and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **268**, 187–191 (2010).

Legrand, M. *et al.* Year-round records of bulk and size-segregated aerosol composition in central Antarctica (Concordia site) – Part 1: Fractionation of sea-salt particles. *Atmospheric Chemistry and Physics* **17**, 14039–14054 (2017).

Lhomme, N., Clarke, G. K. C. & Ritz, C. Global budget of water isotopes inferred from polar ice sheets. *Geophysical Research Letters* **32**, (2005).

Lilien, D. A. *et al.* Brief communication: New radar constraints support presence of ice older than 1.5 Myr at Little Dome C. *The Cryosphere* **15**, 1881–1888 (2021).

Mahaney, W. C. & Mahaney, W. *Atlas of Sand Grain Surface Textures and Applications*. (Oxford University Press, 2002).

Mariotti, A. *et al.* Nonlinear forcing of climate on mountain denudation during glaciations. *Nat. Geosci.* **14**, 16–22 (2021).

Martin, L. C. P. *et al.* Antarctic-like temperature variations in the Tropical Andes recorded by glaciers and lakes during the last deglaciation. *Quaternary Science Reviews* **247**, 106542 (2020).

Merchel, S., Braucher, R., Lachner, J. & Rugel, G. Which is the best ^{9}Be carrier for ^{10}Be/^{9}Be accelerator mass spectrometry? *MethodsX* **8**, 101486 (2021).

Nehrbass-Ahles, C. *et al.* Abrupt CO_2 release to the atmosphere under glacial and early interglacial climate conditions. *Science* **369**, 1000–1005 (2020).

Parrenin, F. *et al.* Is there 1.5-million-year-old ice near Dome C, Antarctica? *The Cryosphere* **11**, 2427–2437 (2017).

Parrenin, F. *et al.* 1-D-ice flow modelling at EPICA Dome C and Dome Fuji, East Antarctica. *Climate of the Past* **3**, 243–259 (2007).

Pivot, S., Baroni, M., Bard, E. & Giraud, X. A Comparison of ^{36}Cl Nuclear Bomb Inputs Deposited in Snow From Vostok and Talos Dome, Antarctica, Using the ^{36}Cl/Cl^{-} ratio. *Journal of Geophysical Research: Atmospheres* **124**, 10973–10988 (2019).

Pol, K. *et al.* New MIS 19 EPICA Dome C high resolution deuterium data: Hints for a problematic preservation of climate variability at sub-millennial scale in the “oldest ice”. *Earth Planet. Sci. Let.* **298**, 95–103 (2010).

Poluianov, S. V., Kovaltsov, G. A., Mishev, A. L. & Usoskin, I. G. Production of cosmogenic isotopes ^{7}Be, ^{10}Be, ^{14}C, ^{22}Na, and ^{36}Cl in the atmosphere: Altitudinal profiles of yield functions. *Journal of Geophysical Research: Atmospheres* **121**, 8125–8136 (2016).

Puchol, N. *et al.* Limited impact of Quaternary glaciations on denudation rates in Central Asia. *GSA Bulletin* **129**, 479–499 (2017).

Quiquet, A., Dumas, C., Ritz, C., Peyaud, V. & Roche, D. M. The GRISLI ice sheet model (version 2.0): calibration and validation for multi-millennial changes of the Antarctic ice sheet. *Geoscientific Model Development* **11**, 5003–5025 (2018).

Raisbeck, G. M., Yiou, F., Cattani, O. & Jouzel, J. ^{10}Be evidence for the Matuyama–Brunhes geomagnetic reversal in the EPICA Dome C ice core. *Nature* **444**, 82–84 (2006).

Raynaud, D. *et al.* The local insolation signature of air content in Antarctic ice. A new step toward an absolute dating of ice records. *Earth and Planetary Science Letters* **261**, 337–349 (2007).

Röthlisberger, R. *et al.* Limited dechlorination of sea-salt aerosols during the last glacial period: Evidence from the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core. *Journal of Geophysical Research: Atmospheres* **108**, (2003).

Schneider, R., Schmitt, J., Köhler, P., Joos, F. & Fischer, H. A reconstruction of atmospheric carbon dioxide and its stable carbon isotopic composition from the penultimate glacial maximum to the last glacial inception. *Climate of the Past* **9**, 2507–2523 (2013).

Sutter, J. *et al.* Modelling the Antarctic Ice Sheet across the mid-Pleistocene transition – implications for Oldest Ice. *The Cryosphere* **13**, 2023–2041 (2019).

Tison, J.-L. *et al.* Retrieving the paleoclimatic signal from the deeper part of the EPICA Dome C ice core. *The Cryosphere* **9**, 1633–1648 (2015).

Veres, D. *et al.* The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years. *Clim. Past* **9**, 1733–1748 (2013).

Willerslev, E. *et al.* Ancient Biomolecules from Deep Ice Cores Reveal a Forested Southern Greenland. *Science* **317**, 111–114 (2007).

Wilson, D. S. *et al.* Antarctic topography at the Eocene–Oligocene boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology* **335–336**, 24–34 (2012).