Reply to comments of Reviewer 1 – Bryn Hubbard

We very much thank Prof. B. Hubbard for his detailed analysis of the manuscript and useful comments. We explain here below how we have taken all those into account in the revised manuscript.

General Comments:

First, the paper names the lowermost 60 m (excluding _6 m located immediately above the ice-bed interface that remained uncored) as 'bottom ice' and divides this in turn into debris-free uppermost 48 m as 'deep ice' and the debris-rich lowermost 12 m as 'basal ice'. Following the analysis, it is argued that all 60 m is influenced by processes dictated by proximity to the bed. I believe the current names work satisfactorily (not perfect though) for the palaeoclimatic arguments presented in this paper, but it does not work well for students of basal ice who may subsequently wish to compare the ice types investigated here with those from elsewhere. Alternatively, a descriptive scheme would serve both purposes. Although it is not explained in the paper (and I think it should be) the 60 m analysed is I believe different from the overlying ice (Fig. 1b). In which case I would call the 60 m the 'basal ice' or 'basal zone ice' and divide the two ice types involved into basal ice facies: probably 'clean' underlain by 'dispersed' or 'dispersed banded'. Indeed, the latter could be of use in distinguishing between the lowermost 2 m of the currently basal ice, into which the paper claims basal debris may have been introduced. If there are insufficient data from the core to ascertain whether the debris is banded or not then I would probably still refer to the two sections as 'clean' and 'dispersed' rather than 'deep ice' and 'basal ice'.

We have adopted the terminology proposed by this referee (based on his review of 2007 and previous work). Everywhere in the text, table and figures, we have replaced "bottom ice" by "basal ice", "deep ice" by "clean ice facies" and "basal ice" by "dispersed ice facies". We have also redefined those terms, where appropriate! (p.6, l. 28 and following)

Second, I am not convinced by the vertical thickening as it is currently presented, especially considering it has such important implications for the age-depth scale. I have no issue with invoking lateral compression, but without modelling I see no independent evidence for absolute thickening as shown in Figure 7. Actually, I wonder whether such thickening is needed to explain the data anyway. Does the argument not still hold as long as the rate of vertical thinning is slowed relative to comparator age-depth scales – i.e., a 'relative thickening' rather than an 'absolute thickening'? Also, no argument is presented in the paper for how much relative thickening is needed to explain the uniformity of the data – but I would be far happier with an argument along the lines of relative thickening than actual thickening. If the authors agree, then it could be explained in a few sentences.

This is indeed a very sensible comment. We have revised the description in the text and amended the caption of the figure along those lines (p.18, line 2 and following and caption of Figure 7).

Specific Comments

Title I would remove 'clear' as it is undefined. I would probably also reword the title to 'EPICA Dome C basal ice reveals palaeoclimatic signal' or 'A palaeoclimatic signal from the . . .'. I believe that this is what the paper concludes.
"clear" has been deleted. We would prefer to keep the title as a question!..

P3 L24 Replace allochtone with allochthonous. How about simplifying further: incorporation of debris from the ice sheet's substrate'.

done

P4 L9 ‘this palaeoclimatic information’
done

P5 L11 ‘less well documented’
done

P6 L13 and elsewhere Need to be consistent in terms of tense (I would delete ‘have’ here and elsewhere and always keep in past tense [the present is also used elsewhere]).
done, where found

L21 Replace ‘bottom’ with ‘lowermost’ as the paper uses ‘bottom’ in a specific sense (see general point).
done

P6 L28 I would define basal ice more broadly as ice that has acquired a distinctive character as a result of processes driven by the presence of the ice-bed interface. Thus, it does not have to be debris rich (and indeed, one can have debris-rich ice that is not basal ice).
Done, see general comment

P7 L20 Delete ‘, if’. L22-3 I would delete from ‘using’ to ‘ice’ to leave ‘be processed in continuity’
done
P9 L2 No need for ‘respectively’.
done
P10 L2 (& P11 L16) I would replace ‘clues for’ with ‘indicators of’ or ‘evidence compatible with’
done
L19 Replace ‘convincing’ with ‘indicative’.
done
L21 I would replace ‘happens to be’ with ‘is’.
done
P10 L28 ‘comparison of the mean deep and bottom ice values with those ’
done
P11 L2 I would replace ‘good’ with ‘close’.
done
P12 L6 ‘considered as two groups’.
done
L18 It may be simpler and just as accurate to shorten the sub-heading to ‘Distribution and relocation of’
done
P13 L28 ‘suggested’ (and I would move the ‘however’ to the beginning of the sentence.
done
P14 L3 I would replace a ‘fair share’ with ‘much’ or similar.
done
P15 L7 This reference to meteoric ice ‘above’ could be placed into context by addressing whether this 60 m section was analysed and reported on here because it is different from the ice above (as I suspect and hope) or because this is howthe core was distributed. This may well be in the paper and I may have missed it, but if it is not then it should be stated.

This is now stated in the paragraph where we define what basal ice is p. 6): "…the bottom 60 meters of the available core acquired distinctive properties, as a result of processes driven by the proximity of the ice-bedrock interface. We will therefore, in accordance with the previous literature (Knight, 1997; Hubbard et al., 2007) refer to it as "basal ice"….

P19 L28 'means'
done

L29 I am not familiar with 'exsudation'; can 'expulsion' be used?
done

P20 L1 These processes would form ice that may be similar in appearance to the 'clear' facies reported at temperate glaciers and to the cryo-warmed ice reported towards the margins of the Greenland Ice Sheet by Thomas Phillips and colleagues. If this is right then both associations should be mentioned here or in the Discussion.
Yes. We have thought about this. But one of the major differences is that our basal ice still contains the usual total gas content values, typical of the ice sheet above, while it is not the case for the clear facies in the Alps or at the margin of the Greenland ice sheet…so we preferred not to associate the two!..
L1-2 I am not sure of the argument linking basal melting to 'propagate the two zones of deep and basal ice upwards'.
The sentence has been rephrased

P20 L25 'scale, thereby providing some'
done

P21 L8 I would delete 'elevated' from 'elevated depth'.
done

L28 Giga-Joules = GJ (?)
done

P22 L12-15 It is not easy to combine all the competing data into coherent theories and a good deal of latitude must be given. However, I am not completely convinced by the treatment of lithic particles and the difference between the uppermost ~10 m of the basal ice (no mechanism of incorporation from the bed) and the lowermost ~2 m into which basal debris particles may have been incorporated. Is it possible from the available data to make a clearer statement as to whether all of the debris above~2m is precipitated and then whether the basal 2 m shows any other evidence of having been influenced by a different process. At present this 10 m / 2 m division seems a little too informal relative to the precision of some of the other arguments. Is the lowermost ~2 m a different basal ice facies (see general comment)?
I guess the reviewer is mentioning l. 12-15 on the next page (23)?...There is no visual difference of ice type along the whole last 12 meters, which then fully correspond to the "dispersed facies", with no change at 2 meters from the bottom. Only when the ice is melted and collected on filters, we start to notice the presence of individual inclusions several millimeters in size in the last meter of ice (not 2 meters as mentioned by the reviewer(?)), which are more compatible with inclusion from the bedrock, rather than having an atmospheric origin. This is described in more details in de Angelis et al. (2013).
P23 L10 The comment immediately above has a bearing here too.

See above
P 40 Fig. 7 If this is kept then I would stress its conceptual nature. Maybe just begin the caption with ‘Schematic illustration of the nature of’
done

Reply to comments of Reviewer 2

We very much thank Reviewer 2 for his positive and formative comments! We respond to each of these here below, and adapted the manuscript where requested.

I strongly recommend this paper for publication in The Cryosphere. The paper contains interesting data and conclusions, and the scholarship is at a high level. I am mainly interested in commenting on aspects of the geochemistry and dating.

Thank you

I think the use of the term "soluble" to refer to the ions is unfortunate, because, as the authors explain at the end, gases are also soluble. I think the useful distinction is between ions forming soluble salts, ions forming insoluble salts, and gases. Gases should be included in soluble constituents at the beginning.

We of course agree that gasses should be considered as "soluble". I have scrolled the manuscript carefully for the term "soluble" and only found the term a few times, with no obvious misleading meaning (?)… In a few occasions, I have converted it to "soluble salts" to make things more explicit!.. I hope I did not miss anything. The term "insoluble" comes up several times, but always associated with the dust content.

The authors discuss the fact that minor melting rearranges the distribution of ions but not gases, and they refer to the poorly known behavior of gases during partial melting. I should think that melting would primarily attack grain boundaries that are rich in salts, whereas clathrates are in the interior of ice crystals and less likely to intercept a melt zone. So it seems that one can certainly say that gases are less susceptible to redistribution than salts

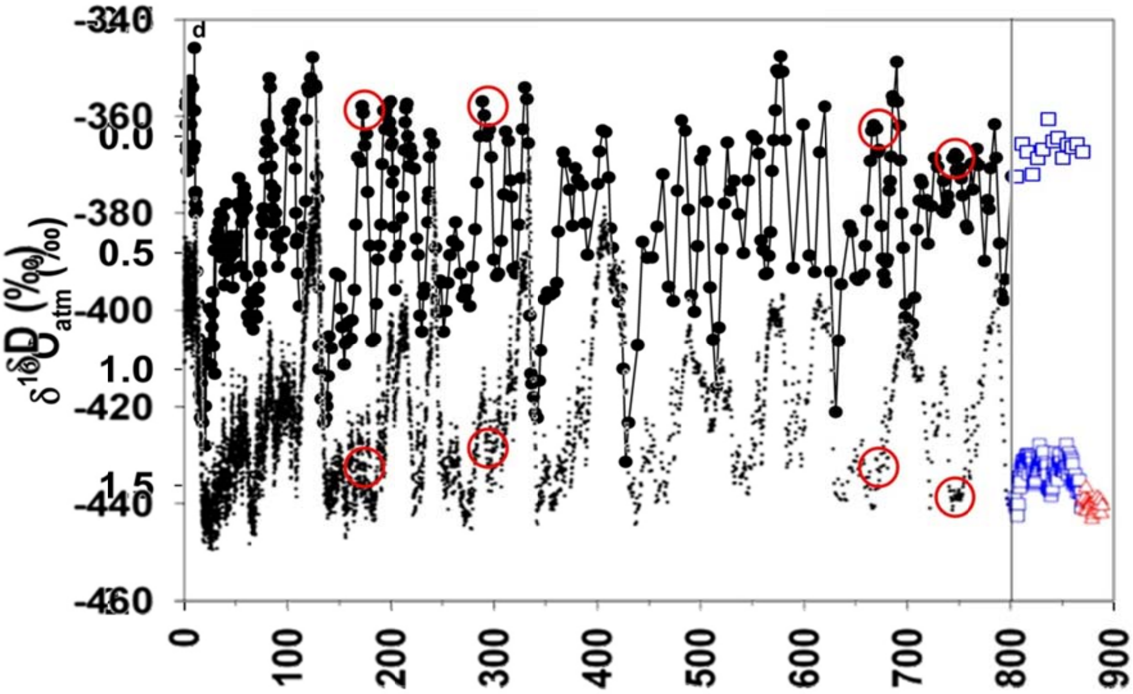
That is indeed probably mostly true. However, as described in section 5.3, we have more and more indication that salts can also be located in considerable amounts (up to 60%) within the grains (Ohno and colleagues). That would make the distinction between salts and gases remobilization less obvious, I would think. On the other hand, the crystals are growing so big in the basal ice, that I guess boundary migration must "sweep"/"remobilize" an important proportion of the former smaller crystals

The discussion at the end of the paper describes or implies several possible scenarios for the age and age distribution of the deep and bottom ice. I think that the data only allow a single interpretation, and that is that the ice must date to a single cold climate event.

We agree with that.!

The interpretation rests on small cycles in the d18Oatm record, each of which is attributed to an orbital cycle. Without more information, this interpretation appears plausible because the d18Oatm record in the deep/bottom ice looks a lot like the record between about 700-760 ka. The similarity includes the fact that d18Oatm is isotopically light when Dome C is cold.

Yes, this is something that has disturbed us initially: isotopically light δ^{18}Oatm is generally associated to interglacials or interstadials, i.e; warmer periods, which is incompatible with cold ice δ^{18}O, as underlined by the reviewer. However, looking into it more carefully and discussing with other specialist of these $\delta^{18}O_{atm}$ signals in ice cores, we noticed that there are exceptions to the rule stated above, with light $\delta^{18}O_{atm}$ sometimes occurring during glacial periods (with relatively warm Northern Hemisphere summers with a strong East Asian *monsoon).In the figure below, we have superimposed the graphs of Fig. 1c (δD vs. age) and Fig. 1d ($\delta^{18}0_{atm}$). One can clearly see that there are multiple occasions where $\delta^{18}0_{atm}$ is light during full glacial periods (red circles) within the paleoclimatically valid record, similarly to our basal ice sequence*



However, this interpretation invokes the presence of interglacial or interstadial ice from the warm periods in the orbital cycle. This presence is improbable because the isotopic temperature of the deep/bottom ice is glacial. There does not seem to be any way to separate the ice and its trapped gases.

Agreed!

So it seems to me that the deep/disturbed ice is all glacial. Either it represents a single glacial period, or it represents the mixing of ice from several glacial periods without any incorporation of interstadial or interglacial ice. Of these options, the first seems more likely. For one thing, the continuous record includes the end of the glacial period ending at 800 ka. The d18O of this glacial ice is low, blending right into the d18O record of the underlying deep/bottom ice. So it seems to me that the most likely interpretation is that the deep/dirty ice represents the earlier part of the 800 ka glacial interval.

Agreed!... this is what we say… but it is apparently a glacial period with occurrence of light $\delta^{18}O_{atm}$ that has been "stretched"…

Any alternative requires a mechanism for mixing glacial ice from different periods with minimal inclusion of warmer ice, as noted above.

Agreed!

The new gas data needs to be tabulated in the paper or in the supplemental material. The Ar/N2 and O2/N2 ratios need to be reported because these ratios might be fractionated if gases were in fact transported by meltwater in the deep and bottom ice.

The gas data have been collected in a supplementary table, as requested. $\delta O_2/N_2$ are available and have been added to the table. They show no significant difference with the meteoric ice above (Landais et al., 2012) and therefore also preclude solubility fractionation during potential melting-refreezing events. Thanks to the referee for this interesting comment! Argon data are unfortunately not available for those samples.

The authors seem to conjecture that respiration may have consumed some O2, and that this consumption may have affected d18Oatm. However given that the CO2 concentration is so low, and around the value expected based on the isotopic temperature, it is very unlikely that respiration has consumed enough O2 to significantly modify the d18Oatm value.

We fully agree with the referee, and have changed the manuscript along those lines…thanks for the comment!...(p. 22, l. 9 and following)

I recommend that the paper be published after 3 actions. First, the authors need to include a table with all gas data either in the SOM or the paper.

done

Second, the discussion of respiration needs to be revised to include low CO2 concentration of the trapped gases (which to me rule out respiration).

done

Third, the authors should respond to the comments about the origin of the ice, although they can keep their favored interpretation.

done, see above

Reply to comments of Reviewer 3

We very much thank Reviewer 2 for his positive and formative comments, fostering discussion items and bringing us back to the "bigger picture"! We respond to each of these comments here below, and adapted the manuscript where requested.

General comments:

Tison et al. present a wide variety of geochemical measurements in an effort to understand the bottom 60m of the Dome C ice core. The climate interpretation of Dome C stops at _3200 m even though there is another _60 m of ice below this. Tison et al. divide the bottom 60 m into 48 m of "deep ice" and 12 m of "basal ice" based on the structure of the ice. The geochemistry of the ice is consistent with that of a cold glacial period and appears to be only minorly altered. They suggest the most likely explanation is that the deep ice has been stretched relative to the ice above due to changing stress conditions from irregular bedrock topography. The implies it may be possible to extend the climate record of EDC another few tens of thousands of years. The science is well described and the paper is well written. The geochemical analyses are extensive and the descriptions of deep ice processes that may alter the ice are presented clearly. The timescale for the deep ice rests on the matching of muted peaks in the d18Oatm to insolation forcing and is not wholly convincing, as the authors acknowledge given the deuterium data. This leads to an uncertainty in whether the deep ice represents 40,000 years or only 10,000 years and highlights that stretching may be the most likely situation but is not definitive.

I recommend publishing this paper with minor revisions as described below. One other point is that the title asks a question that is not clearly answered in the paper. I think the answer to whether a clear paleoclimate signal can be recovered is "no" because there is not sufficient confidence in the timescale to be certain the geochemistry is truly preserved, but that there is hope that other sites, without complicated bedrock, could preserve paleoclimate signal to within meters of the bed. The authors may want to revise the title and paper such that the reader is not left hanging.

We would prefer to keep the title "as is" but it is certainly a great idea to answer the question of the title in the conclusions. We have amended the text along those lines

Stretching:

It does not seem like the mechanism of basal stretching gets sufficient discussion. Since this is the proposed mechanism, more detailed analysis is needed. I wanted to read a discussion of the magnitude of stretching the deep ice likely experienced. As a quick estimate, I compared the implied average annual layer thickness of the deep ice to that of the ice in the final glacial cycle of the climate record (using AICC2012). This suggested that the ice was thicker than might be expected by roughly a factor of 2, assuming the deep ice spanned 40,000 years. This seems within reason, but still a lot of stretching. If the ice only contains 10,000 years, then it has been stretched nearly 10X, which seems much less likely.

We agree with the reviewer, although we thought it was too conjectural to deserve a longer discussion. We have added a few sentences along the lines of the reviewer, and provided a few other hypotheses that might explain the apparently too strong stretching.

I would also have liked a figure of the EDC basal topography. While it is shown in referenced papers, it would be worthwhile to reproduce it here as well.

Yes, we have thought about this too. However, the original of the map is already of relatively bad quality, so that we have preferred to give a detailed description in the text. If the editor wishes so, we could write to the authors to get a better version, if available, of their map and add it as a complement to our figure 1. We have slightly changed the description in the text to make it more precise.

There is also surprisingly little discussion of ice-flow transients. My thought is that the summit of Dome C has likely migrated through time since many interior ice divides (e.g. Summit Greenland and WAIS Divide) are migrating today and I don't know of any evidence one way or the other for Dome C. Given the rough bed topography, it takes a migration of only a few ice thicknesses (ca.10 km) to change bedrock elevation by ca. 200 m. The deep ice may experience stretching because it flowed from a bedrock ridge to the current valley and only recently has the divide migrated over the top.

This was only briefly mentioned at the end of the conclusions. We have added a paragraph reflecting the opinion of the referee.

Implications for Old Ice: Maybe this is beyond the scope of this paper, but I was hoping for a brief (one or two paragraph) discussion of the implications for finding million year-old or older ice. This has been identified as a major ice-core goal in the coming decades, and I think this analysis yields important insight into what might be expected. The two conclusions I drew from this paper were 1) the geochemistry likely remains relatively unaltered although there is migration of species and 2) rough bedrock greatly complicates the inference of deep timescales. But I imagine the authors have much more to add.

We thank the referee for refocusing our conclusions on the" bigger picture". We have amended the conclusions and added a line at the end of the abstract along these suggestions.

Specific comments:
P569,L24 – I don't understand what the sentence beginning "we also discuss" is trying to say. Maybe just deleted?

We have modified the sentence to hopefully make it more explicit

P569,L25 – See comments about final sentence of abstract above and also consider shortening this sentence into a more specific answer of the title.

We have added a sentence at the end of the abstract.

Figures – more color would be helpful (and there's no extra cost!)

We have added colors to most of the figures

Figure 4 – the panels are very small and nearly unintelligible, at least as presented in the PDF. Since all of the panel have the same depth axis, the panels could be enlarged by eliminating the redundant axes labels.

In our opinion, this is indeed a drawback of the pdf layout; our originals read perfectly when printed in full page width. ***Question to the editor:*** *Is it not possible to enlarge those figures to full page width?*

Figure 5 – panels are small like in Figure 4.

See above

Can we retrieve a ~~clear~~ paleoclimatic signal from the deeper part of the EPICA Dome C ice core?

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Can we retrieve a clear paleoclimatic signal from the deeper part of the EPICA Dome C ice core?

Abstract

An important share of paleoclimatic information is buried within the lowermost layers of deep ice cores. Because improving our records further back in time is one of the main challenges in the near future, it is essential to judge how deep these records remain unaltered, since the proximity of the bedrock is likely to interfere both with the recorded temporal sequence and the ice properties. In this paper, we present a multiparametric study (δD-$\delta^{18}O_{ice}$, $\delta^{18}O_{atm}$, total air content, CO_2, CH_4, N_2O, dust, high resolution chemistry, ice texture) of the bottom 60 meters of the EPICA Dome C ice core from central Antarctica. These bottom layers ~~have been subdivided in two sections: the lower 12 meters showing visible solid inclusions (basal ice) and the 48 meters above which we refer to as "deep ice".~~were subdivided in two distinct facies: the lower 12 meters showing visible solid inclusions (basal dispersed ice facies) and the 48 meters above, which we will refer to as the "basal clean ice facies". Some of the data are consistent with a pristine paleoclimatic signal, others show clear anomalies. It is demonstrated that neither large scale bottom refreezing of subglacial water, nor mixing (be it internal or with a local basal end-term from a previous/initial ice sheet configuration) can explain the observed bottom ice properties. We focus on the high-resolution chemical profiles and on the available remote sensing data on the subglacial topography of the site to propose a mechanism by which relative stretching of the bottom ice sheet layers is made possible, due to the progressively confining effect of subglacial valley sides. This stress field change, combined with bottom ice temperature close to the pressure melting point, induces accelerated migration recrystallization, which results in spatial chemical sorting of the impurities, depending on their state (dissolved vs. solid) and if they are

involved or not in salt formation. This chemical sorting effect is responsible for the progressive build-up of the visible solid aggregates that therefore mainly originate "from within", and not from incorporation processes of ~~allochtone material at the ice-bedrock interface~~debris from the ice sheet's substrate. We ~~also~~ further discuss how the proposed mechanism is compatible with the other ~~variables~~ ice properties described. We conclude that the paleoclimatic signal is only marginally affected in terms of global ice properties at the bottom of EPICA Dome C, but that the time scale ~~has been~~was considerably distorted by mechanical stretching of MIS20 due to the increasing influence of the subglacial topography, a process that might have started well above the bottom ice. A clear paleoclimatic signal can therefore not be inferred from the deeper part of the EPICA Dome C ice core. Our work suggests that the existence of a flat monotonic ice-bedrock interface, extending for several times the ice thickness, would be a crucial factor in choosing a future "oldest ice" drilling location in Antarctica.

Keywords

Antarctica; EPICA Dome C; ice core; Bottom ice; Paleoclimate; Multiparametric analyses

1. Introduction: Paleoclimatic signals in basal layers of deep ice cores

Deep ice cores retrieved from the two present-day major ice sheets on Earth, Greenland in the North and Antarctica in the South, ~~have~~ delivered a wealth of unique paleoclimatic archives over the last decades. These ~~have~~ allowed reconstruction of global climatic and environmental conditions over the last 800.000 years, including unprecedented records of cyclic changes in the composition of greenhouse gases (CO_2, CH_4, N_2O). An important share of those paleoclimatic information~~s~~ is buried within the lowermost sections of those deep ice cores, due to the mechanical thinning of annual accumulation layers with depth. Improving the records further back in time is therefore one of the main challenges of ice core science in the near future (IPICS, 2009). A major concern in this regard is to judge how far down we can trust the paleoclimatic signals stored within the ice, since the proximity of the bedrock is likely to interfere both with the recorded temporal sequence and with the ice properties. This in turn is closely linked to the thermal and hydrological regime at the bottom of the ice sheet, as ~~has been~~ shown previously in the literature describing basal layers of deep ice cores (e.g. Goodwin, 1993, Gow et al., 1979, Gow and Meese, 1996, Herron and Langway, 1979, Jouzel et al., 1999, Koerner and Fisher, 1979, Souchez, 1997, Souchez et al., 1998, Souchez et al., 1995a, Souchez et al., 2006, Souchez et al., 1995b, Souchez et al., 1993b, Souchez et al., 2003, Souchez et al., 2002b, Souchez et al., 2000a, Souchez et al., 1994, Tison et al., 1998, Tison et al., 1994, Weis et al., 1997). In some cases, where the ice-bedrock interface is clearly below the pressure-melting point (pmp) as, for example, at the GRIP (-9°C) or the Dye-3 (-12°C) ice coring sites in Greenland, single or multiple mixing events between the present-day ice sheet ice and local ice remnants of previous (or even initial) ice sheet configurations are encountered (Souchez, 1997, Souchez et al., 1998, Souchez et al., 1994, Souchez et al., 2000b, Verbeke et al., 2002). Where the ice-bedrock interface is at the pmp, the meteoric ice has the potential to melt at a rate that will depend on the heat budget at the ice-bedrock interface (geothermal heat flux, internal friction and conduction through the overlying ice). In some cases, where the subglacial topography allows it, like at the Antarctic Vostok site, a subglacial lake will exist. Again, depending on the heat budget but also on the subglacial lake water circulation pattern, lake ice will form at the ice-water interface in substantial amounts (e.g. Jouzel et al., 1999, Souchez et al., 2002a, Souchez et al., 2003, Souchez et al., 2000a). This ice, evidently, does not carry paleoclimatic information. Furthermore, in the case of large subglacial lakes (such as Lake Vostok) where the ice column above can be considered in full hydrostatic equilibrium buoyancy, re-grounding of the ice sheet on the lee side of the lake will induce dynamical perturbations (such as folds), even in the meteoric ice above, as demonstrated for MIS11 (Raynaud D., 2005) and for the ice just above the accreted lake ice (Souchez et al., 2002a, Souchez et al., 2003, Souchez et al., 2002b). A less well documented case however, is the one where no significant water body exists at the ice-bedrock interface. If only melting occurs at the interface, with no water accumulation and no refreezing (as, for example at the NGRIP site in Greenland), can we then rely on the paleoclimatic information gathered in the basal layers? The EPICA Dome C ice core potentially provides us with an opportunity to investigate that specific case. In this paper, we are using a multiparametric approach, combining new and existing low resolution (50cm) data for the bottom 60 meters of ice from the EDC ice core with a new high resolution (1.5 to 8 cm) chemical data set in order to better understand the processes at work and evaluate how these might have altered the environmental archive.

2. The EPICA Dome C ice core

The Dome C deep ice core (EDC) is one of the two ice cores drilled in the framework of the European Project for Ice Coring in Antarctica (EPICA). It is located at Concordia Station (Dome C - 75°06’04”S; 123°20’52” E), about 1200 km south of the French coastal station of Dumont d’Urville, and 720 km north east of the Russian Vostok Station. Detailed GPS surface topography and airborne radar surveys were conducted in 1994-1995 in order to optimize the choice for the drilling location (Rémy and Tabacco, 2000; Tabacco et al., 1998). These provided clear features of the bedrock and surface topography, showing a set of north-south-trending parallel valleys around 20 km wide and 200-400 meters deep in the bedrock, corresponding to smooth elongated undulations a few meters high at the surface.

A final drilling depth of 3259.72m was reached in December 2004, about 15 meters above the ice-bedrock interface (to prevent from eventually making contact with subglacial meltwaters). The ice temperature was -3°C at 3235m and a simple extrapolation to the bottom indicates that the melting point should be reached at the interface (Lefebvre et al., 2008). The top ca. 3200m of the EDC ice core have already been extensively studied and provided a full suite of climatic and environmental data over the last 8 climatic cycles (e.g. Delmonte et al., 2008, Durand et al., 2008, EPICA Community members, 2004, Jouzel et al., 2007, Lambert et al., 2008, Loulergue et al., 2008, Lüthi et al., 2008, Wolff et al., 2006). Raisbeck et al. (2006) ~~have~~ confirmed the

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old age of the deep EDC ice by presenting evidence for enhanced ^{10}Be deposition in the ice at 3160-3170m (corresponding to the 775-786 kyr interval in the EDC2 time scale) consistent with the age and duration of the Matuyama-Brunhes geomagnetic reversal. A coherent interpretation of CO_2 and CH_4 profiles (Lüthi et al., 2008, Loulergue et al., 2008) ~~has~~ also established the presence of Marine Ice Stages (MIS) 18 (ca. 739-767 kyr BP) and 19 (ca. 767-790 kyr BP). However, a detailed study of the isotopic composition of O_2 and its relationship to daily northern hemisphere summer insolation and comparison to marine sediment records ~~has shown~~showed potentially anomalous flow in the lowermost ~~bottom~~ 500m of the core with associated distortion of the EDC2 time scale by a factor of up to 2. This ~~has~~ led to the construction of the new, currently used, EDC3 timescale (Parrenin et al., 2007). Note that efforts are still ongoing to refine this timescale, combining multi-site data sets and using $\delta^{18}O_{atm}$ and O_2/N_2 as proxies for orbital tuning (Landais et al., 2012; Bazin et al., 2013).

As described below, the bottom 60 meters of the available core acquired distinctive properties, as a result of processes driven by the proximity of the ice-bedrock interface. We will therefore, in accordance with the previous literature (e.g. Knight, 1077; Hubbard et al., 2009) refer to it as "basal ice". The last 12 meters of the available core show visible solid inclusions (Fig. 1a), which are traditionally interpreted as a sign of interactions with the bedrock. These ~~and usually qualified as "basal ice". We will therefore use that terminology here below, and reserve the term "deep ice" for the upper part of the bottom 60 meters which are the focus of this study. Solid~~ inclusions ~~within the basal ice~~ are spherical in shape, brownish to reddish in color, and generally increase both in size and density with increasing depth. They however remain evenly distributed within the ice, therefore qualifying as a “basal dispersed facies” in existing classifications (e.g. Hubbard et al., 2007). Between 3248.30 m (first occurrence of inclusion visible by eye) and 3252.15m ~~they~~ the inclusions are only sparse (0 to 10 inclusions per 55 cm ice core length) and less than 1mm in diameter. In the lower 8 meters, inclusions get bigger (up to 3 mm in the last 50 cm sample) and reach more than 20 individual inclusions per 50 cm ice core length. In several cases, especially for the bigger inclusions, these are “enclosed” in a whitish ovoid bubble-like feature (e.g. upper left corner of Fig. 1a). Careful visual examination of the texture of each individual inclusion suggests that these generally consist of a large number of smaller aggregates although individual particles also occur. In most cases, these inclusions appear to be located at crystal boundaries. A detailed study of the morphology, mineralogy and chemistry of some of these individual inclusions is described elsewhere (de Angelis et al.,2013). Finally, it should be kept in mind that these characteristics are valid for ice collected between 6 and 15 meters above the actual ice-bedrock interface. We do not, unfortunately, have any information on the properties of the ice below, the thickness of which ~~has been~~was estimated using a downhole seismometer (J. Schwander, pers. comm., 2011). The upper 48 meters of the basal ice sequence will be referred to as the “basal clean ice facies” (i.e. devoid of visible inclusions), also in line with previous work (Hubbard et al., 2007).

3. Material and Methods

The dispersed facies of the basal ice of the EDC core shows a relatively low debris content, ~~if~~ compared to the other deep ice coring sites described in previous studies

(Camp Century, GRIP, Dye-3, Vostok), and could therefore be processed ~~using “standard” procedures. It has thus been decided, for practical reasons and uniformity, to analyze the bottom ice~~ in continuity with the cutting scheme used for the EDC ice above. The multi-parametric data set discussed in this paper w~~h~~as therefore ~~been~~ obtained applying analytical techniques described in full in previous studies focusing on single parameters. We are summarizing those in the “supplementary material”, referring to the appropriate previous literature for full details.

4. The ~~deep and~~ basal ice properties: a multiparametric approach

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Figure 1 b and c plot the full δD profile of the EPICA ice core, vs. depth and age respectively (EDC3 time scale, Parrenin et al., 2007). As stated above, we will use the “~~basal~~ dispersed ice facies” terminology for the lower 12 meters (red open triangles) and qualify the 48 meters above as the “~~deep~~ clean ice facies” (blue open squares); “~~bottom~~ basal ice” will refer to the whole 60 meters sequence. A combined Vostok-EDC $\delta^{18}O_{atm}$ profile (isotopic composition of atmospheric oxygen in ice) vs. EDC3 time scale is shown in Figure 1d (adapted from Dreyfus et al., 2007, Petit et al., 1999 for the ice above 3200m). The $\delta^{18}O$ benthic record stack of Lisiecki and Raymo (2005) is also plotted as a reference in Figure 1e. The co-isotopic properties of the EPICA Dome C bottom ice (open squares for ~~deep~~ clean ice facies, open triangles for ~~basal~~ dispersed ice facies) are described in Figure 2a (δD vs. $\delta^{18}O$) and 2b (d_{excess} vs. δD) and compared to those of the ice from the last 140 ky (Stenni et al., 2010). Work in progress on the co-isotopic properties of the older ice (down to 3189.45m) shows that the latter do not differ from the trends seen in Figure 2 (B. Stenni et al., unpublished data).

Figure 3 and Table S1 summarize~~s~~ the available low resolution gas and insoluble dust concentrations data. CH_4, CO_2 and N_2O are covered for both the ~~deep~~ clean (squares in Fig. 3a) and ~~basal~~ dispersed (triangles in Fig. 3a) ~~sections~~ facies while total gas content (grey dots in Fig. 3a) is only available for the ~~deep~~ clean ice ~~section~~facies. The full concentrations ranges observed for CH_4 (Loulergue et al., 2008),CO_2 (Lüthi et al., 2008), N_2O (Schilt et al. 2010) and total gas content (Raynaud et al., 2007) during the preceding climatic cycles are also shown for reference, as white, black, light grey and dark grey vertical bars respectively. The limited number of dust concentration measurements available is shown in Figure 3b (same symbols as above) and also compared to the full range of values observed during the previous climatic cycles (black vertical bar, Delmonte et al., 2008)).

~~Deep~~ Clean and dispersed basal ice facies ~~ice~~ concentrations of selected chemical species (MSA, SO_4, Ca, Mg, Na, K, Cl, NO_3) are presented in two complementary ways, ~~respectively~~ in Figures 4 and 5. In Figure 4 high-resolution (1.5 to 5 cm) profiles of discrete sections in the ~~deep~~ clean (open squares) and ~~basal~~ dispersed (open triangles) ~~ice~~ facies are shown, along with the 5-8 cm resolution profile in the ice above 3200m (black dots, courtesy of the EPICA Chemistry Consortium). In Figure 5, the same data set ~~has been~~is re-arranged as a simple frequency distribution within bins of 5 or 1 ngg^{-1} depending on the species. ~~Deep ice~~Clean facies is plotted as open squares on thick solid line and ~~basal ice~~dispersed facies as open triangles on thick dotted line. All data from preceding "full glacial" intervals (i.e. excluding interglacials and complete transitions) are plotted as a background in thin grey lines with incremented symbols (see caption in upper left graph for MSA). Table 1 summarizes the data set used in

Figure 5 in terms of concentration means and 1σ values, with the depth and isotopic ranges associated to each time interval chosen. The “full glacial” intervals ~~have~~ ~~been~~were selected on careful analysis of the δD data set, keeping for each glacial period the samples with the lowest values and using the location of increasing isotopic gradient with depth as a cutting point on both sides. We discuss in the supplementary material section why we believe we can compare the results from these various groups of samples shown in Figure 5 and Table 1, despite the fact that they cover different time windows.

Finally, Figure 6 plots the mean equivalent crystal radii for the deep and basal ice, as obtained from preliminary measurements in the field, and compare those to measurements using Automatic Ice Texture Analyzers as described in Durand et al. (2009). Reliable measurement of crystals radii in the bottom ice using automatic techniques is hampered by the very large increase of crystal sizes, often spanning several individual thin sections. Only “unconventional” measurements such as e.g. sonic logging (still in development) might allow us to document these properties further in the future.

5. Discussion

5.1. ~~Clues for~~Indicators of an “undisturbed” paleoclimatic record

In this first section of the discussion, we will demonstrate that some of the ~~deep~~ clean and ~~basal~~ dispersed basal ice facies properties appear coherent with a climatic signature unmodified by large scale refreezing processes. As shown in Figure 1b,c both the ~~deep~~ clean and ~~basal~~ dispersed ice facies display δD values typical of a mild to cold glacial period, with respective ranges of -427.7 to -442.5 ‰ and -436.7 to -443.2 ‰ (Table 1), as would be expected for MIS 20 based on more recent glacials. In the co-isotopic δD-$\delta^{18}O$ diagram of Figure 2a, all samples align well with those from the previous climatic cycles, with a slope of 8.5, close to the value of 8.2 for the samples above 3200m, i.e. in accordance with a meteoric Water Line. This is very different from the refrozen Vostok lake ice, where the samples were shown to be clearly located on a freezing slope of 4.9, only slightly higher than the theoretical slope calculated from the estimated lake water isotopic value (Souchez et al., 2002a). Also, the d_{excess} values shown in Figure 2b are within the range of those observed in the more recent glacials, while refreezing processes are known to lower the deuterium excess values (Souchez et al., 2002a, Souchez and Lorrain, 1991). These are first arguments to preclude large scale refreezing as a plausible process for the bottom ice formation.

The gas properties of the bottom ice are probably even more ~~convincing~~ indicative of a true climatic signature (Fig. 3a). The total gas content is very stable with a mean value at 0.088 $ml_{air}g^{-1}{}_{ice}$, which ~~happens to be~~is identical to the one obtained for the whole 0-400 ky interval further up in the core (Raynaud et al., 2007). CH_4, N_2O and CO_2 concentrations are also quite stable and typical of mild to full glacial conditions (mean values of respectively 417 ppbv, 247 ppbv and 193 ppmv). $\delta O_2/N_2$ (Table S1) are also typical of meteoric ice with values similar to those described in Landais et al. (2012, their Figure 1, -25°C values). They show no sign of alteration from potential solubility fractionation, as would be expected in the case of significant melting-refreezing processes. Although they show much larger variations, most of insoluble dust concentrations also typically lie within the boundaries of a full glacial state (Fig. 3b).

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Table 1 gives the mean concentration values of the considered suite of chemical species. A systematic comparison of the mean ~~deep~~ clean ~~ice~~ and ~~bottom~~ dispersed ice ~~mean~~ facies values to those of each of the previous full glacial episodes (with similar δD ranges) shows a very ~~good~~ close compatibility, further suggesting that the mean paleoclimatic signal ~~has~~ was not ~~been~~ modified in the vicinity of the ice-bedrock interface. Indeed, any large-scale regelation process of meteoric ice meltwater would induce significant departure of the chemical composition (both in terms of total impurity content and of chemical speciation) of the refrozen ice from the initial values present in the meteoric ice. De Angelis et al. (2005, 2004) ~~have shown~~showed that, in the case of refreezing of the Lake Vostok water, away from any sediment source (their ice type 2), the concentrations were significantly lower than those in meteoric ice, in accordance with the efficient rejection of impurities during freezing at very low rates. Conversely, the upper part of the Vostok lake ice, that is thought to have accreted in a shallow bay upstream of Vostok (ice type 1), shows a total ionic content 5 to 50 times higher than meteoric ice, with a specific signature suggesting contamination from salts originating from deeper sedimentary strata, close to evaporites in composition. Neither of these two signatures are seen in the EDC bottom ice samples.

5.2. ~~Clues for~~Indicators of a “disturbed” paleoclimatic record

There are however some features of the bottom ice that raise questions about its paleoclimatic significance. First of all, as stated above, the presence of visible solid inclusions aggregates in the lower 12 meters could be the result of incorporation processes of sedimentary material at the ice-bedrock interface (Boulton, 1979, , 1996, Cuffey et al., 2000, Gow et al., 1979, Gow and Meese, 1996, Herron and Langway, 1979, Holdsworth, 1974, Iverson, 1993, Iverson and Semmens, 1995, Knight, 1997, Koerner and Fisher, 1979, Souchez et al., 1988, Souchez et al., 2000b, Tison and Lorrain, 1987, Tison et al., 1993, Tison et al., 1989). Then, comparison of Figure 1c and 1e reveals a strong discrepancy between the EDC δD record and the benthic record stack of Lisiecki and Raimo (2005) prior to 800 ky, with the lack of MIS21 in the EDC profile which, instead, displays an unusually long glacial period. Furthermore, the $\delta^{18}O_{atm}$ profile of Figure 1d is also somewhat peculiar, in two ways: first it is extremely stable in the bottom ice despite known large fluctuations in the precession and ice volume at the time, to which the $\delta^{18}O_{atm}$ ~~has~~ was ~~been~~ shown to be very sensitive (Bender, 2002, Dreyfus et al., 2007, Landais et al., 2010), and, second, it displays values continuously close to 0‰, which is generally (but not strictly) more typical of full interglacial rather than full glacial conditions.

Finally, although generally coherent with the previous climatic cycles in terms of mean concentration values, individual chemical species can be ~~regrouped in~~considered as two ~~pools~~ groups with specific and contrasted chemical distribution (Figure 4 and 5, Table 1). MSA, SO_4, Ca and Mg, on the one hand, clearly show increased variability, both in the ~~deep~~ clean and ~~basal~~ dispersed ice facies (see left column of Fig. 4 and 1σ values in Table 1), a trend that seems to initiate in MIS18 already. The frequency distributions in Figure 5 confirm this variability as compared to previous glacials, with a tendency of both skewing towards lower values for MSA, SO_4 or Mg and showing outliers at higher concentration, especially in the ~~deep~~ clean ice facies. On the other hand, Na, K, Cl, and NO_3 behave noticeably differently in the ~~deep~~ clean ice and in the

~~basal~~ dispersed ice facies (right column in Figure 4). The ~~deep~~ clean ice facies (solid line) shows very low variability and narrow frequency peaks in the graphs of Figure 5, while the ~~basal~~ dispersed ice facies (dotted line) behaves similarly to the previous glacial, but with a tendency of skewing towards the higher range of concentrations.

5.3. Distribution and relocation ~~Mechanisms for~~of dissolved and solid impurities ~~distribution and relocation~~ within ice cores

Ohno et al. (2005) discussed the location and chemical forms of water-soluble ~~impurities~~ salts in ice cores. Initially entrapped in-between the snow grains that will evolve into firn and then ice under increasing metamorphism, these impurities could therefore be found either within the ice crystals themselves, or within the unfrozen liquid that separates the grain boundaries as a result of “premelting” (Rempel et al., 2001, Rempel et al., 2002, Wettlaufer, 1999), be it veins, nodes or triple junctions. A common view amongst glaciologists is that because those impurities produce strain-energy within ice grains and because trace acids must exist as acid solutions given their very low eutectic point, they will progressively be forced into grain boundaries as grain growth and recrystallization occur (Glen et al., 1977, Rempel, 2003, Rempel et al., 2001, Rempel et al., 2002, Wettlaufer, 1999). Although most of the sulfur atoms present as sulfuric acid in Antarctic ice samples were observed at triple junctions of grain boundaries in the early days of scanning electron measurements in ice (Mulvaney et al., 1988), there has been growing evidence that sulfur compounds also exist as sulfate trapped as inclusions within grains (e.g. Baker and Cullen, 2003). Ohno et al. (2005), using micro-Raman spectroscopy, underline that at shallow depth (185m) in the Dome

Fuji ice core, the fraction of SO_4^{2-} existing as salts within the micro-inclusions exceeded 50% of the total SO_4^{2-}. Similar fraction values between 30% and 60% were found for Na^+, Ca^{2+} and Mg^{2+} in discrete samples spanning the 5.6 to 87.8 ky BP interval. Relocation of impurities under increasing recrystallization, is likely to become important in the deeper part of meteoric ice cores, where the ice temperature gets closer to the pressure melting point (pmp) and the temperature gradient generally increases. One of those relocation processes, that has been intensively discussed in the recent years, is the mechanism often referred to as “anomalous diffusion” (Rempel, 2003, Rempel et al., 2001, Rempel et al., 2002). In this process, it is surmised that, as grains slowly grow and recrystallize within ice sheets, most of the impurity molecules are preferentially excluded from the solid grains and enriched in the melt. As the polycrystalline mixture of ice and premelt liquid solution flows downwards under gravity at a velocity “v”, it encounters gradual variations in temperature leading to gradients in intergranular concentrations which, in turn, drive molecular diffusion of solutes relative to the porous ice matrix. The net result is that the bulk impurity profile will move downwards at a rate that differs by a finite “anomalous velocity” v_c from the downwards velocity “v” of the ice itself. A typical modeling case study for the conditions at the location of the GRIP ice core predicts separation of the bulk-impurity profile from the contemporaneous ice by a maximum amount of about 90 cm in the bottom layers (3028m). However, Barnes and Wolff (2004) ~~however~~ suggested that the anomalous velocity calculated in Rempel’s model is largely overestimated, since the latter mainly surmises that all impurities are located at triple junctions. As underlined by these authors, if impurities transit at two-grain boundaries, then v_c would be much lower. Also, Ohno et al. (2005), as discussed above, demonstrated that ~~a fair share~~much of these impurities are distributed within the crystal itself, further potentially hampering the "anomalous diffusion" process, as recognized by Rempel (2003). Another important feature of this migration process is that the amplitude of the concentration changes should not be altered, even in the case of asynchronous initial deposition of different species with contrasted concentration levels (Rempel, 2003) . It is therefore difficult to invoke anomalous diffusion to explain the contrasts in species concentration variability observed in our bottom ice at EPICA Dome C (see 4.2.).

Another interesting process discussed by Rempel (2005), is the one in which the density difference between intercrystalline interstitial water (premelt) and ice produces a hydraulic gradient that drives a downwards liquid flow. When the temperature rises towards the glacier bed, the associated permeability increase leads to more rapid fluid transport, internal melting supplying the changing flow. Although the author shows that, in the specific case where the lower region of the glacier floats on a subglacial reservoir, a reduction in the hydraulic gradient results from surface energy effects and causes a decreasing transport rate in the lower few tens of centimeters, the process mentioned above provides a potential mechanism for downwards migration of the chemical compounds accumulated in the premelt layer as recrystallization at high temperature proceeds.

Finally, it is also worth looking at the few detailed studies on impurity distribution within the accreted lake ice of Lake Vostok (de Angelis et al., 2005, de Angelis et al., 2004). Although the form (solid vs. dissolved) and origin of these impurities might differ from those found in meteoric ice above, both ice types (bottom meteoric ice at EDC and accreted ice at Vostok) ~~have been~~were submitted to intense recrystallization at high temperatures (>-5°C), potentially involving impurity relocation. Indeed, a strong 10-fold increase of grain size is observed in the EDC bottom ice - Figure 6, and huge - several tens of cm in size- crystals are reported at Vostok (Montagnat et al., 2001). It is interesting to note that the high-resolution spatial distribution of impurities in both EDC (bottom) and Vostok (lake) ice present striking similarities. Indeed, fine-scale (1 cm) analyses of ion concentration in accreted ice samples at Vostok (e.g. Fig. 5 in de Angelis et al., 2004) show that Cl, Na, F and NO_3 have a uniform distribution throughout the samples, while SO_4, Ca and Mg are much more heterogeneous. This is clearly the behavior we ~~have~~ underlined in our EDC bottom ice (Figures 4 and 5): much higher variability in the ~~bottom~~ basal ice than in the meteoric ice above, and much higher variability for SO_4, Ca, Mg and MSA (ion absent in Vostok refrozen ice due to lake water concentration) than for Na, K, Cl and NO_3 in both the ~~deep~~ clean and dispersed basal ice ~~layers~~facies. In the case of the Vostok accreted ice, de Angelis et al. (2005) observed that Cl, Na and K are incorporated within bubble shaped structures, very likely brine micro-pockets refrozen during the core extraction, while SO_4, Ca and Mg are present in aggregates of insoluble material (initially suspended in the lake water),all impurities being originally randomly distributed within the unconsolidated frazil ice lattice. These authors then surmise that, as consolidation, grain growth and recrystallization occur at high temperature (-3°C), brine micro droplets containing soluble salt ionic species like Cl^-, Na^+ or K^+ are not relocated and remain homogeneously distributed throughout the ice lattice, while ions associated to fine solid salt particles, are excluded and gathered with other mineral particles in inclusions of increasing sizes, leading to a greater heterogeneity. Although SO_4 salts and associated species clearly could not initially exist as a suspension in lake water in the EDC case (where refreezing of a water body is inconsistent with the isotopic and gas data sets (see 4.1. above)), they may be formed through in situ chemical reactions and a similar relocation process of atmospheric inputs under recrystallization could have been at work (see 5.4. below).

5.4. Scenarios for the build-up and evolution of the EPICA deep and basal ice

5.4.1. Mixing?

We ~~have seen~~saw in the previous sections that some of the properties of the EDC bottom ice are consistent with a pristine paleoclimatic record, while others raise some suspicion. We ~~have~~ also demonstrated that significant net refreezing of a water body at the bottom of the ice sheet can be discarded. Another set of processes that ~~have been~~were shown to alter the basal ice properties is mixing or folding under enhanced deformation close to the ice-bedrock interface (Souchez, 1997, Souchez et al., 1998, Souchez et al., 1995b, Souchez et al., 2003). Among the anomalies in EDC bottom ice properties, the stability of the δD profile for an unusual period of time, if we trust the EDC time scale and compare our data to the Lisiecki and Raymo benthic record (Fig.1c, e), is probably the most prominent. Homogenization through mixing is a process that ~~has been~~was invoked by Souchez et al. (2002a, 2002b) to explain the isotopic properties of the 3400-3538m Vostok depth interval, just above the meteoric-lake ice interface. They indeed show that the δD values are there bracketed in a tight range corresponding to mean values between glacial and interglacial, and that the deuterium excess variability is also strongly reduced. This was supported by the ionic signature showing a narrow range of concentrations corresponding to ice formed under mild glacial conditions. If this was the case for the EDC bottom ice, we should expect, from the comparison of Figures 1c and 1e, that the bottom ice shows mean isotopic values between those of MIS20 and MIS21 in Figure 2b. However, the bottom ice is truly of glacial signature. Also, samples from the ~~deep and bottom~~basal ice span the whole glacial deuterium excess range.

Mixing with a local isotopic end-member inherited from a previous or initial ice sheet configuration is also unlikely. It was ~~has~~ only ~~been~~ described for basal ice condition largely below the pmp (see section 1) and generally showed~~s~~ contrasting properties between the present-day ice sheet ice and the local end-member, with a whole range of intermediate values in the mixing zone.

5.4.2. Stretching?

If mixing is therefore improbable at EDC, another mechanical way of explaining the abnormal length of MIS20 is relative vertical stretching under changing stress conditions, i.e. alteration of the stratigraphic time scale. Although, given the location chosen for the EPICA Dome C drilling, stress conditions should be (and are) essentially those of vertical uniaxial compression, Durand et al. (2008) indicate that the fabrics in layers of larger mean crystal sizes (about 6 mm) below 2850 meters show signs of dispersion of the strong single maximum (which is the rule below 1500m depth) along a weak vertical girdle. These changes might be the sign of evolving stress conditions near the bottom of the ice sheet, and were recently interpreted so, to explain anomalous flow below 2700m (Dreyfus et al., 2007) and reworking of sulphate spikes below 2800m under increased recrystallization (Traversi et al., 2006; Traversi et al., 2009).

As seen on the large scale map of the bedrock elevation in the vicinity of the EDC drilling site (Remy and Tobacco, 2000, their Figure 4), the ice core bottom location sits ~~on a bedrock “saddle”~~ at ca. 7~~5~~0 m above sea level, on the eastern flank (200-400 m a.s.l. ridge) of a major S-N trending subglacial valley, with a 400 m a.s.l. ridge 15 km across, on the western flank of the valley. The bottom of the central part of the valley is at ca. 50 meters below sea level. The next 400 meters deep subglacial valley lies about 20 km further to the East.

~~with a 400m high promontory 15 km to the West and the abrupt flank of a 400m deep valley, 20 km to the East.~~

In Figure 7, we schematically show what might be the impact of a confining bedrock topography consisting of elongated valleys about 20 km wide and 200-400 meters deep (Rémy and Tabacco, 2000) on the stress field and the ice fabric in the bottom ice of EPICA DC. As the ice sinks passed the crests of the subglacial valleys, lateral compression on the sides of the valley will progressively combine with the vertical uniaxial compression. The resulting stress field, will therefore transition from uniaxial vertical compression to longitudinal extension, as illustrated by the 3D-arrows in the central part of the drawing of Figure 7. The associated change in fabrics will be from a vertical single maximum to a vertical girdle fabric, in a plane parallel to the subglacial valley sides. This new pattern might be the one already suggested in the discretely changing fabrics described by Durand et al. (2008) below 2800 meters. Because the principal stress transverse to the subglacial valley slowly shifts from extensional to compressive, the result could be a *relative* vertical stretching of individual accumulation layers, depending on the intensity of the principal extension along the valley axis. It is however not possible, with the data at hand, to demonstrate wether this relative vertical stretching results in an absolute increase of annual layer thickness (as shown in Figure 7) or if it only results in a decrease of the thinning rate. In this configuration, one must of course consider a 3-D geometry, in which the vertically stretched ice can be moved away from the drill location. Part of it can be melted at the ice-bedrock interface where the ice is at the pressure-melting point, and the over-deepening of the longitudinal valleys seen in Figure 3 of Rémy and Tobacco (2000) could also provide an escape route for the ice.

5.4.3. Enhanced recrystallization and small scale chemical sorting

In the dynamic context described above (5.4.2), and relying on our multiparametric results, we can now propose a plausible scenario for the evolution of the properties of our ~~deep~~ clean and ~~basal~~ dispersed basal ice facies at EPICA Dome C, as illustrated in Figure 8. A changing stress field and the high temperatures, close to the pmp, will trigger sustained migration recrystallization within the bottom layers. Mean crystal size values (up to more than 10 cm) plotted in Figure 6 are undisputable proof that recrystallization is indeed very active there. This process will tend to relocate the impurities at grain boundaries and contribute to the build-up of aggregates. Note that Raisbeck et al. (2006) already invoked the formation of aggregates to explain abnormal spikes in ^{10}Be in the ~~deep~~ basal ice. Increasing water content in the premelt layer might also slowly initiate downwards density-driven migration of the water and of some of the associated impurities. This however, as our data set shows, will only be revealed in a high resolution chemistry approach, since it will not significantly affect the mean concentration values for a given climatic period, but more the frequency distribution within the observed concentration range. It will also behave differently, depending on the species. Detailed SEM and XRF micro-probe elemental analyses of individual aggregates inside the EDC dispersed basal ice facies are described elsewhere and provide further insights in the potential processes at work and environmental implications (de Angelis et al., 2013). They reveal that $CaCO_3$ and $CaSO_4$ are common within these aggregates. These compounds could then be either newly precipitated salts (as observed concentrations are compatible with saturation for e.g. $CaSO_4$ given estimated vein sizes at those ambient temperatures) or pre-existing solid particles, that were initially present inside the crystals (Ohno et al., 2005). SO_4, Ca, Mg and MSA (which can also be associated with salts, Ohno et al., 2005) mean concentrations in the ~~deep~~ clean ~~ice~~ and the dispersed basal ice facies will therefore remain within the range of other glacials, but their spatial distribution at the high-resolution scale of sampling, will show much greater variability than in meteoric ice above (Figures 4, 5 and 8-right column).

As discussed above, the other group of species (Na, Cl, K, NO_3) shows two important features in the frequency distribution of Figure 5 (right column): a) although the whole data set is spanning the range of the previous glacials, the concentration mode is lower for the ~~deep~~ clean ice facies and higher for the ~~basal~~ dispersed ice facies and b) the frequency distribution in the ~~deep~~ basal ice facies is generally single-modal and narrow, while it is bi-modal in the ~~basal~~ dispersed ice facies with the first mode in the ~~deep~~ basal ice facies range and the second mode skewed towards the high side of the range observed in other glacials. The contrast in concentration level between the ~~deep~~ clean ice facies and the ~~basal~~ dispersed ice facies could simply reflect the slightly colder conditions (thus higher impurity content) at the time ~~basal ice~~the ice of the dispersed basal facies was formed at the surface of the ice sheet, as suggested by the lower δD values compared to the ~~deep~~ clean ice facies(Fig. 1b). Although this contrast is less obvious for the first group of chemical compounds, it might have been there over-written by the invoked aggregation and new in-situ precipitation processes. Alternatively, the observed contrast in behavior of Na, Cl, K, NO_3 between the ~~deep~~ clean and ~~basal~~ dispersed ice facies might reflect the signature of the premelt migration process as theoretically put forward by Rempel (2005). These species would indeed remain in the dissolved state within the premelt layer, and eventually partly and more easily migrate downwards, resulting in the left skewing mode in the ~~deep~~ clean ice facies and the bimodal distribution in the ~~basal~~ dispersed ice facies (low concentration mode corresponding to the remaining fraction in crystals as salts micro-inclusions and high concentration mode to the fraction that migrated in the premelt). Note that the process of upwards pulling of liquid from the underlying reservoir discussed by Rempel (2005), if it exists, provides a means to prevent ~~exsudation~~ expulsion of the premelt from the basal ice, and therefore preservation of this bi-modal frequency distribution. Basal melting would potentially counteract this effect but ~~propagate~~ the two ~~zones of deep and~~ basal ice facies would then migrate upwards into the ice column. Unfortunately, as underlined before, the available data set is missing the lower 6-15 meters of the basal ice section to the ice-bedrock interface, where further arguments might have been found to (in-) validate this premelt migration hypothesis.

The large inclusions visible in the bottom 12 meters of basal ice are principally located at grain boundaries. Theoretical considerations from Alley et al. (1986, eq. 21) suggest a high velocity ice grain boundary migration regime, with decoupling of the grain boundaries from the particle aggregates, because of their relatively large sizes and very low volume fraction. However, as underlined by these authors, this is probably no more valid for the “warm” (EDC bottom) ice, in a full migration recrystallization process, where the increased water content in the vein network will favor Ostwald ripening as the temperature of the ice-impurity system rises above the melting point of the impure grain boundaries. Another feature to consider here is that the particle aggregates might also behave very differently from single particles in terms of drag force on the grain boundaries. Also, as discussed in de Angelis et al. (2013), the significant contribution of organic compounds (such as exopolymeric substances - EPS) to the impurity load might also strongly affect the inclusion/grain boundary geometrical relationships.

5.4.4. Water isotopes, gases and dust

We ~~have~~ focused until now ~~focused~~ on a plausible explanation for the peculiarities of the chemical signature of our ~~deep and~~two basal ice facies at EDC. How do the water isotopes signature, gas and dust properties fit into the proposed mechanism? Although the water co-isotopic signature of our ~~deep and~~ basal ice ~~sections~~ facies does not show large scale signs of modification, the recent work of Pol et al. (2010) suggests that it might not be the case at the crystal size scale, ~~giving~~ thereby providing some independent support to the interpretation of our chemical data set. These authors indeed used high-resolution (cm scale) δD measurements to depict abnormal isotopic diffusion which they attributed to water circulation at grain boundaries (premelt) for large crystals which ~~have~~ spent more than 200.000 years at temperatures >-10°C. The diffusion length diagnosed from the data is about twice larger (40 cm) than expected from solid state diffusion in ice, and it is also suggested that the process might start as early as in MIS 11 (Pol et al., 2011).

Why would the relocation process invoked for the chemical impurities not show up in the total air content or the CH_4 and CO_2 concentrations? First of all, it should be noted that the resolution of our gas data sets is much lower than the one we achieved for the chemical species. Also, one should remember that the gas molecules are exclusively present as clathrates at these ~~elevated~~ depths and little is known on the behavior of those during small-scale phase changes under large overburden pressures. If the glacial MIS20 “stretching” hypothesis is valid, it is not surprising to observe a stable $\delta^{18}O_{atm}$ signal. Landais and Dreyfus (2010) provide an in depth analysis of the potential drivers for the millennial and orbital variations of $\delta^{18}O_{atm}$ and show the strong impact of Northern Hemisphere monsoon activity on the observed values, in response to precessional and millennial shifts of the Intertropical Convergence Zone (ITCZ). Intervals where $\delta^{18}O_{atm}$ is close to 0‰ correspond in that context to episodes where precession favors warm northern hemisphere summers with a strong East-Asian monsoon. In Figure 1f, we ~~have~~ plotted the values for the integrated summer insolation at 30°N, for various thresholds τ, as calculated by Huybers (2006). This integrated summer insolation can be defined as the sum of the diurnal average insolation on days exceeding a specified flux threshold (τ). As can be seen from the comparison between Figures 1f and 1d, high values of $\delta^{18}O_{atm}$ concur with high integrated summer insolation associated with very high diurnal average insolation thresholds (e.g. for τ = 450 (green curve) to 500 (red curve) Wattm^{-2} in Figure 1f), which is the case for our deep basal ice sequence. This relationship in enlarged in Figure 9a, where one can clearly see that maxima in $\delta^{18}O_{atm}$ are well coupled to maxima in integrated summer insolation, to the exception of a missing peak around 750 ky. It can also be suggested that larger $\delta^{18}O$ amplitudes correspond to larger summer insolation values and vice versa, with a threshold around roughly 2 Giga-JoulesGJ. In Figure 9a we have attempted to use the synchronicity of small scale oscillations of the $\delta^{18}O_{atm}$ signal (however well above the precision of measurements - 0.015‰), to the summer insolation one (tie points 1 and 2 in Fig. 9a) to derive the amount of stretching of the deep basal ice sequence. This gives a factor of about 2, which has allowed us to reconstruct a new time scale for the deep and basal ice, assuming linear stretching also applying to the bottom ice, for which $\delta^{18}O_{atm}$ are not available. Unfortunately, this does not resolve the discrepancy with the Lisiecki and Raymo curve (Figure 9b), and suggests that the amount of stretching is probably much larger, with an initial time frame for the deep and basal ice of only about 10.000 years. To build our 60 meters of basal ice sequence in ca. 10000 years would require an "in situ" annual layer thickness of 6 mm, which is 10 times the value observed during the previous glacial, following the recently published AICC2012 climate record (Bazin et al., 2012, supplementary material). This seems too extreme, and suggests stretching might have been supplemented by other processes such as dynamical thickening in the lee of bedrock obstacles or stacking up of several glacials, with missing interglacials. The latter is however unlikely, since interglacial ice is usually harder to deform due to lower impurity content and larger crystal size (Dahl-Jensen et al., 2013). Finally, as demonstrated in de Angelis et al. (2013), the detailed analysis of individual inclusions supports the occurrence of in-situ bacterial activity. To our knowledge, it is not known so far if these might have potential impact on the $\delta^{18}O_{atm}$ of the neighbouring gas phase. It is however unlikely that it might be significant given the observed low CO_2 mixing ratio (Fig. 3a), in line with atmospheric values at glacial times. Despite the very poor resolution of the dust record in our bottom ice the large variability of the data within the glacial range could also result from our increased relocation scheme. Moreover, below 2900m, a significant shift of particle size towards large diameters is in agreement with the formation of aggregates.

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6. Conclusions

We ~~have~~ used a multiparametric approach to discuss the plausibility of recovering an unaltered paleoclimatic signature from the ~~deep and~~ basal ice of the EDC ice core. We ~~have shown~~showed that some of the data (δD values, total air content, gas composition, dust content, mean chemical species concentrations) suggest a pristine meteoric glacial signature while others (length of the glacial, $\delta^{18}0_{atm}$, visible inclusions, variability of the chemical species distribution) suggest mechanical and compositional alteration of the bottom ice. Ice stable isotopes and total air content rule out large scale refreezing processes of a water reservoir as the origin for the bottom ice. Mixing, be it internally (as in Vostok MIS11) or with a local ice remnant of previous or initial ice sheet configuration (as in GRIP and Dye-3) can be equally discarded.

Using a new high resolution data set for selected chemical species in the ~~deep and~~ basal EDC ice and remote sensing information on the general setting of the Dome C area, we propose a mechanism in which the confining bedrock topography contributes to a downwards change in the stress field from uniaxial vertical compression to longitudinal extension along the valley axis. This stress configuration change results in a potential relative vertical stretching of the ice layers, which explains the abnormal length of MIS20. Combined with an ice temperature close to the pmp it also favors rapid migration recrystallization, as witnessed by the large increase in grain size. This, in turn, induces relocation of impurities, with accumulation of newly formed salts and already existing solid particles in the premelt layer, forming aggregates. Those become visible about 12 meters above the bottom of the core and increase in size and number downwards. The basal inclusions thus mainly consist of reworked existing material, rather than representing incorporation of allocthonous material from the ice-bedrock interface. However some potential candidates for the latter (large, single, mineral inclusions) were detected in the last meter layer (de Angelis et al., 2013). Although the mean concentration values were not significantly different from those observed in the previous full glacial periods, some chemical sorting is apparent, especially for those species that are not involved in salt formation. We suggest this might result from a slow process of downwards migration of the premelt layer under the hydraulic gradient resulting from the density difference between ice and interstitial water, although the lack of data from the last 6-15 meters to the ice-bedrock interface prevents us from further validating this hypothesis. The ice isotopic and gas properties are apparently not affected by these small scale processes that however only become detectable at high-resolution sampling (sub-crystal size), where they are involved in smoothing processes. The apparent discrepancy in the $\delta^{18}O_{atm}$ signal is resolved if one considers potential stretching of a glacial time span during which precession favors warm northern hemisphere summers, as ~~has~~ happened temporarily in each of the previous glacial isotopic stages.

We conclude that the paleoclimatic signal is only marginally affected in terms of global ice properties at the bottom of EPICA Dome C, but that the time scale w~~h~~as ~~been~~ considerably distorted by mechanical stretching due to the increasing influence of the subglacial topography. It is interesting to note that MIS18 already shows signs of isotopic smoothing, chemical relocation and increased variability for the species involved in salt formation (MSA, SO_4, Mg and, in a lesser extent Ca), before the timescale (EDC3) got significantly distorted. Along the same line the anomalous flow detected below 2700m, that led to the change from the EDC2 to the EDC3 time scale, might already find its roots in this subglacial topography distortion, although possible changes in the Dome position with time need also to be considered (e.g. Urbini et al., 2008).Many interior ice divides are indeed migrating today and this could also be the case for the EDC location. Given the rough bed topography, it takes a migration of only a few ice thicknesses to change the bedrock elevation by ca. 200 meters. The basal ice may therefore have experienced vertical stretching due to flow from the bedrock ridge to the current valley position, with recent migration of the divide at the top. Today, lively discussions exist and preliminary actions are undertaken within the ice core community to select a suitable location for a new deep drilling targeting the “oldest ice” (above 1 million years old, IPICS, 2009). Our work shows that the location of the EDC ice core on the flank of a valley-type subglacial topography has considerably affected the inference of deep timescales. We conclude that the retrieving of reliable paleoclimatic signals down to a few meters from the ice-bedrock interface would probably be thinkable on a flat monotonic bedrock, for distances several times the local ice thickness, although small scale reworking of some of the proxies should be expected. It is however not clear yet why the gas content and composition is so well preserved at EDC, and not at other deep basal ice location. The presence of a liquid water layer at the interface might partly explain that discrepancy, although this could not be verified here.

Future work on the EPICA DC bottom ice will involve high resolution gas measurements in selected areas and an in-depth analysis of the crystallographic properties below 3200 meters. Hopefully, these will allow us to validate and refine the general mechanism discussed here.

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Tables

Glacial	Depth range (m)		Isotopic range (δD ‰)		MSA (ngg^{-1})		SO_4 (ngg^{-1})		Ca (ngg^{-1})		Mg (ngg^{-1})	
			min	max	mean	*s*	mean	*s*	mean	*s*	mean	*s*
MIS 2	507.7	583.5	-449.3	-432.8	**18.24**	*7.00*	**213.78**	*85.15*	**43.27**	*14.89*	**19.31**	*4.08*
MIS 4	1007.6	1042.2	-446.4	-430.5	**20.94**	*4.00*	**194.80**	*52.52*	**30.85**	*10.96*	**14.28**	*3.84*
MIS 6	1801.8	1997.0	-447.1	-419.8	**18.60**	*5.00*	**170.01**	*51.73*	**23.60**	*12.25*	**13.54**	*4.04*
MIS 8	2320.0	2398.6	-444.5	-421.5	**27.90**	*6.13*	**192.05**	*50.92*	**23.37**	*12.98*	**14.92**	*4.28*
MIS 10	2599.9	2650.0	-445.0	-425.1	**26.77**	*7.88*	**183.55**	*43.56*	**22.92**	*9.84*	**14.92**	*3.86*
MIS 12	2783.2	2794.9	-440.9	-422.5	**23.44**	*5.04*	**187.36**	*45.54*	**43.47**	*19.09*	**19.82**	*5.50*
MIS 14.2	2915.7	2919.9	-436.4	-429.3	**23.75**	*6.37*	**162.06**	*21.72*	**20.46**	*6.19*	**15.80**	*2.75*
MIS 16	3037.6	3039.8	-441.0	-412.3	**32.61**	*6.95*	**167.86**	*39.55*	**36.09**	*17.21*	**16.37**	*5.84*
MIS 18	3137.8	3153.1	-441.4	-423.7	**36.40**	*23.47*	**195.35**	*139.18*	**31.26**	*19.76*	**20.03**	*25.47*
~~Deep Ice~~Clean Facies	3201.0	3248.0	-442.5	-427.7	**21.50**	*20.32*	**150.39**	*107.98*	**29.53**	*16.87*	**11.49**	*12.48*
~~Bottom Ice~~Dispersed Facies	3248.0	3259.3	-443.2	-436.7	**25.27**	*18.43*	**139.58**	*91.46*	**42.10**	*29.44*	**16.25**	*11.23*

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Glacial	Depth range (m)		Isotopic range (δD ‰)		Na (ngg^{-1})		Cl (ngg^{-1})		NO_3 (ngg^{-1})		K (ngg^{-1})	
			min	max	mean	*s*	mean	*s*	mean	*s*	mean	*s*
MIS 2	507.7	583.5	-449.3	-432.8	**97.37**	*17.54*	**160.68**	*48.64*	**40.93**	*16.01*	**7.45**	*1.89*
MIS 4	1007.6	1042.2	-446.4	-430.5	**79.81**	*17.75*	**129.89**	*25.25*	**29.38**	*12.41*	**4.91**	*2.34*
MIS 6	1801.8	1997.0	-447.1	-419.8	**71.57**	*16.65*	**107.56**	*40.45*	**24.72**	*12.63*	**3.74**	*2.36*
MIS 8	2320.0	2398.6	-444.5	-421.5	**76.76**	*35.00*	**112.06**	*38.05*	**26.24**	*17.20*	**3.84**	*5.24*
MIS 10	2599.9	2650.0	-445.0	-425.1	**77.80**	*32.30*	**112.76**	*61.56*	**30.21**	*19.92*	**5.77**	*9.76*
MIS 12	2783.2	2794.9	-440.9	-422.5	**72.70**	*19.82*	**138.46**	*34.04*	**48.69**	*22.43*	**3.93**	*3.32*
MIS 14.2	2915.7	2919.9	-436.4	-429.3	**70.88**	*15.13*	**110.46**	*21.66*	**34.33**	*17.31*	**3.16**	*5.70*
MIS 16	3037.6	3039.8	-441.0	-412.3	**78.23**	*12.32*	**111.67**	*21.46*	**32.89**	*11.94*	**3.07**	*4.96*
MIS 18	3137.8	3153.1	-441.4	-423.7	**80.44**	*13.94*	**114.44**	*31.38*	**26.28**	*13.95*	**3.26**	*3.98*
~~Deep Ice~~Clean Facies	3201.0	3248.0	-442.5	-427.7	**71.78**	*3.79*	**99.91**	*13.39*	**29.03**	*2.42*	**1.94**	*2.40*
~~Bottom Ice~~Dispersed Facies	3248.0	3259.3	-443.2	-436.7	**93.16**	*15.43*	**141.68**	*30.42*	**46.26**	*15.37*	**2.68**	*4.17*

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Table 1: Mean concentration and 1σ values (ngg^{-1} or ppb) for selected chemical species in the ~~Deep~~ Clean and Dispersed Basal ice facies of the EPICA Dome C ice core, as compared to those of the ~~following~~ previous full glacial periods (see text for details). Depth (meters) and δD (‰) ranges are given for each time interval considered.

Figure Captions

Figure 1: a) visual appearance of the EDC basal ice in the lower meters of the core (photo: D. Dahl-Jensen), b) EDC δD_{ice} vs. depth, c) EDC δD_{ice} vs. age (EDC3 time scale extended to the ~~deep and~~ basal ice layers), d) Combined Vostok and EDC $\delta^{18}O_{atm}$ vs. age (adapted from Dreyfus et al., 2007), e) $\delta^{18}O$ vs. age for the benthic record stack of Lisiecki and Raymo (2005), and f) Integrated summer insolation for various thresholds (τ) at 30°N vs. age, as calculated by Huybers (2006). For reasons described in the text, ice below 3189.45m depth is referred to as « ~~deep~~ clean ice facies » (blue squares) and « ~~basal~~ dispersed ice facies » (red triangles) describes the ice below 3248.30m, where solid inclusions are visible.

Figure 2: a) δD_{ice} (‰) vs. $\delta^{18}O_{ice}$ (‰) and b) d (deuterium excess ‰) vs. δD_{ice} (‰) for the ~~deep~~ clean (open squares) and ~~basal~~ dispersed (open triangles) basal ice facies at EPICA Dome C, as compared to the ice from the 0-140 ky interval (black dots, Stenni et al., 2010). See text for details.

Figure 3: Gas and dust properties of the ~~deep~~ clean (squares) and ~~basal~~ dispersed (triangles) basal ice facies at EPICA Dome C: a) total gas content ($ml_{air}g_{ice}^{-1}$, dark grey), methane (ppbV, white), nitrous oxide (ppbV, light grey) and carbon dioxide (ppmV, black) - vertical bars of equivalent shading cover the full concentrations range observed for CH_4, CO_2, N_2O and total gas content during the preceding climatic cycles, b) dust concentrations (ppb) -black vertical bar covers the full concentration range during the previous climatic cycles.

Figure 4: Concentrations (in ppb or ngg^{-1}) of selected chemical species in the ~~deep~~ clean (open squares) and ~~basal~~ dispersed (open triangles) basal ice facies of the EPICA Dome C core, as compared to those of the preceding climatic cycles (black dots, courtesy of the EPICA chemical consortium). Resolution is between 5 and 8 cm above 3200m depth and between 1.5 and 5 cm in the ~~deep and~~ basal ice below 3200 m. Note the change of depth scale below 3200m.

Figure 5: Frequency distribution of concentrations (in bins of 1 or 5 ngg^{-1} or ppb) of selected chemical species in the ~~deep~~ clean (open squares - thick black solid line) and ~~basal~~ dispersed (open triangles - thick black dotted line) basal ice facies of the EPICA Dome C core, as compared to those for the preceding full glacial periods (incremented symbols and thin grey lines - courtesy of EPICA Chemistry Consortium). See text for definition of « full glacials ».

Figure 6: Mean equivalent crystals radii in the ~~deep and~~ basal ice layers of the EPICA Dome C ice core, as compared to measurements in ice above 3200m depth from Durand et al. (2007). ~~Deep and b~~Basal ice measurements are preliminary results obtained using the linear intercept technique « on site», while the data from above 3200m were obtained using Automatic Ice Texture Analyzers (AITAs - Wang and Azuma, 1999; Russell-Head and Wilson, 2001; Wilen et al., 2003).

Figure 7: Schematic illustration of the hypothesized impact of the confining bedrock topography (bedrock valleys about 20 km wide and 200-400 meters deep - from Remy and Tabacco, 2000)

on the stress regime, layer thickness and ice fabric patterns in the bottom ice of EPICA Dome C. Vertical stretching is accommodated by basal melting and/or along sub-glacial valley flow. For clarity, this illustration enhances the process so that absolute annual layer thickness increases downwards. A milder effect would only result in a decrease of the thinning rate (see text for details).

Figure 8: Sketch of potential chemical sorting effects during enhanced migration recrystallization processes under a changing stress field, close to the pressure melting point, in the deep clean and basal dispersed basal ice facies of EPICA Dome C. Processes in italic/dotted arrows are hypothetical (see text for details).

Figure 9: Attempting to reconstruct the time scale for the deep and basal ice sequence: a) Zoom on the $\delta^{18}O_{atm}$ curve vs. Integrated summer insolation at 30°N (see Fig. 1e) and b) Comparison of the benthic $\delta^{18}O$ curve (open circles) to the EPICA δDice profile (black dots), where the deep and basal ice time scale has was been linearly « compressed » using tie points 1 and 2 in a) (see text for details)

Figure S1: Plot of the mean (a) and 1σ (b) values for the various chemical elements measured in each of the glacial periods considered in this study and for the Deep Clean (open squares) and Basal Dispersed (open triangles) basal ice samples as a function of the duration (in thousand years) of the « full glacial period » selected on the basis of the δD-values. Isotopic Stage 18, which is already thought to show increased variability for some of the elements, is shown as an open star. Duration is estimated from the EDC-3 time scale (Parrenin, 2007).

Supplementary Material

S1. Material and Methods

S1.1.Chemical analyses

At the LGGE (Laboratoire de Glaciologie et Géophysique de l'Environnement), preliminary discontinuous samples were rinsed in 3 successive baths of ultrapure water. This decontamination procedure has been proved to be the most efficient even for organic traces in Antarctic ice (de Angelis et al., 2012) but is not suitable for high resolution sampling. Ice lamellae devoted to high resolution studies (both at LGGE and British Antarctic Survey - BAS) were thus decontaminated with a plane and cut into successive samples 1.5 to 2.5cm long, a dry cleaning procedure previously checked and intensively used for analyzing mineral ions in Antarctic firn and ice cores (Littot et al.,2002) . Concentrations were determined by ionic chromatography (IC) with a typical analytical uncertainty varying from 1 to 5%.

S1.2 Water Isotopes

Measurements of the EDC δD and δ^{18}O were conducted on continuous ‘‘bag samples’’ with a depth resolution of 0.55 m, using classical isotope ratio mass spectrometry (IRMS) techniques. The δD measurements were performed in France at Laboratoire des Sciences du Climat et l'Environnement (LSCE) using an automatic injection device and the uranium reduction technique, with a precision of 0.5 per mil. The δ^{18}O measurements of the whole core up to 3189.45 m were performed in Italy at the Department of Earth Sciences of the University of Parma (DST) and at the Department of Mathematics and Geosciences of the University of Trieste (DMG) using the CO_2-water equilibration technique and with a precision of 0.05 per mil. The δ^{18}O measurements of the bottom part have been conducted in Denmark at the Centre for Ice and Climate in Copenhagen using the CO_2-water equilibration technique. The data are reported against VSMOW values. Inter-comparison of reference waters among the involved laboratories were conducted over the analysis period and the same water standard was used in both LSCE and DST/DMG laboratories.

S1.3 Total gas content, Gas Mixing ratios and isotopes

The measurements of the total gas content have been performed at LGGE using an original barometrical method implemented with an experimental setup called STAN (Lipenkov et al., 1995). This technique allows a precise evaluation of the pressure and temperature of the air extracted from an ice sample having a mass of 20-30 g by its melting-refreezing under vacuum in a volume-calibrated cell. After correction of the measured pressure for the partial pressure of saturated water vapour and of the calibrated volume for the volume occupied by refrozen bubble free ice, the gas content *V* is calculated using the ideal gas law. The *V* values are then corrected for gas loss from air inclusions (i.e. gas hydrates and relaxation features such as gas cavities at depths under consideration) cut at the surface of the sample (Martinerie et al., 1990). The absolute precision of the STAN measurements has been estimated to be within ±0.6%. However the overall error of obtained *V* values amounts 1% because of the uncertainties in the cut-bubble correction. The replication of the results estimated by repeated measurements in the same horizontal slice of an ice core has been confirmed to be better than 1%.

For CO_2 measurements at the University of Bern, ice samples of about 7 g were pulverized in a cooled and evacuated vacuum chamber using a needle cracker principle. After this dry extraction process, the extracted air was expanded from the vacuum chamber into an infrared laser spectrometer which is used to derive the CO_2 concentration. At the LGGE about 40g of ice were pulverized in a cooled vacuum chamber using a ball mill principle. In this system the extracted air is transferred into a GC in order to derive the CO_2 concentration. A more detailed description of the systems used in Bern and at the LGGE is found in Siegenthaler et al. (2005) and Barnola et al. (1987), respectively. The CO_2 data set shown in this paper has a resolution of about 2.2 m and a precision of 1.6 - 2 ppmv (corresponding to mean Bern and LGGE precision, respectively), whereas up to 8 replicate measurements were performed.

For CH_4 and N_2O measurements, ice samples of about 40 g (University of Bern) or 50 g (LGGE) were melted in sealed and evacuated glass containers. After refreezing of the samples the extracted ancient air is injected into a sampling loop and analyzed by gas chromatography. The gas chromatographs are equipped with a thermal conductivity detector (TCD, for total air amount),a flame ionization detector (FID, for CH_4), and an electron capture detector (ECD) for N_2O (University of Bern only). A detailed description of this melt-refreezing method and the measurement systems can be found in Flückiger et al. (2004) and Chappellaz et al. (1997). The precision of the CH_4 and N_2O measurements is 10 and 5.6 ppbV respectively. Note that the N_2O measurements are potentially affected by in-situ production in the ice leading to elevated values (see Schilt et al., 2010). The mean resolution of the CH_4 and N_2O measurements for the depth interval 3191 to 3259 m is 1.4 and 2.1 m, respectively.

The composition of the oxygen 18 in entrapped air, which gives access to the isotopic composition of the atmosphere,$\delta^{18}O_{atm}$, has been measured at LSCE using the melt-freezing method for air extraction followed by mass-spectrometry measurement as described in Landais et al. (2003) and Dreyfus (2008). The measurement precision for the 2004-2005 dataset is 0.02 ‰ (pooled standard deviation).

S1.4 Crystal size

Crystal sizes in the basal ice were determined in the field, using a simple version of the linear intercept method (Pickering, 1976). In this method, the number (N) of grain boundaries crossed by a random linear traverse of length (N) across the thin section is averaged over many traverses. The mean grain diameter (d) is then estimated as $d = \bar{N}/\bar{L}$. At NEEM, crystals with cross sections up to 40 cm were observed, with occasional bands of smaller crystals. We therefore simply counted the amount of crystals along a center line of a 3mm thick slab observed through polarized light, and divided by the length of the core (55cm).

S1.5 Dust

At the LGGE), a set of 24 discontinuous 7-cm long samples was selected. Ice was decontaminated through 3 successive baths of ultrapure water. Insoluble dust concentration and size distribution measurements were performed by Coulter Counter Multisizer IIe in a clean room setting. Each data represents the average of three consecutive measurements performed following ultrasonic treatment. A density of 2,5 g/cm^3 was assumed for all particles in agreement with earlier studies. Analytical procedure followed in this study is identical to that described in Lambert et al. (2008).

S2. Validity of the comparison between previous “full glacial” periods and the Clean and Dispersed basal ice facies

As discussed in section 3, we have chosen to compare the chemistry of the Clean and Dispersed basal ice facies to the one of the previous glacial climatic episodes, showing minimum δD values. To achieve this, we have selected these successive “full glacial” episodes by isolating in the δD data set the periods with minimal values, using locations of increasing δ-gradients as cutting points on both sides. Table 1 shows that the δD ranges obtained for the various selected periods are quite similar. However, these various glacial episodes obviously cover different depth and time intervals. Before we discuss and compare the mean values and the variability between those groups and the Clean and Dispersed basal ice facies, it is essential to show that no artificial “time smoothing” is induced by the methodology. For example, one might expect that, depending on the resolution of the data set, increasing the time window at a given resolution would damp the variability. In figure S1, we have plotted, for each chemical species considered and for each group of samples, their mean (Fig. S1a) and 1σ (Fig. S1b) value as a function of the duration of the period, based on the EDC-3 time scale (Parrenin, 2007, extended for the basal ice layer). Although there is some variability, no clear trend of the chemical signals is seen with duration of the episodes. Furthermore, if “time smoothing” was to occur, it should result in a decrease of the variability, at a given resolution, as we go down the EDC core, which is the reverse of what is observed comparing the Clean and Dispersed basal ice facies to the “full glacial” episodes above. Finally, the contrast between the signature of different elements within the Clean or within the Dispersed basal ice facies concerns samples that are strictly from the same time window, at the same resolution, so that it is sound to discuss it.

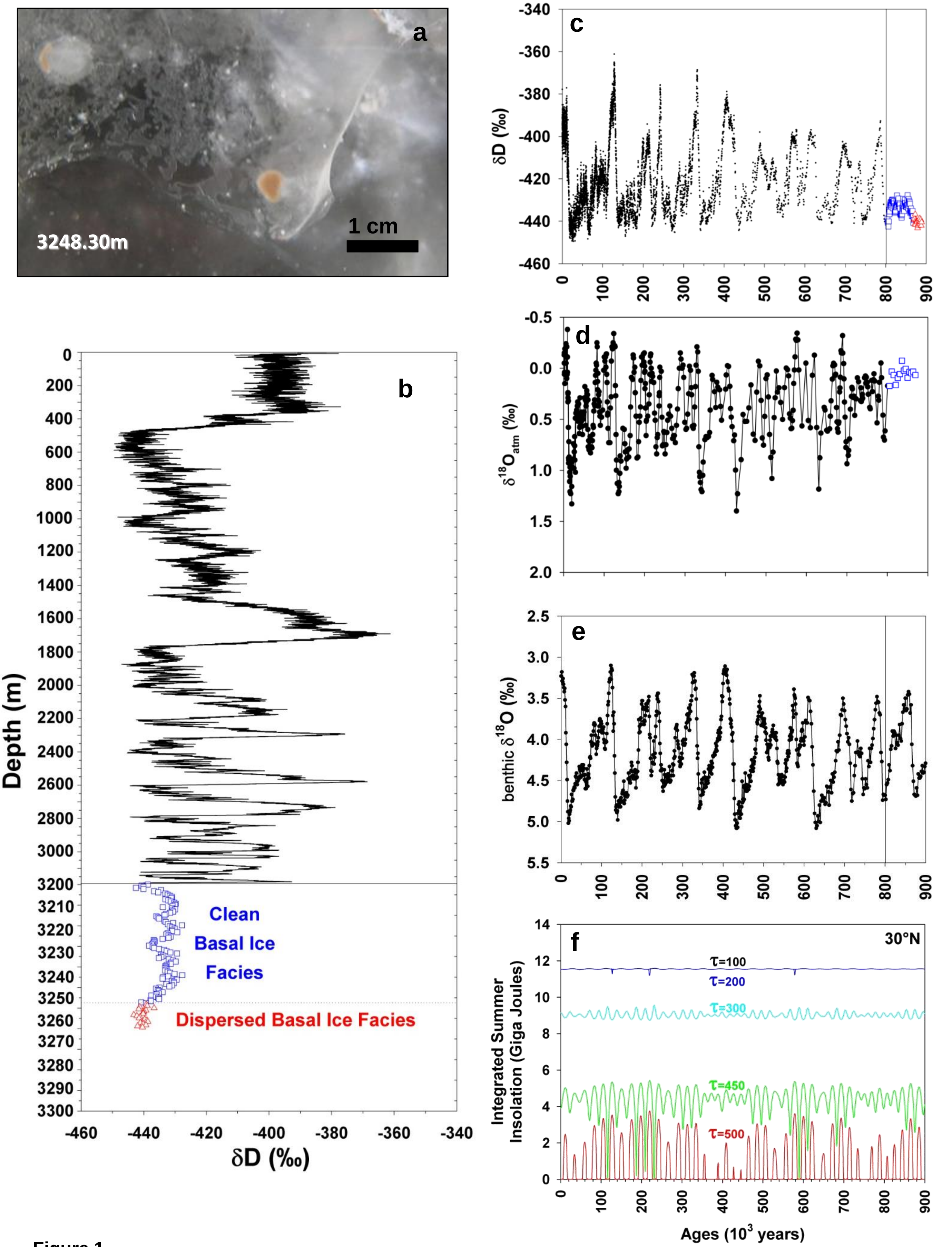
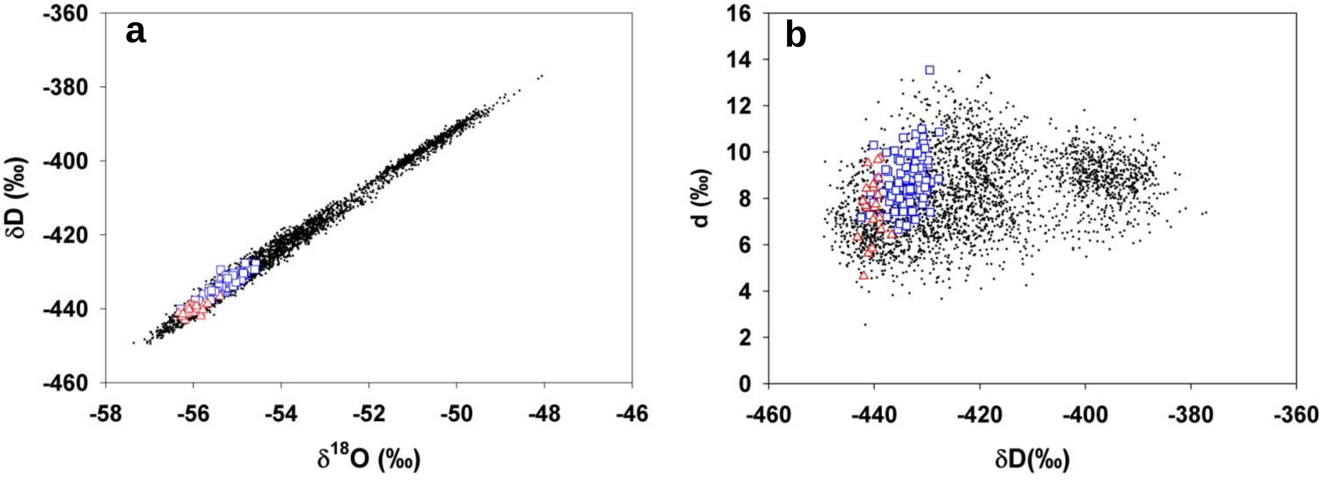
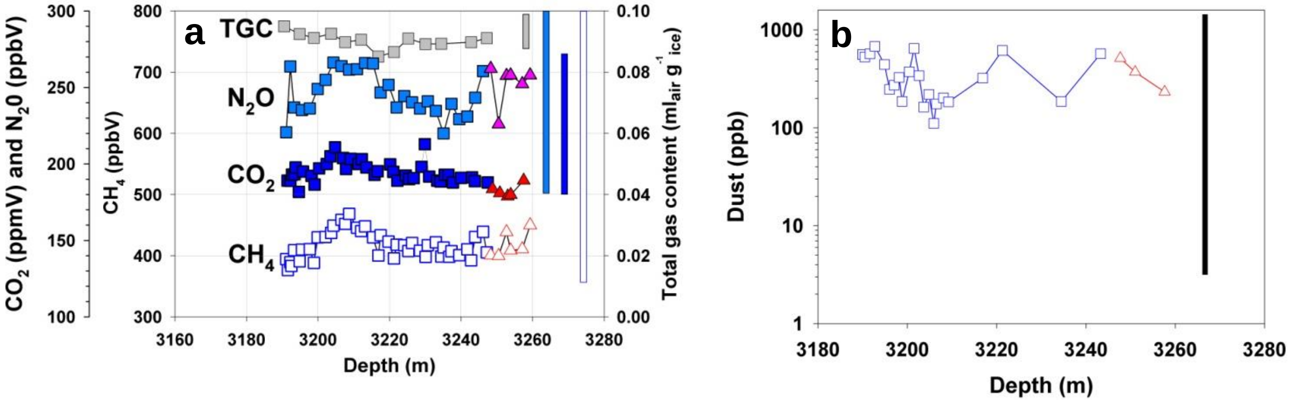

a
3248.30m
1 cm
b
Depth (m)
δD (‰)
Clean
Basal Ice
Facies
Dispersed Basal Ice Facies
c
δD (‰)
d
$\delta^{18}O_{atm}$ (‰)
e
benthic $\delta^{18}O$ (‰)
f
30°N
τ=100
τ=200
τ=300
τ=450
τ=500
Integrated Summer
Insolation (Giga Joules)
Ages (10^3 years)

Figure 1



a
-360
-380
-400
-420
-440
-460
δD (‰)
-58
-56
-54
-52
-50
-48
-46
δ18O (‰)
b
16
14
12
10
8
6
4
2
0
d (‰)
-460
-440
-420
-400
-380
-360
δD(‰)

Figure 2



a
TGC
N2O
CO2
CH4
CO2 (ppmV) and N20 (ppbV)
CH4 (ppbV)
Total gas content (ml_air g^-1 ice)
Depth (m)
b
Dust (ppb)
Depth (m)

Figure 3

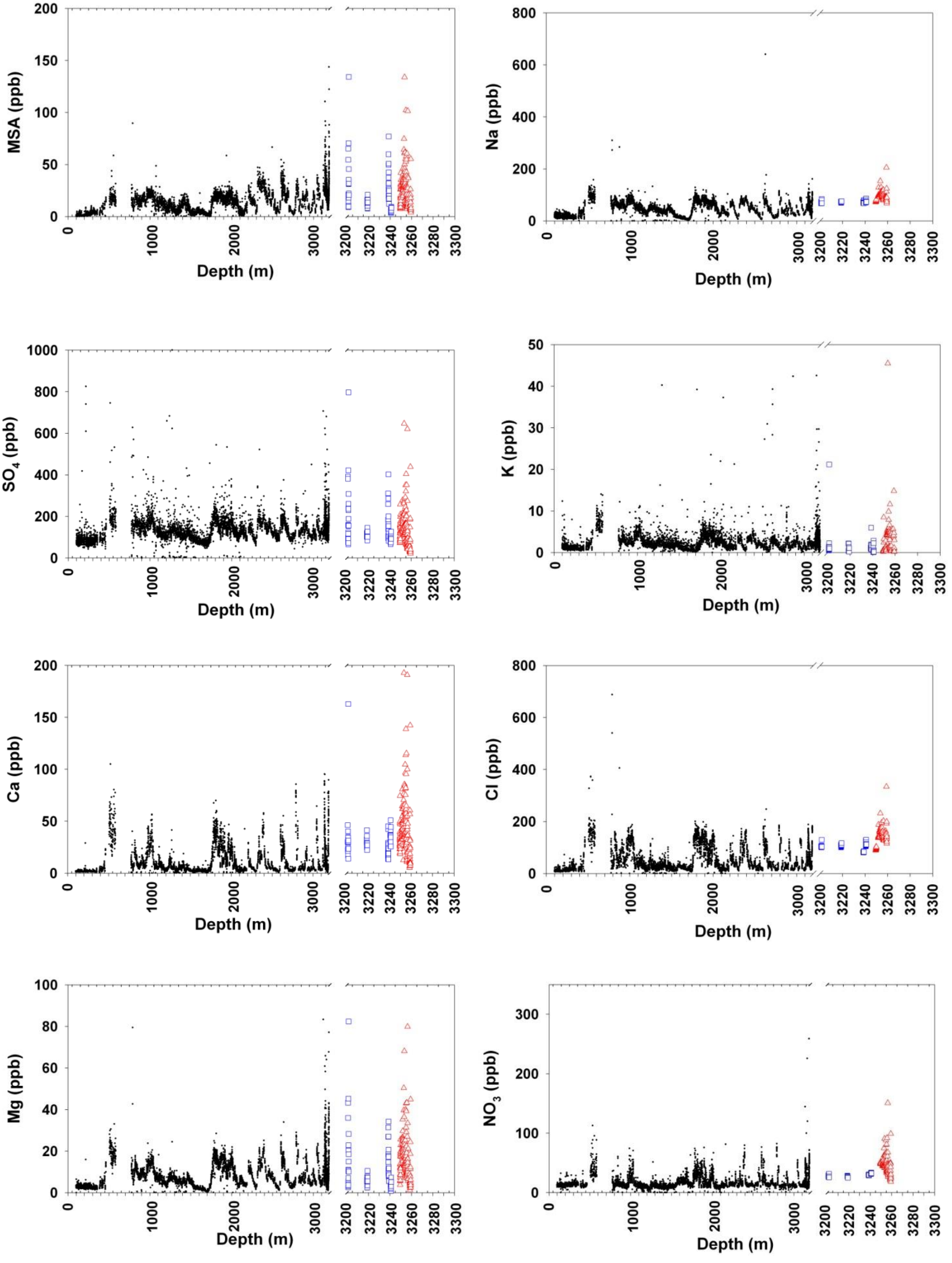


Figure 4

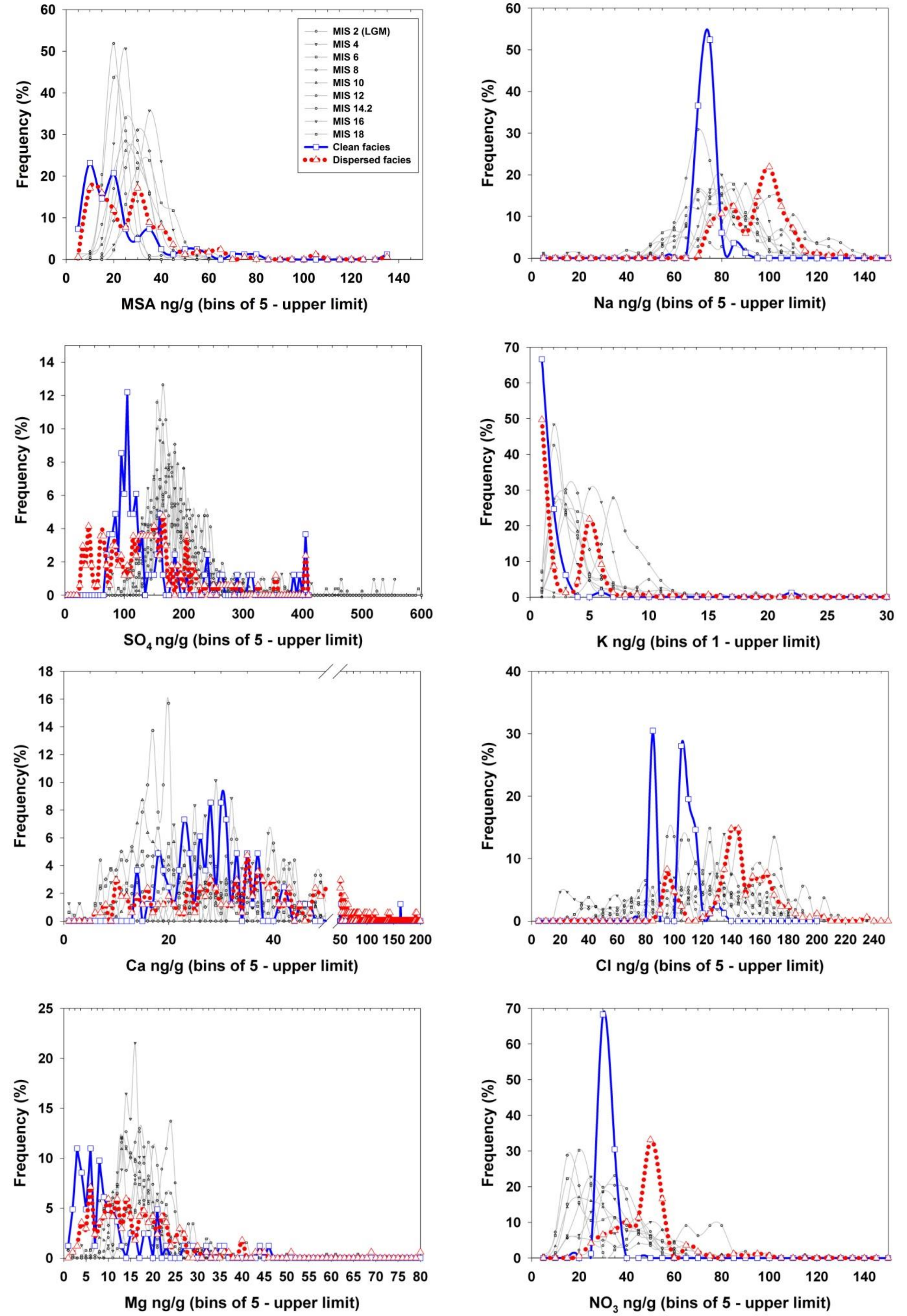

MIS 2 (LGM)
MIS 4
MIS 6
MIS 8
MIS 10
MIS 12
MIS 14.2
MIS 16
MIS 18
Clean facies
Dispersed facies
Frequency (%)
MSA ng/g (bins of 5 - upper limit)
Na ng/g (bins of 5 - upper limit)
SO4 ng/g (bins of 5 - upper limit)
K ng/g (bins of 1 - upper limit)
Frequency(%)
Ca ng/g (bins of 5 - upper limit)
Cl ng/g (bins of 5 - upper limit)
Mg ng/g (bins of 5 - upper limit)
NO3 ng/g (bins of 5 - upper limit)

Figure 5

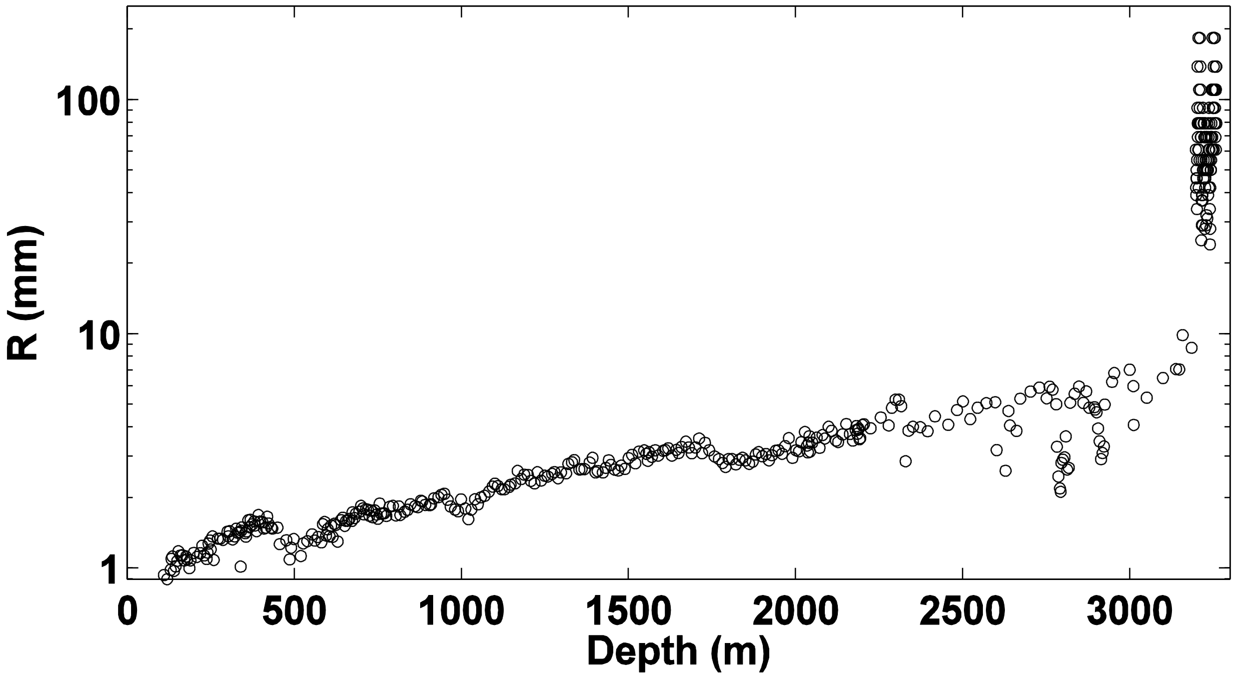


Figure 6

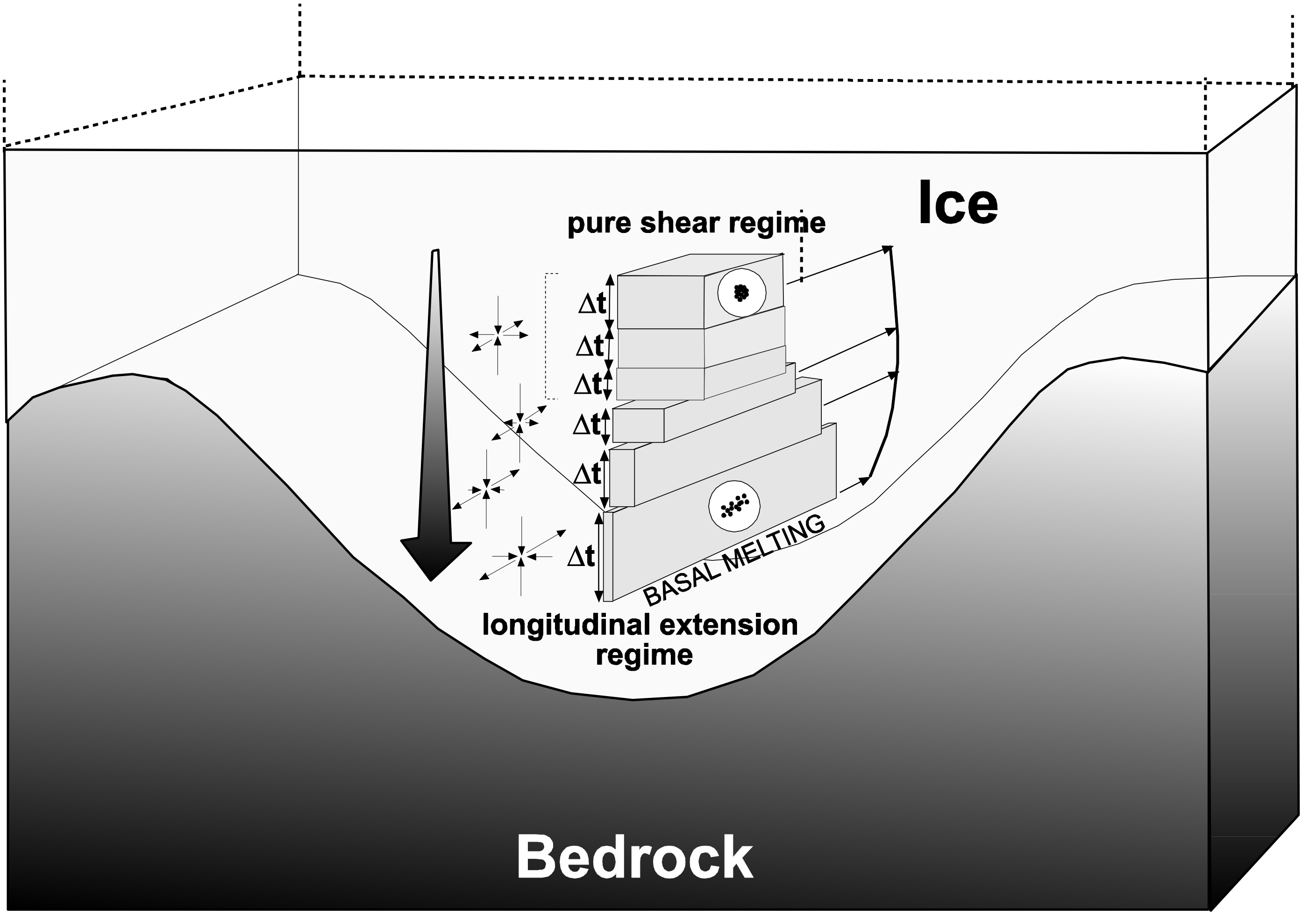
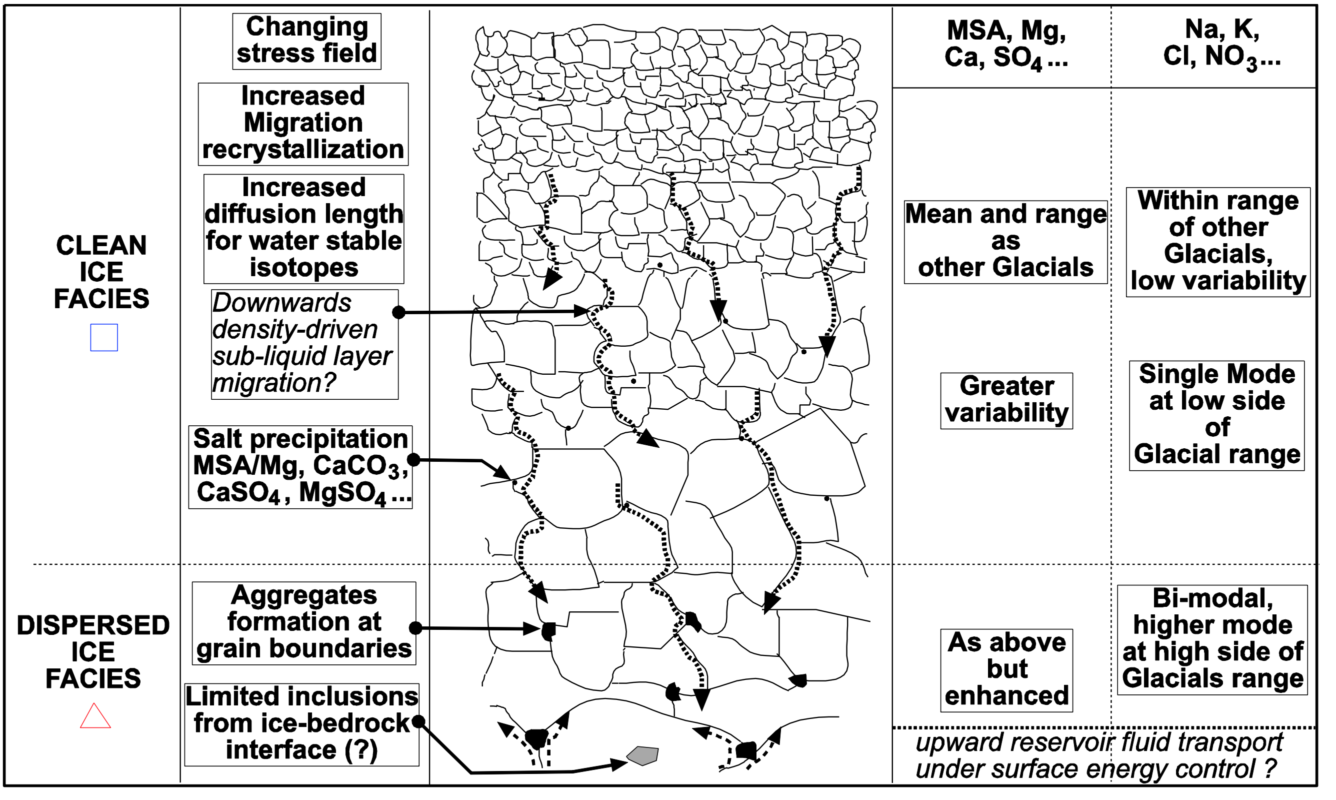

Ice
pure shear regime
Δt
Δt
Δt
Δt
Δt
Δt
BASAL MELTING
longitudinal extension regime
Bedrock

Figure 7



CLEAN
ICE
FACIES
DISPERSED
ICE
FACIES
Changing stress field
Increased Migration recrystallization
Increased diffusion length for water stable isotopes
Downwards density-driven sub-liquid layer migration?
Salt precipitation MSA/Mg, CaCO3, CaSO4, MgSO4 ...
Aggregates formation at grain boundaries
Limited inclusions from ice-bedrock interface (?)
MSA, Mg, Ca, SO4 ...
Na, K, Cl, NO3...
Mean and range as other Glacials
Within range of other Glacials, low variability
Greater variability
Single Mode at low side of Glacial range
As above but enhanced
Bi-modal, higher mode at high side of Glacials range
upward reservoir fluid transport under surface energy control ?

Figure 8

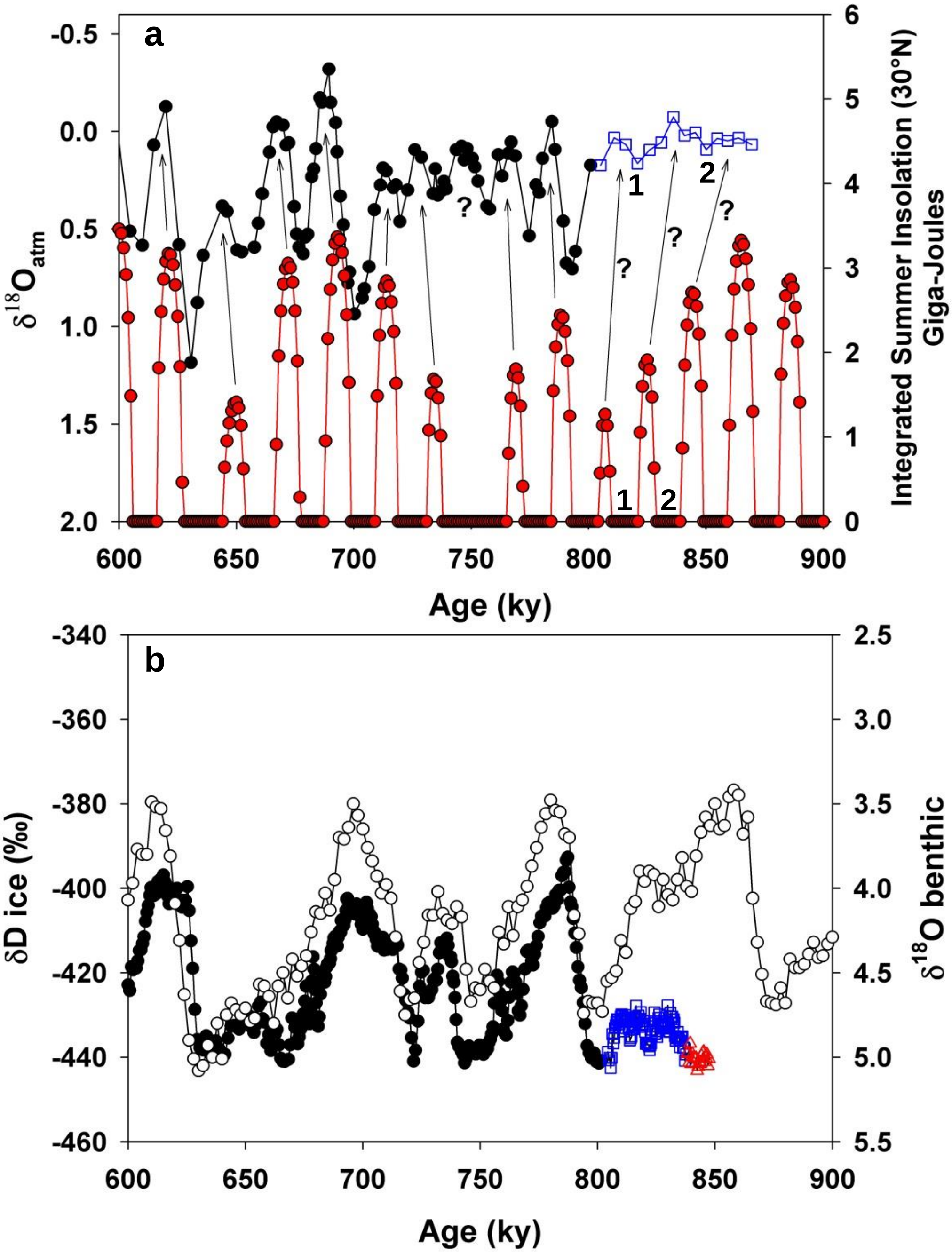

a
b
δ18Oatm
Integrated Summer Insolation (30°N) Giga-Joules
Age (ky)
δD ice (‰)
δ18O benthic
1
2
?

Figure 9

Glacial	Depth range (m)		Isotopic range (δD ‰)		MSA (ngg^{-1})		SO_4 (ngg^{-1})		Ca (ngg^{-1})		Mg (ngg^{-1})	
			min	**max**	**mean**	***σ***	**mean**	***σ***	**mean**	***σ***	**mean**	***σ***
MIS 2	507.7	583.5	-449.3	-432.8	**18.24**	*7.00*	**213.78**	*85.15*	**43.27**	*14.89*	**19.31**	*4.08*
MIS 4	1007.6	1042.2	-446.4	-430.5	**20.94**	*4.00*	**194.80**	*52.52*	**30.85**	*10.96*	**14.28**	*3.84*
MIS 6	1801.8	1997.0	-447.1	-419.8	**18.60**	*5.00*	**170.01**	*51.73*	**23.60**	*12.25*	**13.54**	*4.04*
MIS 8	2320.0	2398.6	-444.5	-421.5	**27.90**	*6.13*	**192.05**	*50.92*	**23.37**	*12.98*	**14.92**	*4.28*
MIS 10	2599.9	2650.0	-445.0	-425.1	**26.77**	*7.88*	**183.55**	*43.56*	**22.92**	*9.84*	**14.92**	*3.86*
MIS 12	2783.2	2794.9	-440.9	-422.5	**23.44**	*5.04*	**187.36**	*45.54*	**43.47**	*19.09*	**19.82**	*5.50*
MIS 14.2	2915.7	2919.9	-436.4	-429.3	**23.75**	*6.37*	**162.06**	*21.72*	**20.46**	*6.19*	**15.80**	*2.75*
MIS 16	3037.6	3039.8	-441.0	-412.3	**32.61**	*6.95*	**167.86**	*39.55*	**36.09**	*17.21*	**16.37**	*5.84*
MIS 18	3137.8	3153.1	-441.4	-423.7	**36.40**	*23.47*	**195.35**	*139.18*	**31.26**	*19.76*	**20.03**	*25.47*
Clean Ice Facies	3201.0	3248.0	-442.5	-427.7	**21.50**	*20.32*	**150.39**	*107.98*	**29.53**	*16.87*	**11.49**	*12.48*
Dispersed Ice facies	3248.0	3259.3	-443.2	-436.7	**25.27**	*18.43*	**139.58**	*91.46*	**42.10**	*29.44*	**16.25**	*11.23*

Glacial	Depth range (m)		Isotopic range (δD ‰)		Na (ngg^{-1})		Cl (ngg^{-1})		NO_3 (ngg^{-1})		K (ngg^{-1})	
			min	**max**	**mean**	***σ***	**mean**	***σ***	**mean**	***σ***	**mean**	***σ***
MIS 2	507.7	583.5	-449.3	-432.8	**97.37**	*17.54*	**160.68**	*48.64*	**40.93**	*16.01*	**7.45**	*1.89*
MIS 4	1007.6	1042.2	-446.4	-430.5	**79.81**	*17.75*	**129.89**	*25.25*	**29.38**	*12.41*	**4.91**	*2.34*
MIS 6	1801.8	1997.0	-447.1	-419.8	**71.57**	*16.65*	**107.56**	*40.45*	**24.72**	*12.63*	**3.74**	*2.36*
MIS 8	2320.0	2398.6	-444.5	-421.5	**76.76**	*35.00*	**112.06**	*38.05*	**26.24**	*17.20*	**3.84**	*5.24*
MIS 10	2599.9	2650.0	-445.0	-425.1	**77.80**	*32.30*	**112.76**	*61.56*	**30.21**	*19.92*	**5.77**	*9.76*
MIS 12	2783.2	2794.9	-440.9	-422.5	**72.70**	*19.82*	**138.46**	*34.04*	**48.69**	*22.43*	**3.93**	*3.32*
MIS 14.2	2915.7	2919.9	-436.4	-429.3	**70.88**	*15.13*	**110.46**	*21.66*	**34.33**	*17.31*	**3.16**	*5.70*
MIS 16	3037.6	3039.8	-441.0	-412.3	**78.23**	*12.32*	**111.67**	*21.46*	**32.89**	*11.94*	**3.07**	*4.96*
MIS 18	3137.8	3153.1	-441.4	-423.7	**80.44**	*13.94*	**114.44**	*31.38*	**26.28**	*13.95*	**3.26**	*3.98*
Clean Ice Facies	3201.0	3248.0	-442.5	-427.7	**71.78**	*3.79*	**99.91**	*13.39*	**29.03**	*2.42*	**1.94**	*2.40*
Dispersed Ice facies	3248.0	3259.3	-443.2	-436.7	**93.16**	*15.43*	**141.68**	*30.42*	**46.26**	*15.37*	**2.68**	*4.17*

Table 1: Mean concentration and 1σ values (ngg^{-1} or ppb) for selected chemical species in the Clean and Dispersed basal ice facies of the EPICA Dome C ice as compared to those of the previous full glacial periods (see text for details). Depth (meters) and δD (‰) ranges are given for each time interval considered.

Facies	Total gas Content		CO_2		CH_4		N_20		$\delta^{18}O_{atm}$		$\delta O_2/N_2$	
	Depth (m)	Total gas content ($ml_{air}g_{ice}^{-1}$)	Depth (m)	CO_2 (ppmV)	Depth (m)	CH_4(ppbV)	Depth(m)	N_20(ppbV)	Depth(m)	$\delta^{18}O_{atm}$		$\delta O_2/N_2$
Basal Clean	3190.53	0.10	3191.48	189.10	3191.12	394.30	3191.115	220.70	3190.54	0.17	3190.53	-10.45
	3194.89	0.09	3192.30	189.00	3191.58	376.40	3192.265	263.70	3190.54	0.25	3194.94	-8.75
	3198.88	0.09	3192.73	193.00	3192.27	389.30	3193.315	237.00	3194.94	0.03	3199.34	-12.10
	3203.68	0.09	3193.41	193.20	3192.56	383.30	3195.515	235.30	3194.94	0.05	3203.74	-15.41
	3207.63	0.09	3193.75	197.70	3193.32	409.00	3197.715	236.30	3199.34	0.01	3208.14	-16.60
	3212.08	0.09	3194.68	181.70	3194.89	390.80	3199.915	249.00	3199.34	0.14	3212.54	-10.50
	3216.89	0.09	3195.79	195.00	3195.52	410.00	3202.115	255.00	3203.74	0.17	3216.94	-10.03
	3221.26	0.09	3198.21	192.20	3197.72	410.70	3204.315	266.30	3203.74	0.18	3221.34	-5.70
	3225.28	0.09	3199.08	186.50	3198.88	388.30	3206.588	264.00	3208.14	0.06	3225.74	-9.01
	3230.09	0.09	3200.34	197.10	3199.92	430.00	3208.745	261.70	3208.14	0.15	3230.14	-6.29
	3234.49	0.09	3202.46	200.00	3202.12	430.70	3210.915	262.00	3212.54	0.05	3234.54	-6.42
	3236.70	0.06	3203.48	205.00	3203.68	437.30	3213.165	266.00	3212.54	0.08	3238.93	-9.89
	3242.83	0.09	3204.78	210.80	3204.32	449.00	3215.395	265.70	3216.94	-0.08	3243.34	-6.35
	3247.23	0.09	3207.02	203.90	3206.59	458.70	3217.515	246.70	3216.94	-0.05	3247.74	-8.84
			3207.88	196.70	3207.63	452.10	3219.715	251.70	3221.34	0.06		
			3209.18	203.30	3208.75	468.30	3221.995	237.00	3221.34	0.00		
			3211.35	199.90	3210.92	445.70	3224.115	244.30	3225.74	0.02		
			3212.28	203.10	3212.08	440.30	3226.315	240.30	3230.14	0.08		
			3213.55	197.70	3213.17	448.00	3228.515	236.30	3230.14	0.13		
			3215.83	192.90	3215.40	430.00	3230.715	241.00	3234.54	0.04		
			3216.68	195.20	3216.89	400.50	3232.945	234.70	3234.54	0.05		
			3220.18	199.70	3217.52	433.30	3235.115	220.00	3238.94	0.04		
			3221.08	194.80	3219.72	423.00	3237.315	239.30	3238.94	0.07		
			3222.19	189.10	3221.26	395.60	3239.515	229.30	3243.34	0.00		
			3224.55	192.40	3222.00	418.00	3241.755	231.00	3243.34	0.08		
			3225.48	190.10	3224.12	417.00	3243.965	243.30	3247.74	0.12		
			3226.75	190.70	3225.28	407.70	3246.145	260.70	3247.74	0.03		
			3228.98	198.10	3226.32	420.70						
			3229.88	212.90	3228.52	408.30						
			3231.13	191.70	3230.09	398.10						
			3233.37	189.10	3230.72	417.30						
			3234.28	188.60	3232.95	422.00						
			3235.45	192.90	3234.49	398.80						
			3236.48	192.90	3235.12	413.30						
			3237.74	187.90	3236.70	398.30						
			3240.01	190.90	3237.32	407.30						
			3243.08	191.20	3239.52	401.00						
			3243.89	188.80	3241.76	410.30						
			3247.48	187.90	3242.83	392.30						
					3243.97	430.70						
					3246.15	439.00						
					3247.23	405.40						
Basal Dispersed			3248.81	183.6	3248.315	400.7	3248.315	262.30				
			3250.86	180.9	3250.515	399.7	3250.515	226.00				
			3253.04	178.8	3252.715	438.7	3252.715	257.70				
			3253.9	179.8	3253.865	408.7	3253.865	258.00				
			3257.53	189.2	3257.115	410.7	3257.115	252.30				
					3259.315	450	3259.315	258.00				

Table S1: Gas composition in the EDC basal Clean and basal Dispersed facies. $\delta O_2/N_2$ values are expressed wrt. atmospheric air and corrected for gravitational effects (Landais et al., 2012).