

## **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 how the 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*

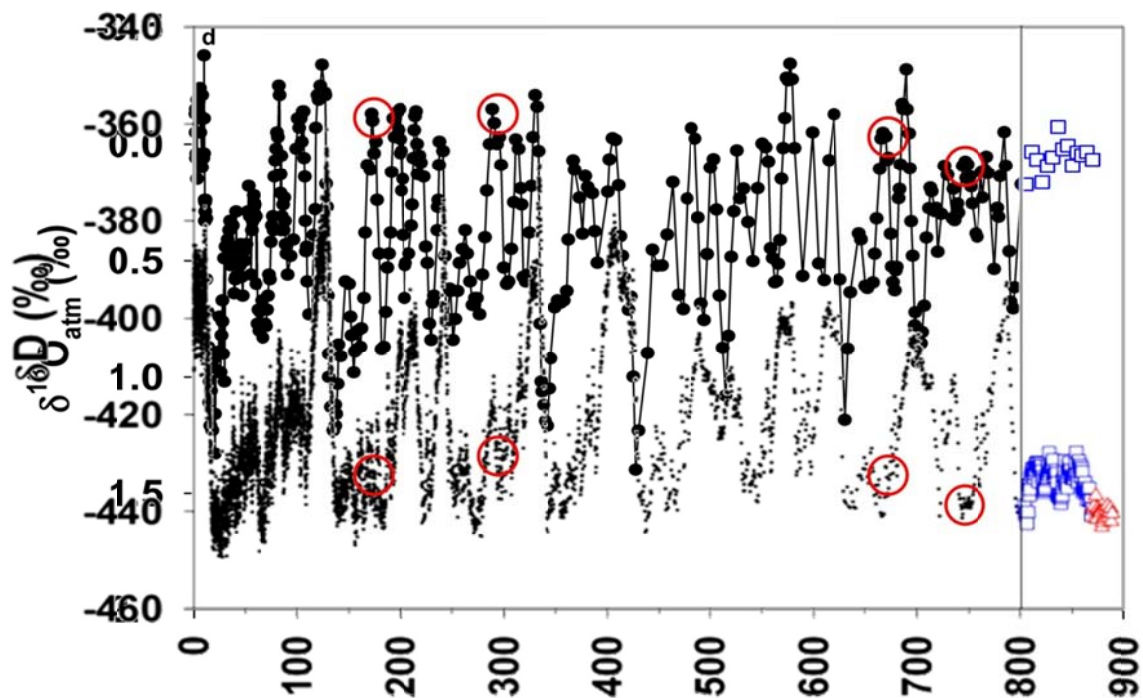
The discussion at the end of the paper describes or implies several possible scenarios for the age and age distribution of the deep and bottom ice. I think that the data only allow a single interpretation, and that is that the ice must date to a single cold climate event.

*We agree with that.!*

The interpretation rests on small cycles in the  $\delta^{18}\text{O}_{\text{atm}}$  record, each of which is attributed to an orbital cycle. Without more information, this interpretation appears plausible because the  $\delta^{18}\text{O}_{\text{atm}}$  record in the deep/bottom ice looks a lot like the record between about 700-760 ka. The similarity includes the fact that  $\delta^{18}\text{O}_{\text{atm}}$  is isotopically light when Dome C is cold.

*Yes, this is something that has disturbed us initially: isotopically light  $\delta^{18}\text{O}_{\text{atm}}$  is generally associated to interglacials or interstadials, i.e; warmer periods, which is incompatible with cold ice  $\delta^{18}\text{O}$ , as underlined by the reviewer. However, looking into it more carefully and discussing with other specialist of these  $\delta^{18}\text{O}_{\text{atm}}$  signals in ice cores, we noticed that there are exceptions to the rule stated above, with light  $\delta^{18}\text{O}_{\text{atm}}$  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 ( $\delta D$  vs. age) and Fig. 1d ( $\delta^{18}O_{atm}$ ). One can clearly see that there are multiple occasions where  $\delta^{18}O_{atm}$  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/N<sub>2</sub> and O<sub>2</sub>/N<sub>2</sub> 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 O<sub>2</sub>, and that this consumption may have affected d<sup>18</sup>O<sub>atm</sub>. However given that the CO<sub>2</sub> concentration is so low, and around the value expected based on the isotopic temperature, it is very unlikely that respiration has consumed enough O<sub>2</sub> to significantly modify the d<sup>18</sup>O<sub>atm</sub> 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 CO<sub>2</sub> 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 3 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. This 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  $\delta^{18}O_{atm}$  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*

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

3

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**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?

44 **Abstract**

45 An important share of paleoclimatic information is buried within the lowermost layers of  
46 deep ice cores. Because improving our records further back in time is one of the main  
47 challenges in the near future, it is essential to judge how deep these records remain  
48 unaltered, since the proximity of the bedrock is likely to interfere both with the recorded  
49 temporal sequence and the ice properties. In this paper, we present a multiparametric  
50 study ( $\delta D$ - $\delta^{18}O_{ice}$ ,  $\delta^{18}O_{atm}$ , total air content,  $CO_2$ ,  $CH_4$ ,  $N_2O$ , dust, high resolution  
51 chemistry, ice texture) of the bottom 60 meters of the EPICA Dome C ice core from  
52 central Antarctica. These bottom layers ~~have been subdivided in two sections: the lower  
53 12 meters showing visible solid inclusions (basal ice) and the 48 meters above which  
54 we refer to as “deep ice”.~~ were subdivided in two distinct facies: the lower 12 meters  
55 showing visible solid inclusions (basal dispersed ice facies) and the 48 meters above,  
56 which we will refer to as the “basal clean ice facies”. Some of the data are consistent  
57 with a pristine paleoclimatic signal, others show clear anomalies. It is demonstrated that  
58 neither large scale bottom refreezing of subglacial water, nor mixing (be it internal or  
59 with a local basal end-term from a previous/initial ice sheet configuration) can explain  
60 the observed bottom ice properties. We focus on the high-resolution chemical profiles  
61 and on the available remote sensing data on the subglacial topography of the site to  
62 propose a mechanism by which relative stretching of the bottom ice sheet layers is  
63 made possible, due to the progressively confining effect of subglacial valley sides. This  
64 stress field change, combined with bottom ice temperature close to the pressure melting  
65 point, induces accelerated migration recrystallization, which results in spatial chemical  
66 sorting of the impurities, depending on their state (dissolved vs. solid) and if they are

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

#### 80 **Keywords**

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

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

84 Deep ice cores retrieved from the two present-day major ice sheets on Earth,  
85 Greenland in the North and Antarctica in the South, ~~have~~ delivered a wealth of unique  
86 paleoclimatic archives over the last decades. These ~~have~~ allowed reconstruction of  
87 global climatic and environmental conditions over the last 800.000 years, including  
88 unprecedented records of cyclic changes in the composition of greenhouse gases (CO<sub>2</sub>,  
89 CH<sub>4</sub>, N<sub>2</sub>O). An important share of those paleoclimatic informations is buried within the  
90 lowermost sections of those deep ice cores, due to the mechanical thinning of annual  
91 accumulation layers with depth. Improving the records further back in time is therefore  
92 one of the main challenges of ice core science in the near future (IPICS, 2009). A major  
93 concern in this regard is to judge how far down we can trust the paleoclimatic signals  
94 stored within the ice, since the proximity of the bedrock is likely to interfere both with the  
95 recorded temporal sequence and with the ice properties. This in turn is closely linked to  
96 the thermal and hydrological regime at the bottom of the ice sheet, as ~~has been~~ shown  
97 previously in the literature describing basal layers of deep ice cores (e.g. Goodwin,  
98 1993, Gow et al., 1979, Gow and Meese, 1996, Herron and Langway, 1979, Jouzel et  
99 al., 1999, Koerner and Fisher, 1979, Souchez, 1997, Souchez et al., 1998, Souchez et  
100 al., 1995a, Souchez et al., 2006, Souchez et al., 1995b, Souchez et al., 1993b, Souchez  
101 et al., 2003, Souchez et al., 2002b, Souchez et al., 2000a, Souchez et al., 1994, Tison  
102 et al., 1998, Tison et al., 1994, Weis et al., 1997). In some cases, where the ice-bedrock  
103 interface is clearly below the pressure-melting point (pmp) as, for example, at the GRIP  
104 (-9°C) or the Dye-3 (-12°C) ice coring sites in Greenland, single or multiple mixing  
105 events between the present-day ice sheet ice and local ice remnants of previous (or

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106 even initial) ice sheet configurations are encountered (Souchez, 1997, Souchez et al.,  
107 1998, Souchez et al., 1994, Souchez et al., 2000b, Verbeke et al., 2002). Where the  
108 ice-bedrock interface is at the pmp, the meteoric ice has the potential to melt at a rate  
109 that will depend on the heat budget at the ice-bedrock interface (geothermal heat flux,  
110 internal friction and conduction through the overlying ice). In some cases, where the  
111 subglacial topography allows it, like at the Antarctic Vostok site, a subglacial lake will  
112 exist. Again, depending on the heat budget but also on the subglacial lake water  
113 circulation pattern, lake ice will form at the ice-water interface in substantial amounts  
114 (e.g. Jouzel et al., 1999, Souchez et al., 2002a, Souchez et al., 2003, Souchez et al.,  
115 2000a). This ice, evidently, does not carry paleoclimatic information. Furthermore, in the  
116 case of large subglacial lakes (such as Lake Vostok) where the ice column above can  
117 be considered in full hydrostatic equilibrium buoyancy, re-grounding of the ice sheet on  
118 the lee side of the lake will induce dynamical perturbations (such as folds), even in the  
119 meteoric ice above, as demonstrated for MIS11 (Raynaud D., 2005) and for the ice just  
120 above the accreted lake ice (Souchez et al., 2002a, Souchez et al., 2003, Souchez et  
121 al., 2002b). A less well documented case however, is the one where no significant water  
122 body exists at the ice-bedrock interface. If only melting occurs at the interface, with no  
123 water accumulation and no refreezing (as, for example at the NGRIP site in Greenland),  
124 can we then rely on the paleoclimatic information gathered in the basal layers? The  
125 EPICA Dome C ice core potentially provides us with an opportunity to investigate that  
126 specific case. In this paper, we are using a multiparametric approach, combining new  
127 and existing low resolution (50cm) data for the bottom 60 meters of ice from the EDC  
128 ice core with a new high resolution (1.5 to 8 cm) chemical data set in order to better

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129 understand the processes at work and evaluate how these might have altered the  
130 environmental archive.

## 131 **2. The EPICA Dome C ice core**

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

142 A final drilling depth of 3259.72m was reached in December 2004, about 15 meters  
143 above the ice-bedrock interface (to prevent from eventually making contact with  
144 subglacial meltwaters). The ice temperature was -3°C at 3235m and a simple  
145 extrapolation to the bottom indicates that the melting point should be reached at the  
146 interface (Lefebvre et al., 2008). The top ca. 3200m of the EDC ice core have already  
147 been extensively studied and provided a full suite of climatic and environmental data  
148 over the last 8 climatic cycles (e.g. Delmonte et al., 2008, Durand et al., 2008, EPICA  
149 Community members, 2004, Jouzel et al., 2007, Lambert et al., 2008, Loulergue et al.,  
150 2008, Lüthi et al., 2008, Wolff et al., 2006). Raisbeck et al. (2006) ~~have~~ confirmed the

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151 old age of the deep EDC ice by presenting evidence for enhanced  $^{10}\text{Be}$  deposition in the  
152 ice at 3160-3170m (corresponding to the 775-786 kyr interval in the EDC2 time scale)  
153 consistent with the age and duration of the Matuyama-Brunhes geomagnetic reversal. A  
154 coherent interpretation of  $\text{CO}_2$  and  $\text{CH}_4$  profiles (Lüthi et al., 2008, Loulergue et al.,  
155 2008) ~~has~~ also established the presence of Marine Ice Stages (MIS) 18 (ca. 739-767  
156 kyr BP) and 19 (ca. 767-790 kyr BP). However, a detailed study of the isotopic  
157 composition of  $\text{O}_2$  and its relationship to daily northern hemisphere summer insolation  
158 and comparison to marine sediment records ~~has shown~~showed potentially anomalous  
159 flow in the lower ~~most bottom~~ 500m of the core with associated distortion of the EDC2  
160 time scale by a factor of up to 2. This ~~has~~ led to the construction of the new, currently  
161 used, EDC3 timescale (Parrenin et al., 2007). Note that efforts are still ongoing to refine  
162 this timescale, combining multi-site data sets and using  $\delta^{18}\text{O}_{\text{atm}}$  and  $\text{O}_2/\text{N}_2$  as proxies for  
163 orbital tuning ( Landais et al., 2012; Bazin et al., 2013).

164 As described below, the bottom 60 meters of the available core acquired distinctive  
165 properties, as a result of processes driven by the proximity of the ice-bedrock interface.  
166 We will therefore, in accordance with the previous literature (e.g. Knight, 1077; Hubbard  
167 et al., 2009) refer to it as “basal ice”. The last 12 meters of the available core show  
168 visible solid inclusions (Fig. 1a), which are traditionally interpreted as a sign of  
169 interactions with the bedrock. ~~These and usually qualified as “basal ice”. We will~~  
170 ~~therefore use that terminology here below, and reserve the term “deep ice” for the upper~~  
171 ~~part of the bottom 60 meters which are the focus of this study. Solid inclusions within~~  
172 ~~the basal ice~~ are spherical in shape, brownish to reddish in color, and generally  
173 increase both in size and density with increasing depth. They however remain evenly

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174 distributed within the ice, therefore qualifying as a “basal dispersed facies” in existing  
175 classifications (e.g. Hubbard et al., 2007). Between 3248.30 m (first occurrence of  
176 inclusion visible by eye) and 3252.15m ~~they~~ the inclusions are only sparse (0 to 10  
177 inclusions per 55 cm ice core length) and less than 1mm in diameter. In the lower 8  
178 meters, inclusions get bigger (up to 3 mm in the last 50 cm sample) and reach more  
179 than 20 individual inclusions per 50 cm ice core length. In several cases, especially for  
180 the bigger inclusions, these are “enclosed” in a whitish ovoid bubble-like feature (e.g.  
181 upper left corner of Fig. 1a). Careful visual examination of the texture of each individual  
182 inclusion suggests that these generally consist of a large number of smaller aggregates  
183 although individual particles also occur. In most cases, these inclusions appear to be  
184 located at crystal boundaries. A detailed study of the morphology, mineralogy and  
185 chemistry of some of these individual inclusions is described elsewhere (de Angelis et  
186 al.,2013). Finally, it should be kept in mind that these characteristics are valid for ice  
187 collected between 6 and 15 meters above the actual ice-bedrock interface. We do not,  
188 unfortunately, have any information on the properties of the ice below, the thickness of  
189 which ~~has been~~ was estimated using a downhole seismometer (J. Schwander, pers.  
190 comm., 2011). The upper 48 meters of the basal ice sequence will be referred to as the  
191 “basal clean ice facies” (i.e. devoid of visible inclusions), also in line with previous work  
192 (Hubbard et al., 2007).

### 193 **3. Material and Methods**

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

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

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

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

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218 | Figure 3 [and Table S1](#) summarizes the available low resolution gas and insoluble dust  
219 | concentrations data. CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>O are covered for both the [deep-clean](#) (squares in  
220 | Fig. 3a) and [basal-dispersed](#) (triangles in Fig. 3a) [sections-facies](#) while total gas content  
221 | (grey dots in Fig. 3a) is only available for the [deep-clean](#) ice [section-facies](#). The full  
222 | concentrations ranges observed for CH<sub>4</sub> (Louergue et al., 2008), CO<sub>2</sub> (Lüthi et al.,  
223 | 2008), N<sub>2</sub>O (Schilt et al. 2010) and total gas content (Raynaud et al., 2007) during the  
224 | preceding climatic cycles are also shown for reference, as white, black, light grey and  
225 | dark grey vertical bars respectively. The limited number of dust concentration  
226 | measurements available is shown in Figure 3b (same symbols as above) and also  
227 | compared to the full range of values observed during the previous climatic cycles (black  
228 | vertical bar, Delmonte et al., 2008)).

229 | [Deep-Clean](#) and [dispersed](#) basal [ice facies](#) ~~ice~~ concentrations of selected chemical  
230 | species (MSA, SO<sub>4</sub>, Ca, Mg, Na, K, Cl, NO<sub>3</sub>) are presented in two complementary ways,  
231 | [respectively](#) in Figures 4 and 5. In Figure 4 high-resolution (1.5 to 5 cm) profiles of  
232 | discrete sections in the [deep-clean](#) (open squares) and [basal-dispersed](#) (open triangles)  
233 | ~~ice-facies~~ are shown, along with the 5-8 cm resolution profile in the ice above 3200m  
234 | (black dots, courtesy of the EPICA Chemistry Consortium). In Figure 5, the same data  
235 | set [has-been](#) re-arranged as a simple frequency distribution within bins of 5 or 1 ngg<sup>-1</sup>  
236 | depending on the species. [Deep-iceClean facies](#) is plotted as open squares on thick  
237 | solid line and [basal-icedispersed facies](#) as open triangles on thick dotted line. All data  
238 | from preceding “full glacial” intervals (i.e. excluding interglacials and complete  
239 | transitions) are plotted as a background in thin grey lines with incremented symbols  
240 | (see caption in upper left graph for MSA). Table 1 summarizes the data set used in

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

249 Finally, Figure 6 plots the mean equivalent crystal radii for the deep and basal ice, as  
250 obtained from preliminary measurements in the field, and compare those to  
251 measurements using Automatic Ice Texture Analyzers as described in Durand et al.  
252 (2009). Reliable measurement of crystals radii in the bottom ice using automatic  
253 techniques is hampered by the very large increase of crystal sizes, often spanning  
254 several individual thin sections. Only “unconventional” measurements such as e.g. sonic  
255 logging (still in development) might allow us to document these properties further in the  
256 future.

## 257 5. Discussion

258 5.1. ~~Clues for~~Indicators of an “undisturbed” paleoclimatic record

259 In this first section of the discussion, we will demonstrate that some of the ~~deep-clean~~  
260 and ~~basal-dispersed basal~~ ice facies properties appear coherent with a climatic  
261 signature unmodified by large scale refreezing processes. As shown in Figure 1b,c both  
262 the ~~deep-clean~~ and ~~basal-dispersed~~ ice facies display  $\delta D$  values typical of a mild to cold

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263 glacial period, with respective ranges of -427.7 to -442.5 ‰ and -436.7 to -443.2 ‰  
264 (Table 1), as would be expected for MIS 20 based on more recent glacials. In the co-  
265 isotopic  $\delta D$ - $\delta^{18}O$  diagram of Figure 2a, all samples align well with those from the  
266 previous climatic cycles, with a slope of 8.5, close to the value of 8.2 for the samples  
267 above 3200m, i.e. in accordance with a meteoric Water Line. This is very different from  
268 the refrozen Vostok lake ice, where the samples were shown to be clearly located on a  
269 freezing slope of 4.9, only slightly higher than the theoretical slope calculated from the  
270 estimated lake water isotopic value (Souchez et al., 2002a). Also, the  $d_{\text{excess}}$  values  
271 shown in Figure 2b are within the range of those observed in the more recent glacials,  
272 while refreezing processes are known to lower the deuterium excess values (Souchez  
273 et al., 2002a, Souchez and Lorrain, 1991). These are first arguments to preclude large  
274 scale refreezing as a plausible process for the bottom ice formation.

275 | The gas properties of the bottom ice are probably even more ~~convincing-indicative~~ of a  
276 | true climatic signature (Fig. 3a). The total gas content is very stable with a mean value  
277 | at  $0.088 \text{ ml}_{\text{air}}\text{g}^{-1}_{\text{ice}}$ , which ~~happens-to-be~~ identical to the one obtained for the whole 0-  
278 | 400 ky interval further up in the core (Raynaud et al., 2007).  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{CO}_2$   
279 | concentrations are also quite stable and typical of mild to full glacial conditions (mean  
280 | values of respectively 417 ppbv, 247 ppbv and 193 ppmv),  $\delta^{18}\text{O}_2/\text{N}_2$  (Table S1) are also  
281 | typical of meteoric ice with values similar to those described in Landais et al. (2012,  
282 | their Figure 1, -25°C values). They show no sign of alteration from potential solubility  
283 | fractionation, as would be expected in the case of significant melting-refreezing  
284 | processes. Although they show much larger variations, most of insoluble dust  
285 | concentrations also typically lie within the boundaries of a full glacial state (Fig. 3b).

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

303 5.2. ~~Clues for~~Indicators of a “disturbed” paleoclimatic record

304 There are however some features of the bottom ice that raise questions about its  
305 paleoclimatic significance. First of all, as stated above, the presence of visible solid  
306 inclusions aggregates in the lower 12 meters could be the result of incorporation  
307 processes of sedimentary material at the ice-bedrock interface (Boulton, 1979, , 1996,

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308 Cuffey et al., 2000, Gow et al., 1979, Gow and Meese, 1996, Herron and Langway,  
309 1979, Holdsworth, 1974, Iverson, 1993, Iverson and Semmens, 1995, Knight, 1997,  
310 Koerner and Fisher, 1979, Souchez et al., 1988, Souchez et al., 2000b, Tison and  
311 Lorrain, 1987, Tison et al., 1993, Tison et al., 1989). Then, comparison of Figure 1c and  
312 1e reveals a strong discrepancy between the EDC  $\delta D$  record and the benthic record  
313 stack of Lisiecki and Raimo (2005) prior to 800 ky, with the lack of MIS21 in the EDC  
314 profile which, instead, displays an unusually long glacial period. Furthermore, the  
315  $\delta^{18}O_{atm}$  profile of Figure 1d is also somewhat peculiar, in two ways: first it is extremely  
316 stable in the bottom ice despite known large fluctuations in the precession and ice  
317 volume at the time, to which the  $\delta^{18}O_{atm}$  ~~has was been~~ shown to be very sensitive  
318 (Bender, 2002, Dreyfus et al., 2007, Landais et al., 2010), and, second, it displays  
319 values continuously close to 0‰, which is generally (but not strictly) more typical of full  
320 interglacial rather than full glacial conditions.

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



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

335 | 5.3. Distribution and relocation Mechanisms for dissolved and solid impurities

336 | ~~distribution and relocation~~ within ice cores

337 | Ohno et al. (2005) discussed the location and chemical forms of water-soluble  
338 | ~~impurities-salts~~ in ice cores. Initially entrapped in-between the snow grains that will  
339 | evolve into firn and then ice under increasing metamorphism, these impurities could  
340 | therefore be found either within the ice crystals themselves, or within the unfrozen liquid  
341 | that separates the grain boundaries as a result of “premelting” (Rempel et al., 2001,  
342 | Rempel et al., 2002, Wettlaufer, 1999), be it veins, nodes or triple junctions. A common  
343 | view amongst glaciologists is that because those impurities produce strain-energy within  
344 | ice grains and because trace acids must exist as acid solutions given their very low  
345 | eutectic point, they will progressively be forced into grain boundaries as grain growth  
346 | and recrystallization occur (Glen et al., 1977, Rempel, 2003, Rempel et al., 2001,  
347 | Rempel et al., 2002, Wettlaufer, 1999). Although most of the sulfur atoms present as  
348 | sulfuric acid in Antarctic ice samples were observed at triple junctions of grain  
349 | boundaries in the early days of scanning electron measurements in ice (Mulvaney et al.,  
350 | 1988), there has been growing evidence that sulfur compounds also exist as sulfate  
351 | trapped as inclusions within grains (e.g. Baker and Cullen, 2003). Ohno et al. (2005),  
352 | using micro-Raman spectroscopy, underline that at shallow depth (185m) in the Dome

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353 Fuji ice core, the fraction of  $\text{SO}_4^{2-}$  existing as salts within the micro-inclusions exceeded  
354 50% of the total  $\text{SO}_4^{2-}$ . Similar fraction values between 30% and 60% were found for  
355  $\text{Na}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  in discrete samples spanning the 5.6 to 87.8 ky BP interval.  
356 Relocation of impurities under increasing recrystallization, is likely to become important  
357 in the deeper part of meteoric ice cores, where the ice temperature gets closer to the  
358 pressure melting point (pmp) and the temperature gradient generally increases. One of  
359 those relocation processes, that has been intensively discussed in the recent years, is  
360 the mechanism often referred to as “anomalous diffusion” (Rempel, 2003, Rempel et al.,  
361 2001, Rempel et al., 2002). In this process, it is surmised that, as grains slowly grow  
362 and recrystallize within ice sheets, most of the impurity molecules are preferentially  
363 excluded from the solid grains and enriched in the melt. As the polycrystalline mixture of  
364 ice and premelt liquid solution flows downwards under gravity at a velocity “v”, it  
365 encounters gradual variations in temperature leading to gradients in intergranular  
366 concentrations which, in turn, drive molecular diffusion of solutes relative to the porous  
367 ice matrix. The net result is that the bulk impurity profile will move downwards at a rate  
368 that differs by a finite “anomalous velocity”  $v_c$  from the downwards velocity “v” of the ice  
369 itself. A typical modeling case study for the conditions at the location of the GRIP ice  
370 core predicts separation of the bulk-impurity profile from the contemporaneous ice by a  
371 maximum amount of about 90 cm in the bottom layers (3028m). However, Barnes and  
372 Wolff (2004) ~~however~~ suggested that the anomalous velocity calculated in Rempel’s  
373 model is largely overestimated, since the latter mainly surmises that all impurities are  
374 located at triple junctions. As underlined by these authors, if impurities transit at two-  
375 grain boundaries, then  $v_c$  would be much lower. Also, Ohno et al. (2005), as discussed

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376 | above, demonstrated that ~~a fair share~~much of these impurities are distributed within the  
377 | crystal itself, further potentially hampering the “anomalous diffusion” process, as  
378 | recognized by Rempel (2003). Another important feature of this migration process is  
379 | that the amplitude of the concentration changes should not be altered, even in the case  
380 | of asynchronous initial deposition of different species with contrasted concentration  
381 | levels (Rempel, 2003) . It is therefore difficult to invoke anomalous diffusion to explain  
382 | the contrasts in species concentration variability observed in our bottom ice at EPICA  
383 | Dome C (see 4.2.).

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

395 | Finally, it is also worth looking at the few detailed studies on impurity distribution within  
396 | the accreted lake ice of Lake Vostok (de Angelis et al., 2005, de Angelis et al., 2004).  
397 | Although the form (solid vs. dissolved) and origin of these impurities might differ from  
398 | those found in meteoric ice above, both ice types (bottom meteoric ice at EDC and

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399 | accreted ice at Vostok) ~~have been~~ were submitted to intense recrystallization at high  
400 | temperatures ( $>-5^{\circ}\text{C}$ ), potentially involving impurity relocation. Indeed, a strong 10-fold  
401 | increase of grain size is observed in the EDC bottom ice - Figure 6, and huge - several  
402 | tens of cm in size- crystals are reported at Vostok (Montagnat et al., 2001). It is  
403 | interesting to note that the high-resolution spatial distribution of impurities in both EDC  
404 | (bottom) and Vostok (lake) ice present striking similarities. Indeed, fine-scale (1 cm)  
405 | analyses of ion concentration in accreted ice samples at Vostok (e.g. Fig. 5 in de  
406 | Angelis et al., 2004) show that Cl, Na, F and  $\text{NO}_3$  have a uniform distribution throughout  
407 | the samples, while  $\text{SO}_4$ , Ca and Mg are much more heterogeneous. This is clearly the  
408 | behavior we ~~have~~ underlined in our EDC bottom ice (Figures 4 and 5): much higher  
409 | variability in the ~~bottom-basal~~ ice than in the meteoric ice above, and much higher  
410 | variability for  $\text{SO}_4$ , Ca, Mg and MSA (ion absent in Vostok refrozen ice due to lake water  
411 | concentration) than for Na, K, Cl and  $\text{NO}_3$  in both the ~~deep-clean~~ and ~~dispersed~~ basal  
412 | ice ~~layers~~facies. In the case of the Vostok accreted ice, de Angelis et al. (2005)  
413 | observed that Cl, Na and K are incorporated within bubble shaped structures, very likely  
414 | brine micro-pockets refrozen during the core extraction, while  $\text{SO}_4$ , Ca and Mg are  
415 | present in aggregates of insoluble material (initially suspended in the lake water), all  
416 | impurities being originally randomly distributed within the unconsolidated frazil ice  
417 | lattice. These authors then surmise that, as consolidation, grain growth and  
418 | recrystallization occur at high temperature ( $-3^{\circ}\text{C}$ ), brine micro droplets containing  
419 | soluble ~~salt~~ ionic species like  $\text{Cl}^-$ ,  $\text{Na}^+$  or  $\text{K}^+$  are not relocated and remain  
420 | homogeneously distributed throughout the ice lattice, while ions associated to fine solid  
421 | salt particles, are excluded and gathered with other mineral particles in inclusions of

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422 increasing sizes, leading to a greater heterogeneity. Although SO<sub>4</sub> salts and associated  
423 species clearly could not initially exist as a suspension in lake water in the EDC case  
424 (where refreezing of a water body is inconsistent with the isotopic and gas data sets  
425 (see 4.1. above)), they may be formed through in situ chemical reactions and a similar  
426 relocation process of atmospheric inputs under recrystallization could have been at  
427 work (see 5.4. below).

428 5.4. Scenarios for the build-up and evolution of the EPICA deep and basal ice

429 5.4.1. *Mixing?*

430

431 | We ~~have seen~~saw in the previous sections that some of the properties of the EDC  
432 bottom ice are consistent with a pristine paleoclimatic record, while others raise some  
433 suspicion. We ~~have~~ also demonstrated that significant net refreezing of a water body at  
434 the bottom of the ice sheet can be discarded. Another set of processes that ~~have~~  
435 ~~been~~were shown to alter the basal ice properties is mixing or folding under enhanced  
436 deformation close to the ice-bedrock interface (Souchez, 1997, Souchez et al., 1998,  
437 Souchez et al., 1995b, Souchez et al., 2003). Among the anomalies in EDC bottom ice  
438 properties, the stability of the  $\delta D$  profile for an unusual period of time, if we trust the  
439 EDC time scale and compare our data to the Lisiecki and Raymo benthic record (Fig.1c,  
440 e), is probably the most prominent. Homogenization through mixing is a process that  
441 | ~~has been~~was invoked by Souchez et al. (2002a, 2002b) to explain the isotopic  
442 properties of the 3400-3538m Vostok depth interval, just above the meteoric-lake ice  
443 interface. They indeed show that the  $\delta D$  values are there bracketed in a tight range

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444 corresponding to mean values between glacial and interglacial, and that the deuterium  
445 excess variability is also strongly reduced. This was supported by the ionic signature  
446 showing a narrow range of concentrations corresponding to ice formed under mild  
447 glacial conditions. If this was the case for the EDC bottom ice, we should expect, from  
448 the comparison of Figures 1c and 1e, that the bottom ice shows mean isotopic values  
449 between those of MIS20 and MIS21 in Figure 2b. However, the bottom ice is truly of  
450 glacial signature. Also, samples from the ~~deep and bottom~~basal ice span the whole  
451 glacial deuterium excess range.

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

457

458 *5.4.2. Stretching?*

459

460 If mixing is therefore improbable at EDC, another mechanical way of explaining the  
461 abnormal length of MIS20 is relative vertical stretching under changing stress  
462 conditions, i.e. alteration of the stratigraphic time scale. Although, given the location  
463 chosen for the EPICA Dome C drilling, stress conditions should be (and are) essentially  
464 those of vertical uniaxial compression, Durand et al. (2008) indicate that the fabrics in  
465 layers of larger mean crystal sizes ( about 6 mm) below 2850 meters show signs of  
466 dispersion of the strong single maximum (which is the rule below 1500m depth) along a

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467 weak vertical girdle. These changes might be the sign of evolving stress conditions near  
468 the bottom of the ice sheet, and were recently interpreted so, to explain anomalous flow  
469 below 2700m (Dreyfus et al., 2007) and reworking of sulphate spikes below 2800m  
470 under increased recrystallization (Traversi et al., 2006; Traversi et al., 2009).

471 As seen on the large scale map of the bedrock elevation in the vicinity of the EDC  
472 drilling site (Remy and Tobacco, 2000, their Figure 4), the ice core bottom location sits  
473 on a bedrock “saddle” at ca. 750 m above sea level, on the eastern flank (200-400 m  
474 a.s.l. ridge) of a major S-N trending subglacial valley, with a 400 m a.s.l. ridge 15 km  
475 across, on the western flank of the valley. The bottom of the central part of the valley is  
476 at ca. 50 meters below sea level. The next 400 meters deep subglacial valley lies about  
477 20 km further to the East.  
478 ~~with a 400m high promontory 15 km to the West and the abrupt flank of a 400m deep~~  
479 ~~valley, 20 km to the East.~~

480 In Figure 7, we schematically show what might be the impact of a confining bedrock  
481 topography consisting of elongated valleys about 20 km wide and 200-400 meters deep  
482 (Rémy and Tabacco, 2000) on the stress field and the ice fabric in the bottom ice of  
483 EPICA DC. As the ice sinks passed the crests of the subglacial valleys, lateral  
484 compression on the sides of the valley will progressively combine with the vertical  
485 uniaxial compression. The resulting stress field, will therefore transition from uniaxial  
486 vertical compression to longitudinal extension, as illustrated by the 3D-arrows in the  
487 central part of the drawing of Figure 7. The associated change in fabrics will be from a  
488 vertical single maximum to a vertical girdle fabric, in a plane parallel to the subglacial  
489 valley sides. This new pattern might be the one already suggested in the discretely

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490 changing fabrics described by Durand et al. (2008) below 2800 meters. Because the  
491 principal stress transverse to the subglacial valley slowly shifts from extensional to  
492 compressive, the result could be a *relative* vertical stretching of individual accumulation  
493 layers, depending on the intensity of the principal extension along the valley axis. It is  
494 however not possible, with the data at hand, to demonstrate whether this relative vertical  
495 stretching results in an absolute increase of annual layer thickness (as shown in Figure  
496 7) or if it only results in a decrease of the thinning rate. In this configuration, one must of  
497 course consider a 3-D geometry, in which the vertically stretched ice can be moved  
498 away from the drill location. Part of it can be melted at the ice-bedrock interface where  
499 the ice is at the pressure-melting point, and the over-deepening of the longitudinal  
500 valleys seen in Figure 3 of Rémy and Tobacco (2000) could also provide an escape  
501 route for the ice.

#### 502 5.4.3. Enhanced recrystallization and small scale chemical sorting

503  
504 In the dynamic context described above (5.4.2), and relying on our multiparametric  
505 results, we can now propose a plausible scenario for the evolution of the properties of  
506 our deep-clean and basal-dispersed basal ice facies at EPICA Dome C, as illustrated in  
507 Figure 8. A changing stress field and the high temperatures, close to the pmp, will  
508 trigger sustained migration recrystallization within the bottom layers. Mean crystal size  
509 values (up to more than 10 cm) plotted in Figure 6 are undisputable proof that  
510 recrystallization is indeed very active there. This process will tend to relocate the  
511 impurities at grain boundaries and contribute to the build-up of aggregates. Note that  
512 Raisbeck et al. (2006) already invoked the formation of aggregates to explain abnormal



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513 | spikes in  $^{10}\text{Be}$  in the deep-basal ice. Increasing water content in the premelt layer might  
514 | also slowly initiate downwards density-driven migration of the water and of some of the  
515 | associated impurities. This however, as our data set shows, will only be revealed in a  
516 | high resolution chemistry approach, since it will not significantly affect the mean  
517 | concentration values for a given climatic period, but more the frequency distribution  
518 | within the observed concentration range. It will also behave differently, depending on  
519 | the species. Detailed SEM and XRF micro-probe elemental analyses of individual  
520 | aggregates inside the EDC dispersed basal ice facies are described elsewhere and  
521 | provide further insights in the potential processes at work and environmental  
522 | implications (de Angelis et al., 2013). They reveal that  $\text{CaCO}_3$  and  $\text{CaSO}_4$  are common  
523 | within these aggregates. These compounds could then be either newly precipitated  
524 | salts (as observed concentrations are compatible with saturation for e.g.  $\text{CaSO}_4$  given  
525 | estimated vein sizes at those ambient temperatures) or pre-existing solid particles, that  
526 | were initially present inside the crystals (Ohno et al., 2005).  $\text{SO}_4$ , Ca, Mg and MSA  
527 | (which can also be associated with salts, Ohno et al., 2005) mean concentrations in the  
528 | ~~deep-clean ice~~ and the dispersed basal ice facies will therefore remain within the range  
529 | of other glacials, but their spatial distribution at the high-resolution scale of sampling,  
530 | will show much greater variability than in meteoric ice above (Figures 4, 5 and 8-right  
531 | column).

532 | As discussed above, the other group of species (Na, Cl, K,  $\text{NO}_3$ ) shows two important  
533 | features in the frequency distribution of Figure 5 (right column): a) although the whole  
534 | data set is spanning the range of the previous glacials, the concentration mode is lower  
535 | for the deep-clean ice facies and higher for the basal-dispersed ice facies and b) the

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536 frequency distribution in the deep-basal ice facies is generally single-modal and narrow,  
537 while it is bi-modal in the basal-dispersed ice facies with the first mode in the deep-basal  
538 ice facies range and the second mode skewed towards the high side of the range  
539 observed in other glacials. The contrast in concentration level between the deep-clean  
540 ice facies and the basal-dispersed ice facies could simply reflect the slightly colder  
541 conditions (thus higher impurity content) at the time ~~basal ice~~the ice of the dispersed  
542 basal facies was formed at the surface of the ice sheet, as suggested by the lower  $\delta D$   
543 values compared to the deep-clean ice facies(Fig. 1b). Although this contrast is less  
544 obvious for the first group of chemical compounds, it might have been there over-written  
545 by the invoked aggregation and new in-situ precipitation processes. Alternatively, the  
546 observed contrast in behavior of Na, Cl, K,  $NO_3$  between the deep-clean and basal  
547 dispersed ice facies might reflect the signature of the premelt migration process as  
548 theoretically put forward by Rempel (2005). These species would indeed remain in the  
549 dissolved state within the premelt layer, and eventually partly and more easily migrate  
550 downwards, resulting in the left skewing mode in the deep-clean ice facies and the  
551 bimodal distribution in the basal-dispersed ice facies (low concentration mode  
552 corresponding to the remaining fraction in crystals as salts micro-inclusions and high  
553 concentration mode to the fraction that migrated in the premelt). Note that the process  
554 of upwards pulling of liquid from the underlying reservoir discussed by Rempel (2005), if  
555 it exists, provides a means to prevent exsudation-expulsion of the premelt from the  
556 basal ice, and therefore preservation of this bi-modal frequency distribution. Basal  
557 melting would potentially counteract this effect but propagate the two zones of deep and  
558 basal ice facies would then migrate upwards into the ice column. Unfortunately, as

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559 underlined before, the available data set is missing the lower 6-15 meters of the basal  
560 ice section to the ice-bedrock interface, where further arguments might have been found  
561 to (in-) validate this premelt migration hypothesis.

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

575

576 *5.4.4. Water isotopes, gases and dust*

577

578 | We ~~have focused~~ until now ~~focused~~ on a plausible explanation for the peculiarities of  
579 | the chemical signature of our ~~deep and two~~ basal ice ~~facies~~ at EDC. How do the water  
580 | isotopes signature, gas and dust properties fit into the proposed mechanism? Although  
581 | the water co-isotopic signature of our ~~deep and~~ basal ice ~~sections facies~~ does not show

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582 large scale signs of modification, the recent work of Pol et al. (2010) suggests that it  
583 | might not be the case at the crystal size scale, ~~giving~~ thereby providing some  
584 independent support to the interpretation of our chemical data set. These authors  
585 indeed used high-resolution (cm scale)  $\delta D$  measurements to depict abnormal isotopic  
586 diffusion which they attributed to water circulation at grain boundaries (pre-melt) for large  
587 | crystals which ~~have~~ spent more than 200.000 years at temperatures  $> -10^{\circ}\text{C}$ . The  
588 diffusion length diagnosed from the data is about twice larger (40 cm) than expected  
589 from solid state diffusion in ice, and it is also suggested that the process might start as  
590 early as in MIS 11 (Pol et al., 2011).

591 Why would the relocation process invoked for the chemical impurities not show up in the  
592 total air content or the  $\text{CH}_4$  and  $\text{CO}_2$  concentrations? First of all, it should be noted that  
593 the resolution of our gas data sets is much lower than the one we achieved for the  
594 chemical species. Also, one should remember that the gas molecules are exclusively  
595 | present as clathrates at these ~~elevated~~ depths and little is known on the behavior of  
596 those during small-scale phase changes under large overburden pressures. If the  
597 glacial MIS20 “stretching” hypothesis is valid, it is not surprising to observe a stable  
598  $\delta^{18}\text{O}_{\text{atm}}$  signal. Landais and Dreyfus (2010) provide an in depth analysis of the potential  
599 drivers for the millennial and orbital variations of  $\delta^{18}\text{O}_{\text{atm}}$  and show the strong impact of  
600 Northern Hemisphere monsoon activity on the observed values, in response to  
601 precessional and millennial shifts of the Intertropical Convergence Zone (ITCZ).  
602 Intervals where  $\delta^{18}\text{O}_{\text{atm}}$  is close to 0‰ correspond in that context to episodes where  
603 precession favors warm northern hemisphere summers with a strong East-Asian  
604 | monsoon. In Figure 1f, we ~~have~~ plotted the values for the integrated summer insolation

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605 at 30°N, for various thresholds  $\tau$ , as calculated by Huybers (2006). This integrated  
606 summer insolation can be defined as the sum of the diurnal average insolation on days  
607 exceeding a specified flux threshold ( $\tau$ ). As can be seen from the comparison between  
608 Figures 1f and 1d, high values of  $\delta^{18}\text{O}_{\text{atm}}$  concur with high integrated summer insolation  
609 associated with very high diurnal average insolation thresholds ( e.g. for  $\tau = 450$  (green  
610 | curve) to 500 (red curve)  $\text{Wattm}^{-2}$  in Figure 1f), which is the case for our ~~deep-basal~~ ice  
611 | sequence. This relationship is enlarged in Figure 9a, where one can clearly see that  
612 | maxima in  $\delta^{18}\text{O}_{\text{atm}}$  are well coupled to maxima in integrated summer insolation, to the  
613 | exception of a missing peak around 750 ky. It can also be suggested that larger  $\delta^{18}\text{O}$   
614 | amplitudes correspond to larger summer insolation values and vice versa, with a  
615 | threshold around roughly 2 ~~Giga-Joules~~GJ. In Figure 9a we ~~have~~ attempted to use the  
616 | synchronicity of small scale oscillations of the  $\delta^{18}\text{O}_{\text{atm}}$  signal (however well above the  
617 | precision of measurements - 0.015‰), to the summer insolation one (tie points 1 and 2  
618 | in Fig. 9a) to derive the amount of stretching of the ~~deep-basal~~ ice sequence. This gives  
619 | a factor of about 2, which ~~has~~ allowed us to reconstruct a new time scale for the ~~deep~~  
620 | ~~and~~-basal ice, assuming linear stretching also applying to the bottom ice, for which  
621 |  $\delta^{18}\text{O}_{\text{atm}}$  are not available. Unfortunately, this does not resolve the discrepancy with the  
622 | Lisiecki and Raymo curve (Figure 9b), and suggests that the amount of stretching is  
623 | probably much larger, with an initial time frame for the ~~deep-and~~-basal ice of only about  
624 | 10.000 years. To build our 60 meters of basal ice sequence in ca. 10000 years would  
625 | require an "in situ" annual layer thickness of 6 mm, which is 10 times the value  
626 | observed during the previous glacial, following the recently published AICC2012 climate

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627 record (Bazin et al., 2012, supplementary material). This seems too extreme, and  
628 suggests stretching might have been supplemented by other processes such as  
629 dynamical thickening in the lee of bedrock obstacles or stacking up of several glacials,  
630 with missing interglacials. The latter is however unlikely, since interglacial ice is usually  
631 harder to deform due to lower impurity content and larger crystal size (Dahl-Jensen et  
632 al., 2013). Finally, as demonstrated in de Angelis et al. (2013), the detailed analysis of  
633 individual inclusions supports the occurrence of in-situ bacterial activity. To our  
634 knowledge, it is not known so far if these might have potential impact on the  $\delta^{18}\text{O}_{\text{atm}}$  of  
635 the neighbouring gas phase. It is however unlikely that it might be significant given the  
636 observed low  $\text{CO}_2$  mixing ratio (Fig. 3a), in line with atmospheric values at glacial times.

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637 Despite the very poor resolution of the dust record in our bottom ice the large variability  
638 of the data within the glacial range could also result from our increased relocation  
639 scheme. Moreover, below 2900m, a significant shift of particle size towards large  
640 diameters is in agreement with the formation of aggregates.

## 641 6. Conclusions

642 We ~~have~~ used a multiparametric approach to discuss the plausibility of recovering an  
643 unaltered paleoclimatic signature from the ~~deep and~~ basal ice of the EDC ice core. We  
644 ~~have shown~~ showed that some of the data ( $\delta\text{D}$  values, total air content, gas composition,  
645 dust content, mean chemical species concentrations) suggest a pristine meteoric glacial  
646 signature while others (length of the glacial,  $\delta^{18}\text{O}_{\text{atm}}$ , visible inclusions, variability of the  
647 chemical species distribution) suggest mechanical and compositional alteration of the  
648 bottom ice. Ice stable isotopes and total air content rule out large scale refreezing

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649 processes of a water reservoir as the origin for the bottom ice. Mixing, be it internally (as  
650 in Vostok MIS11) or with a local ice remnant of previous or initial ice sheet configuration  
651 (as in GRIP and Dye-3) can be equally discarded.

652 | Using a new high resolution data set for selected chemical species in the ~~deep and~~  
653 basal EDC ice and remote sensing information on the general setting of the Dome C  
654 area, we propose a mechanism in which the confining bedrock topography contributes  
655 to a downwards change in the stress field from uniaxial vertical compression to  
656 longitudinal extension along the valley axis. This stress configuration change results in a  
657 potential relative vertical stretching of the ice layers, which explains the abnormal length  
658 of MIS20. Combined with an ice temperature close to the pmp it also favors rapid  
659 migration recrystallization, as witnessed by the large increase in grain size. This, in turn,  
660 induces relocation of impurities, with accumulation of newly formed salts and already  
661 existing solid particles in the premelt layer, forming aggregates. Those become visible  
662 about 12 meters above the bottom of the core and increase in size and number  
663 downwards. The basal inclusions thus mainly consist of reworked existing material,  
664 rather than representing incorporation of allochthonous material from the ice-bedrock  
665 interface. However some potential candidates for the latter (large, single, mineral  
666 inclusions) were detected in the last meter layer (de Angelis et al., 2013). Although the  
667 mean concentration values were not significantly different from those observed in the  
668 previous full glacial periods, some chemical sorting is apparent, especially for those  
669 species that are not involved in salt formation. We suggest this might result from a slow  
670 process of downwards migration of the premelt layer under the hydraulic gradient  
671 resulting from the density difference between ice and interstitial water, although the lack

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672 of data from the last 6-15 meters to the ice-bedrock interface prevents us from further  
673 validating this hypothesis. The ice isotopic and gas properties are apparently not  
674 affected by these small scale processes that however only become detectable at high-  
675 resolution sampling (sub-crystal size), where they are involved in smoothing processes.  
676 The apparent discrepancy in the  $\delta^{18}\text{O}_{\text{atm}}$  signal is resolved if one considers potential  
677 stretching of a glacial time span during which precession favors warm northern  
678 hemisphere summers, as ~~has~~ happened temporarily in each of the previous glacial  
679 isotopic stages.

680 We conclude that the paleoclimatic signal is only marginally affected in terms of global  
681 ice properties at the bottom of EPICA Dome C, but that the time scale ~~was~~ ~~been~~  
682 considerably distorted by mechanical stretching due to the increasing influence of the  
683 subglacial topography. It is interesting to note that MIS18 already shows signs of  
684 isotopic smoothing, chemical relocation and increased variability for the species  
685 involved in salt formation (MSA,  $\text{SO}_4$ , Mg and, in a lesser extent Ca), before the  
686 timescale (EDC3) got significantly distorted. Along the same line the anomalous flow  
687 detected below 2700m, that led to the change from the EDC2 to the EDC3 time scale,  
688 might already find its roots in this subglacial topography distortion, although possible  
689 changes in the Dome position with time need also to be considered (e.g. Urbini et al.,  
690 2008). Many interior ice divides are indeed migrating today and this could also be the  
691 case for the EDC location. Given the rough bed topography, it takes a migration of only  
692 a few ice thicknesses to change the bedrock elevation by ca. 200 meters. The basal ice  
693 may therefore have experienced vertical stretching due to flow from the bedrock ridge to  
694 the current valley position, with recent migration of the divide at the top. Today, lively



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695 discussions exist and preliminary actions are undertaken within the ice core community  
696 to select a suitable location for a new deep drilling targeting the “oldest ice” (above 1  
697 million years old, IPICS, 2009). Our work shows that the location of the EDC ice core on  
698 the flank of a valley-type subglacial topography has considerably affected the inference  
699 of deep timescales. We conclude that the retrieving of reliable paleoclimatic signals  
700 down to a few meters from the ice-bedrock interface would probably be thinkable on a  
701 flat monotonic bedrock, for distances several times the local ice thickness, although  
702 small scale reworking of some of the proxies should be expected. It is however not clear  
703 yet why the gas content and composition is so well preserved at EDC, and not at other  
704 deep basal ice location. The presence of a liquid water layer at the interface might partly  
705 explain that discrepancy, although this could not be verified here.

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

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

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Glacial	Depth range (m)		Isotopic range ( $\delta D$ ‰)		Na ( $\text{ngg}^{-1}$ )		Cl ( $\text{ngg}^{-1}$ )		NO <sub>3</sub> ( $\text{ngg}^{-1}$ )		K ( $\text{ngg}^{-1}$ )	
			min	max	mean	<i>s</i>	mean	<i>s</i>	mean	<i>s</i>	mean	<i>s</i>
MIS 2	507.7	583.5	-449.3	-432.8	<b>97.37</b>	17.54	<b>160.68</b>	48.64	<b>40.93</b>	16.01	<b>7.45</b>	1.89
MIS 4	1007.6	1042.2	-446.4	-430.5	<b>79.81</b>	17.75	<b>129.89</b>	25.25	<b>29.38</b>	12.41	<b>4.91</b>	2.34
MIS 6	1801.8	1997.0	-447.1	-419.8	<b>71.57</b>	16.65	<b>107.56</b>	40.45	<b>24.72</b>	12.63	<b>3.74</b>	2.36
MIS 8	2320.0	2398.6	-444.5	-421.5	<b>76.76</b>	35.00	<b>112.06</b>	38.05	<b>26.24</b>	17.20	<b>3.84</b>	5.24
MIS 10	2599.9	2650.0	-445.0	-425.1	<b>77.80</b>	32.30	<b>112.76</b>	61.56	<b>30.21</b>	19.92	<b>5.77</b>	9.76
MIS 12	2783.2	2794.9	-440.9	-422.5	<b>72.70</b>	19.82	<b>138.46</b>	34.04	<b>48.69</b>	22.43	<b>3.93</b>	3.32
MIS 14.2	2915.7	2919.9	-436.4	-429.3	<b>70.88</b>	15.13	<b>110.46</b>	21.66	<b>34.33</b>	17.31	<b>3.16</b>	5.70
MIS 16	3037.6	3039.8	-441.0	-412.3	<b>78.23</b>	12.32	<b>111.67</b>	21.46	<b>32.89</b>	11.94	<b>3.07</b>	4.96
MIS 18	3137.8	3153.1	-441.4	-423.7	<b>80.44</b>	13.94	<b>114.44</b>	31.38	<b>26.28</b>	13.95	<b>3.26</b>	3.98
<b>Deep-IceClean Facies</b>	3201.0	3248.0	-442.5	-427.7	<b>71.78</b>	3.79	<b>99.91</b>	13.39	<b>29.03</b>	2.42	<b>1.94</b>	2.40
<b>Bottom-IceDispersed Facies</b>	3248.0	3259.3	-443.2	-436.7	<b>93.16</b>	15.43	<b>141.68</b>	30.42	<b>46.26</b>	15.37	<b>2.68</b>	4.17

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1009 **Table 1:** Mean concentration and  $1\sigma$  values ( $\text{ngg}^{-1}$  or ppb) for selected chemical species in the **Deep-Clean** and  
 1010 **Dispersed** Basal ice **facies** of the EPICA Dome C ice core, as compared to those of the **following-previous** full glacial  
 1011 periods (see text for details). Depth (meters) and  $\delta D$  (‰) ranges are given for each time interval considered.



1012 **Figure Captions**

1013 **Figure 1:** a) visual appearance of the EDC basal ice in the lower meters of the core (photo: D.  
1014 Dahl-Jensen), b) EDC  $\delta D_{ice}$  vs. depth, c) EDC  $\delta D_{ice}$  vs. age (EDC3 time scale extended to the  
1015 ~~deep-and~~ basal ice layers), d) Combined Vostok and EDC  $\delta^{18}O_{atm}$  vs. age (adapted from  
1016 Dreyfus et al., 2007), e)  $\delta^{18}O$  vs. age for the benthic record stack of Lisiecki and Raymo (2005),  
1017 and f) Integrated summer insolation for various thresholds ( $\tau$ ) at 30°N vs. age, as calculated by  
1018 Huybers (2006). For reasons described in the text, ice below 3189.45m depth is referred to as  
1019 « ~~deep-clean~~ ice facies » (blue squares) and « ~~basal-dispersed~~ ice facies » (red triangles)  
1020 describes the ice below 3248.30m, where solid inclusions are visible.

1021 **Figure 2:** a)  $\delta D_{ice}$  (‰) vs.  $\delta^{18}O_{ice}$  (‰) and b) d (deuterium excess ‰) vs.  $\delta D_{ice}$  (‰) for the ~~deep~~  
1022 ~~clean~~ (open squares) and ~~basal-dispersed~~ (open triangles) ~~basal~~ ice facies at EPICA Dome C,  
1023 as compared to the ice from the 0-140 ky interval (black dots, Stenni et al., 2010). See text for  
1024 details.

1025 **Figure 3:** Gas and dust properties of the ~~deep-clean~~ (squares) and ~~basal-dispersed~~ (triangles)  
1026 ~~basal~~ ice facies at EPICA Dome C: a) total gas content ( $ml_{air}g_{ice}^{-1}$ , dark grey), methane (ppbV,  
1027 white), nitrous oxide (ppbV, light grey) and carbon dioxide (ppmV, black) - vertical bars of  
1028 equivalent shading cover the full concentrations range observed for  $CH_4$ ,  $CO_2$ ,  $N_2O$  and total  
1029 gas content during the preceding climatic cycles, b) dust concentrations (ppb) -black vertical bar  
1030 covers the full concentration range during the previous climatic cycles.

1031 **Figure 4:** Concentrations (in ppb or  $ngg^{-1}$ ) of selected chemical species in the ~~deep-clean~~ (open  
1032 squares) and ~~basal-dispersed~~ (open triangles) ~~basal~~ ice facies of the EPICA Dome C core, as  
1033 compared to those of the preceding climatic cycles (black dots, courtesy of the EPICA chemical  
1034 consortium). Resolution is between 5 and 8 cm above 3200m depth and between 1.5 and 5 cm  
1035 in the ~~deep-and~~ basal ice below 3200 m. Note the change of depth scale below 3200m.

1036 **Figure 5:** Frequency distribution of concentrations (in bins of 1 or 5  $ngg^{-1}$  or ppb) of selected  
1037 chemical species in the ~~deep-clean~~ (open squares - thick black solid line) and ~~basal-dispersed~~  
1038 (open triangles - thick black dotted line) ~~basal~~ ice facies of the EPICA Dome C core, as  
1039 compared to those for the preceding full glacial periods (incremented symbols and thin grey  
1040 lines - courtesy of EPICA Chemistry Consortium). See text for definition of « full glacials ».

1041 **Figure 6:** Mean equivalent crystals radii in the ~~deep-and~~ basal ice layers of the EPICA Dome C  
1042 ice core, as compared to measurements in ice above 3200m depth from Durand et al. (2007).  
1043 ~~Deep-and-b~~ basal ice measurements are preliminary results obtained using the linear intercept  
1044 technique « on site », while the data from above 3200m were obtained using Automatic Ice  
1045 Texture Analyzers (AITAs - Wang and Azuma, 1999; Russell-Head and Wilson, 2001; Wilen et  
1046 al., 2003).

1047 **Figure 7:** Schematic ~~illustration~~ of the hypothesized impact of the confining bedrock topography  
1048 (bedrock valleys about 20 km wide and 200-400 meters deep - from Remy and Tabacco, 2000)

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

1049 on the stress regime, layer thickness and ice fabric patterns in the bottom ice of EPICA Dome C.  
1050 Vertical stretching is accommodated by basal melting and/or along sub-glacial valley flow. For  
1051 clarity, this illustration enhances the process so that absolute annual layer thickness increases  
1052 downwards. A milder effect would only result in a decrease of the thinning rate (see text for  
1053 details).

1054 **Figure 8:** Sketch of potential chemical sorting effects during enhanced migration  
1055 recrystallization processes under a changing stress field, close to the pressure melting point, in  
1056 the deep-clean and basal-dispersed basal ice facies of EPICA Dome C. Processes in  
1057 italic/dotted arrows are hypothetical (see text for details).

1058 **Figure 9:** Attempting to reconstruct the time scale for the ~~deep-and~~ basal ice sequence: a)  
1059 Zoom on the  $\delta^{18}\text{O}_{\text{atm}}$  curve vs. Integrated summer insolation at 30°N (see Fig. 1e) and b)  
1060 Comparison of the benthic  $\delta^{18}\text{O}$  curve (open circles) to the EPICA  $\delta\text{D}_{\text{ice}}$  profile (black dots),  
1061 where the ~~deep-and~~ basal ice time scale has-was-been linearly « compressed » using tie points  
1062 1 and 2 in a) (see text for details)

1063 **Figure S1:** Plot of the mean (a) and  $1\sigma$  (b) values for the various chemical elements measured  
1064 in each of the glacial periods considered in this study and for the Deep-Clean (open squares)  
1065 and Basal-Dispersed (open triangles) basal ice samples as a function of the duration (in  
1066 thousand years) of the « full glacial period » selected on the basis of the  $\delta\text{D}$ -values. Isotopic  
1067 Stage 18, which is already thought to show increased variability for some of the elements, is  
1068 shown as an open star. Duration is estimated from the EDC-3 time scale (Parrenin, 2007).

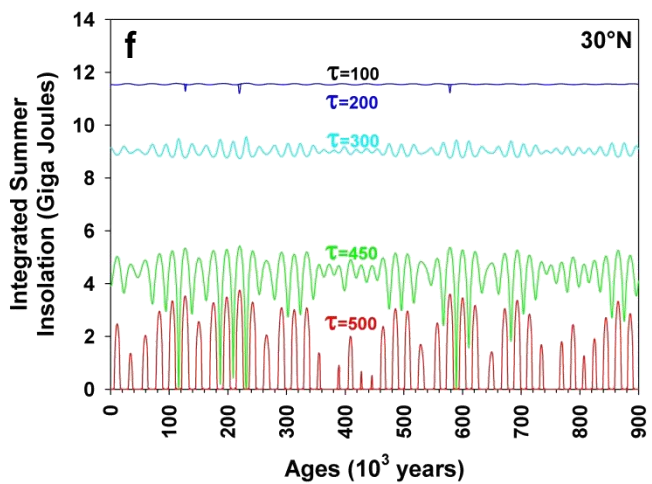
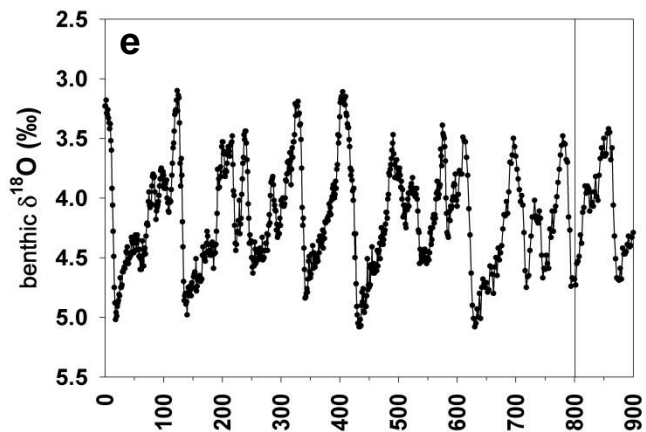
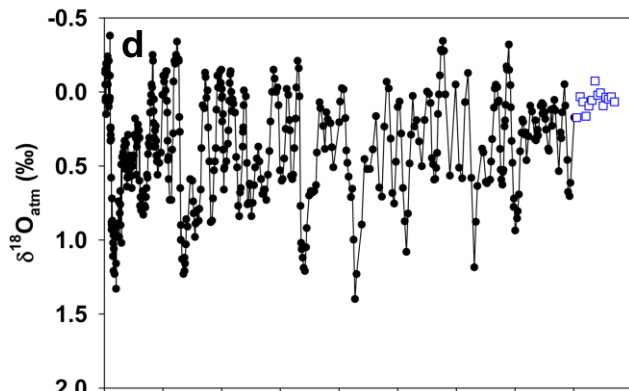
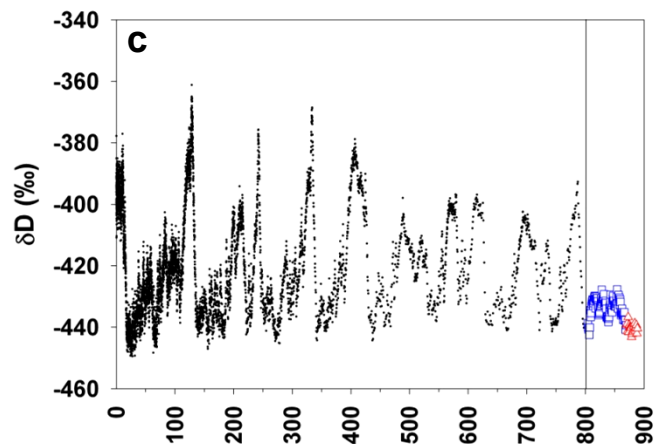
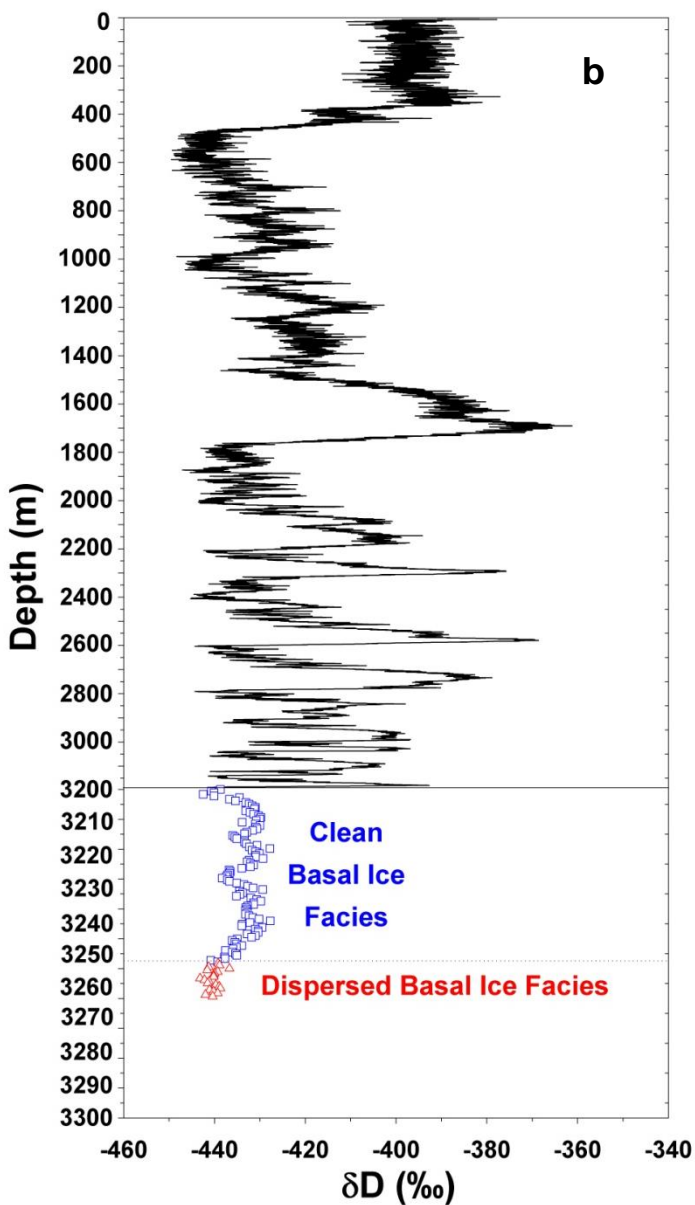
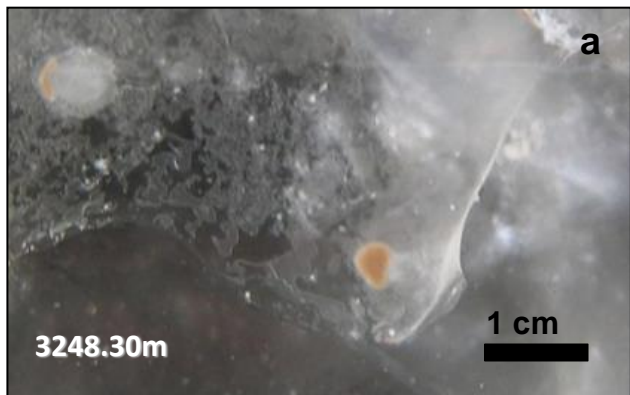


Figure 1

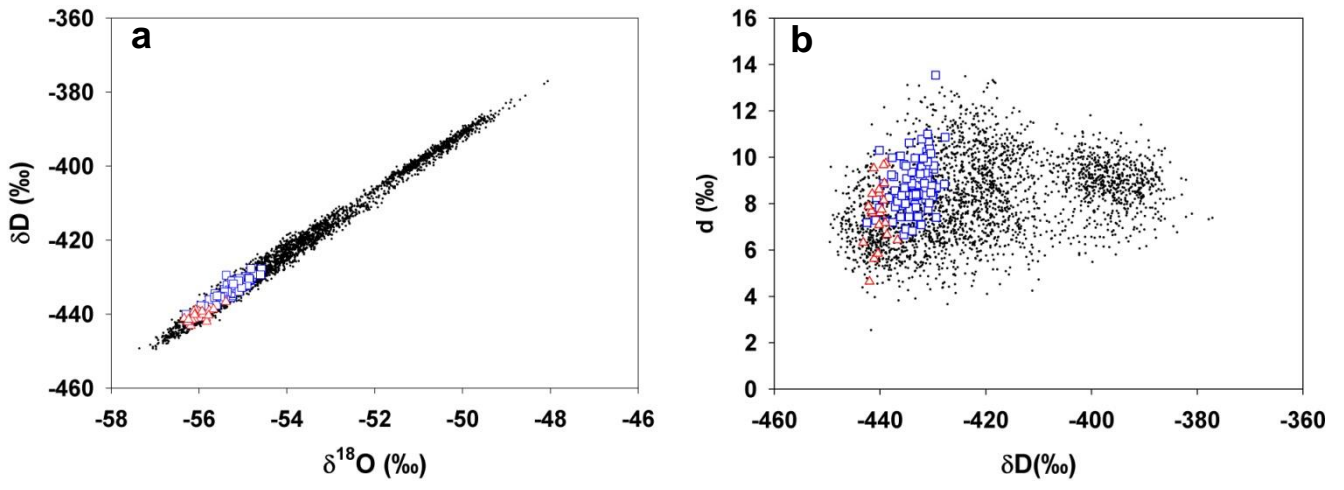


Figure 2

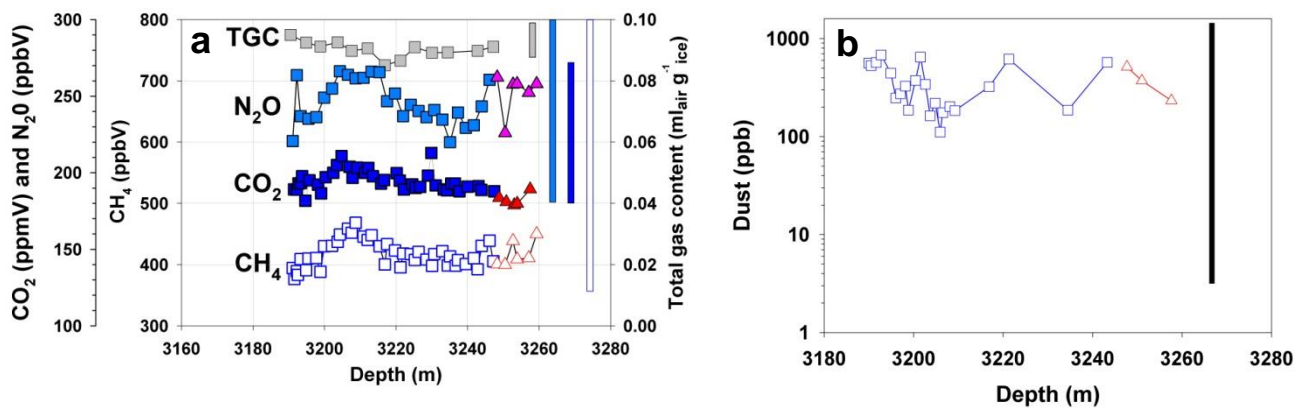


Figure 3

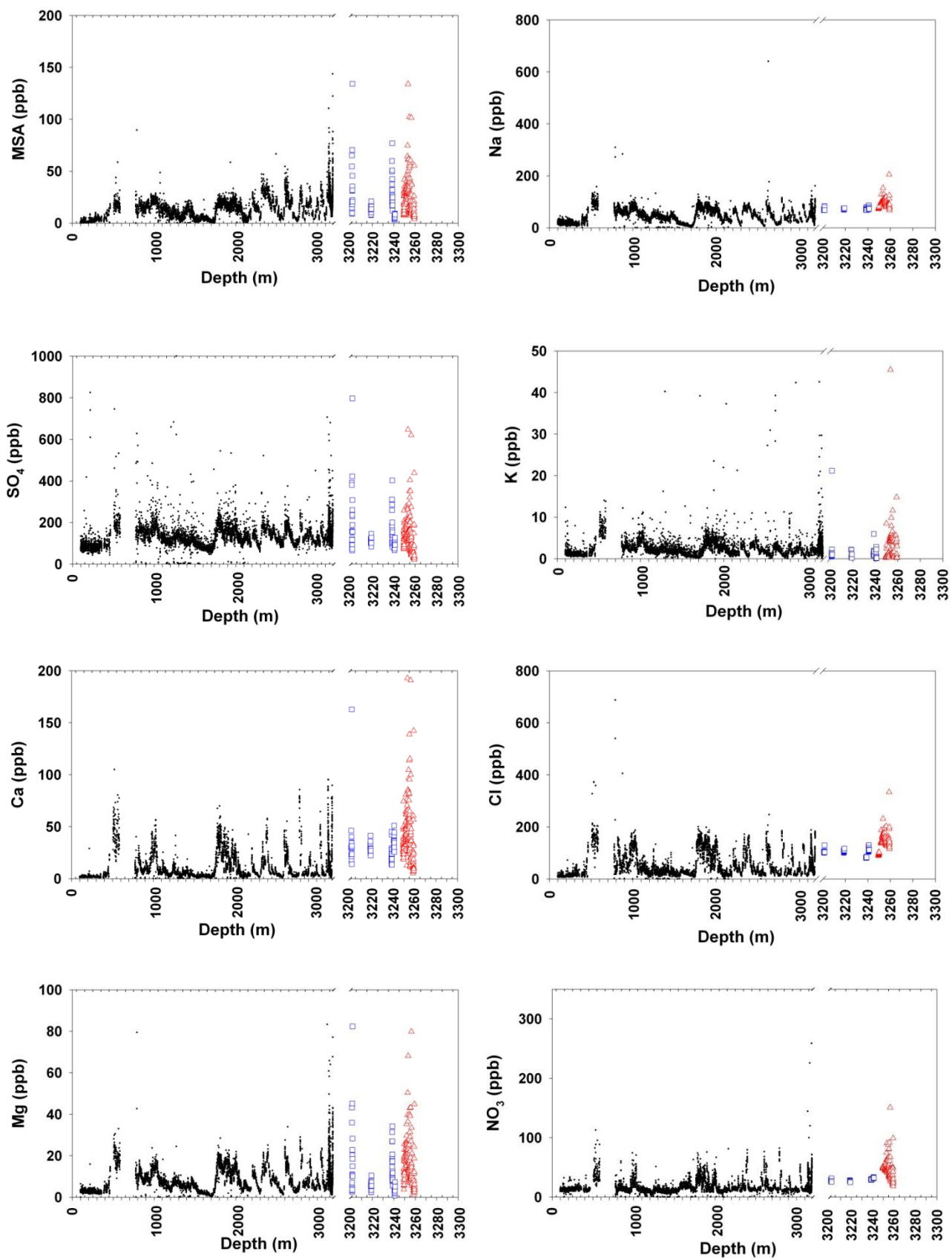


Figure 4

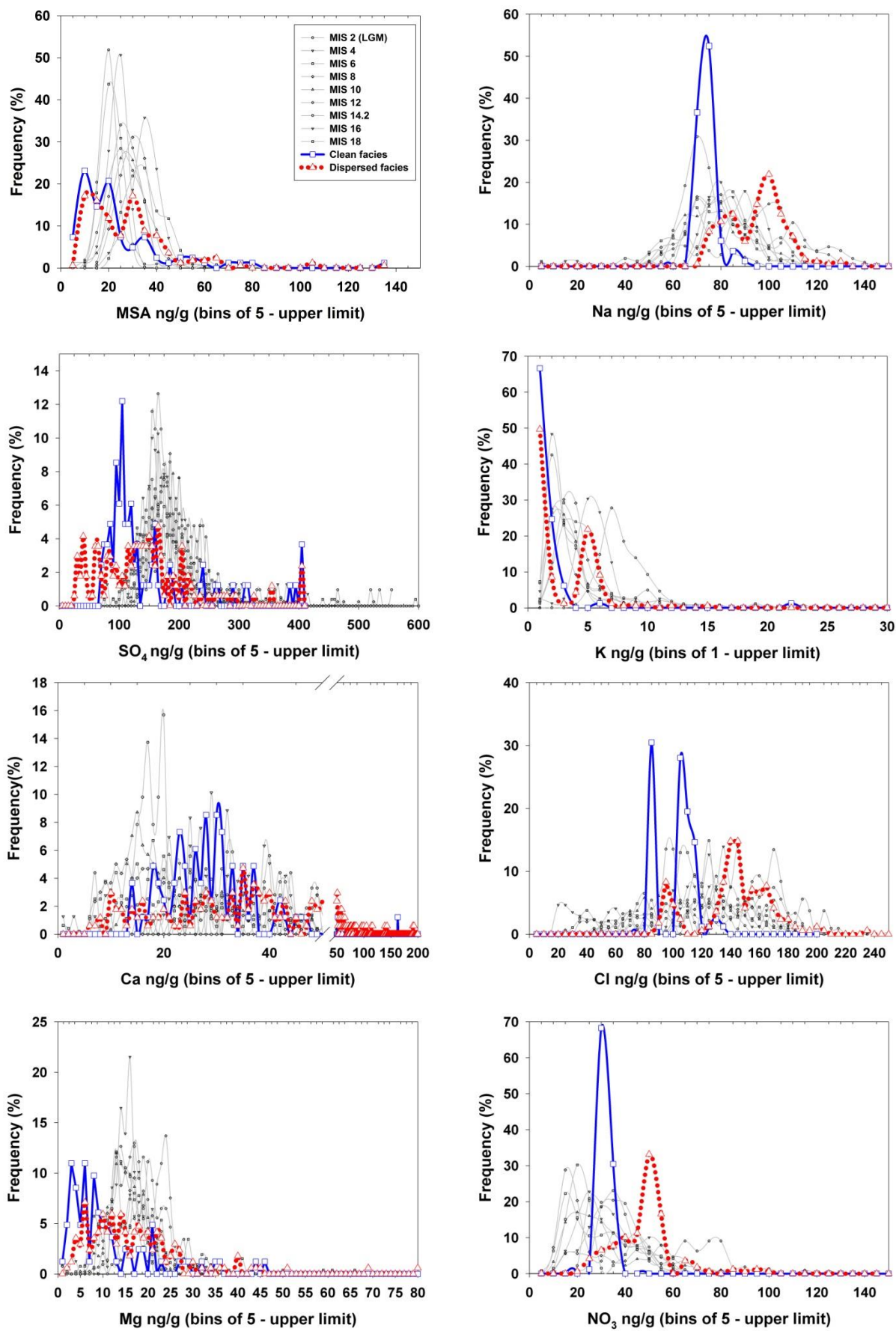


Figure 5

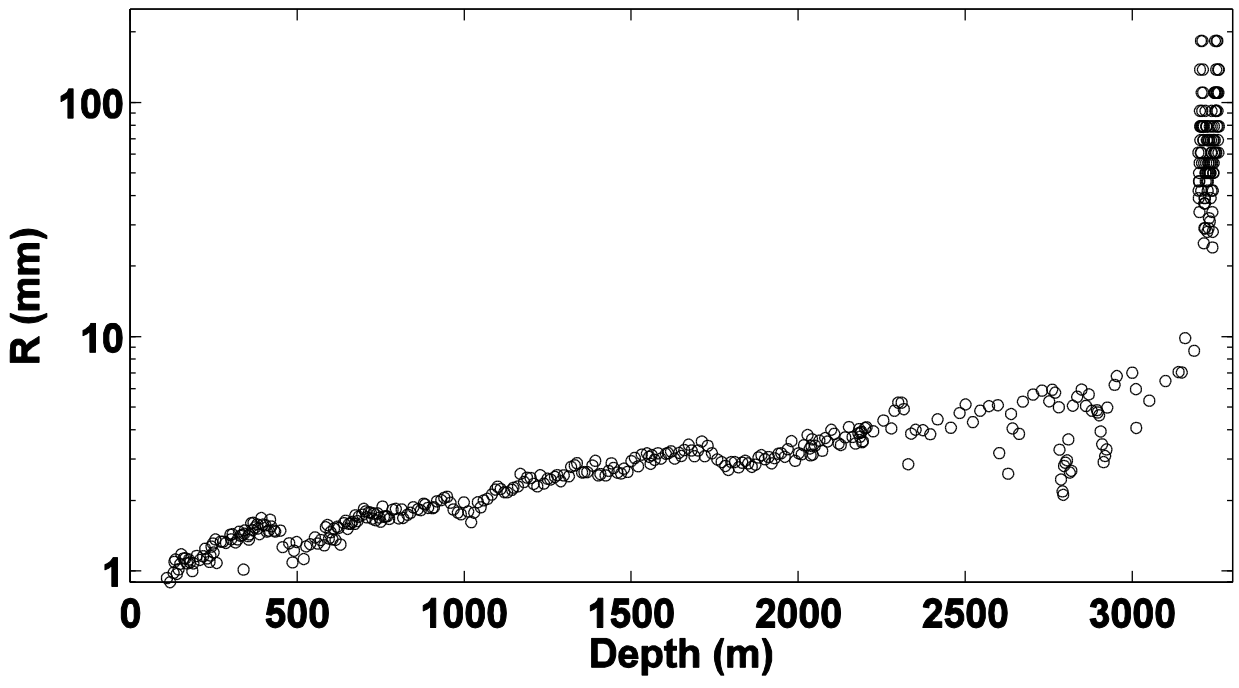


Figure 6



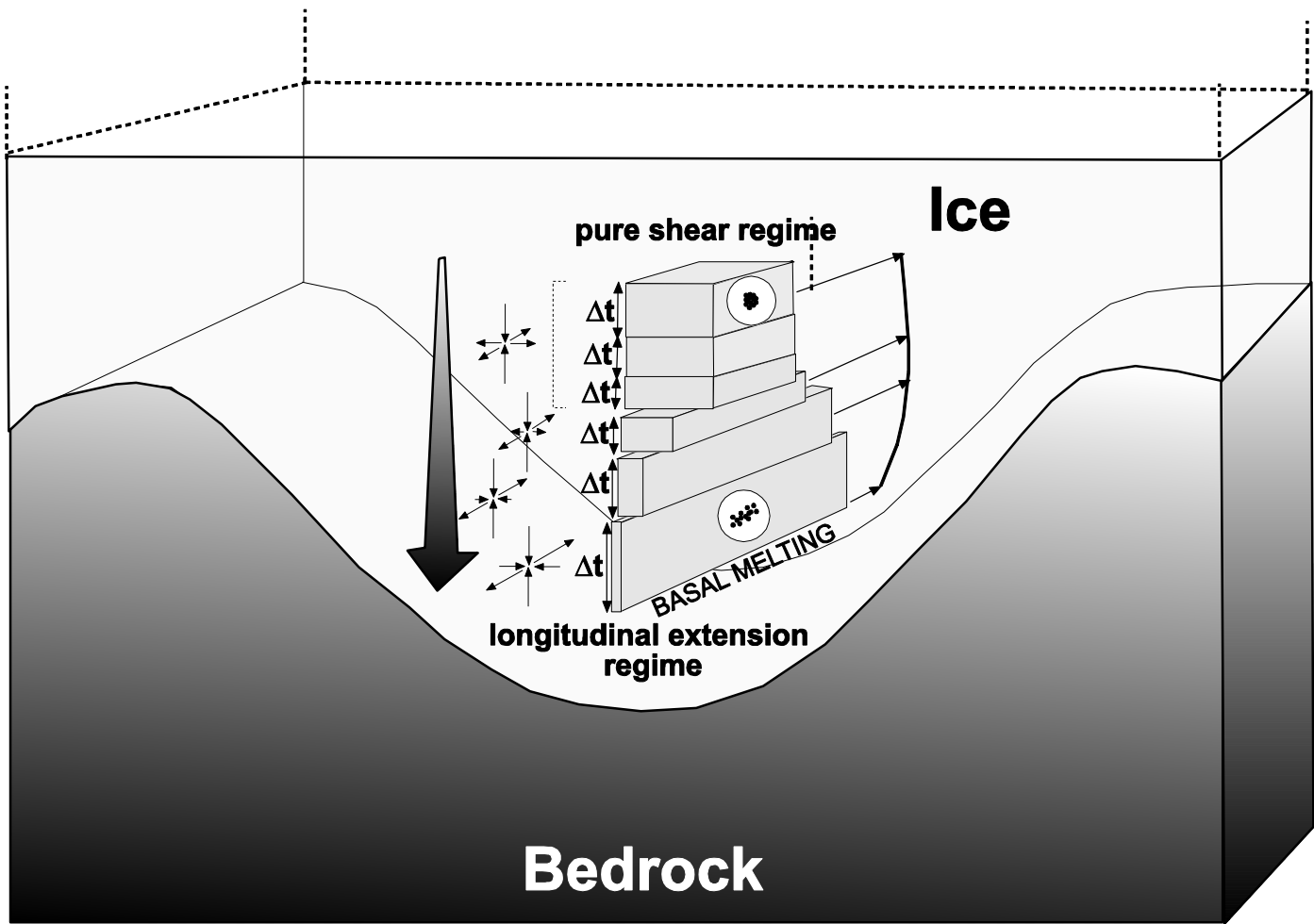


Figure 7

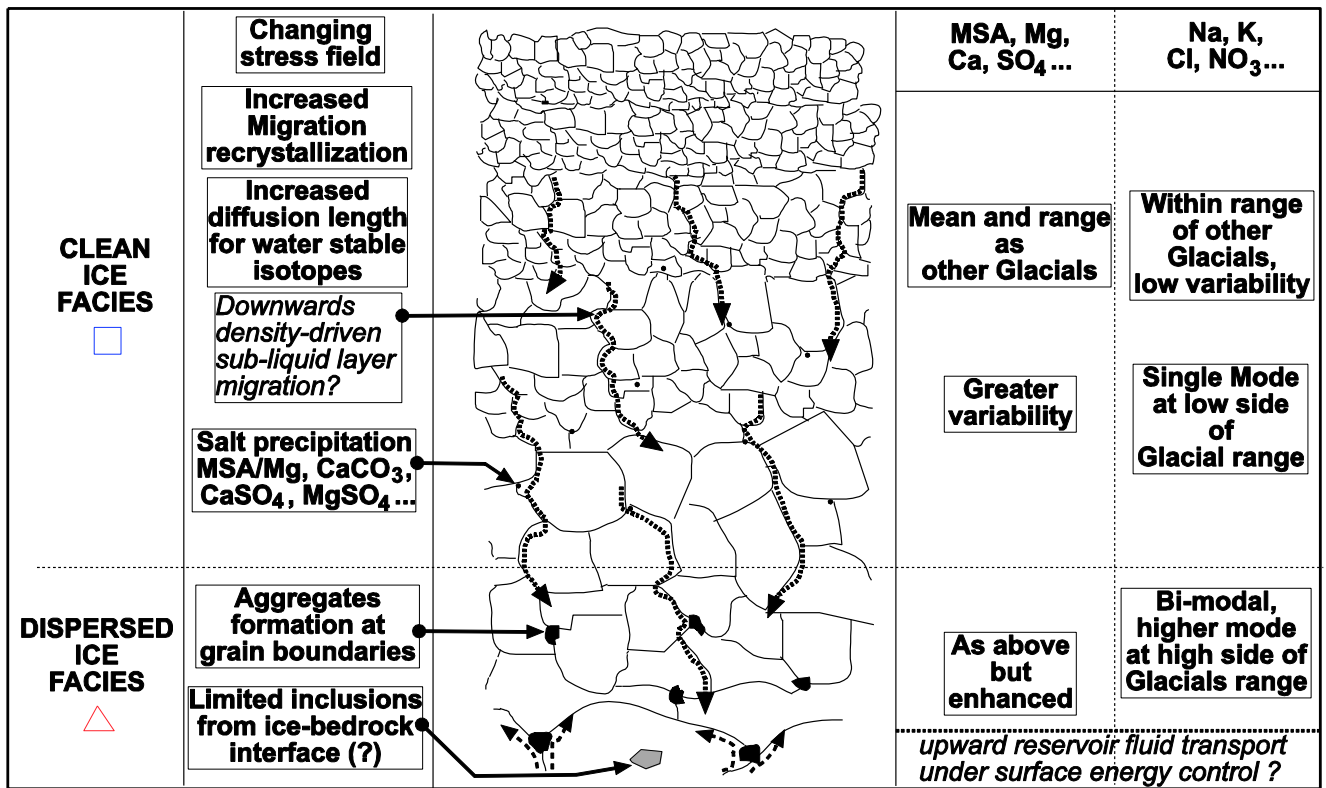


Figure 8

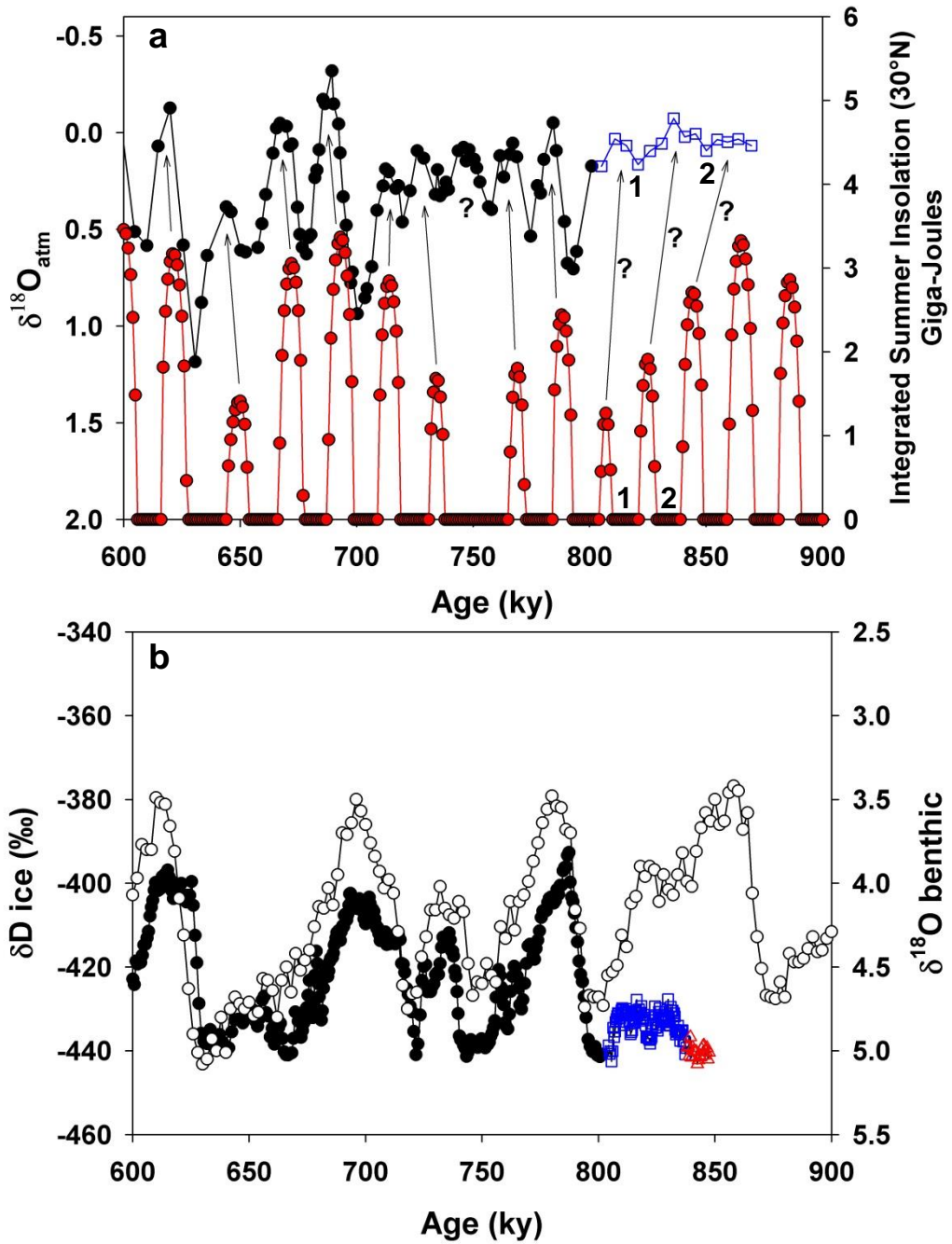


Figure 9

## 1 **Supplementary Material**

2

### 3 S1. Material and Methods

4

#### 5 *S1.1. Chemical analyses*

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

#### 16 *S1.2 Water Isotopes*

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

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

32 The measurements of the total gas content have been performed at LGGE using an  
33 original barometrical method implemented with an experimental setup called STAN  
34 (Lipenkov et al., 1995). This technique allows a precise evaluation of the pressure and  
35 temperature of the air extracted from an ice sample having a mass of 20-30 g by its  
36 melting-refreezing under vacuum in a volume-calibrated cell. After correction of the  
37 measured pressure for the partial pressure of saturated water vapour and of the  
38 calibrated volume for the volume occupied by refrozen bubble free ice, the gas content  
39  $V$  is calculated using the ideal gas law. The  $V$  values are then corrected for gas loss

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

40 from air inclusions (i.e. gas hydrates and relaxation features such as gas cavities at  
41 depths under consideration) cut at the surface of the sample (Martinerie et al., 1990).  
42 The absolute precision of the STAN measurements has been estimated to be within  
43  $\pm 0.6\%$ . However the overall error of obtained  $V$  values amounts 1% because of the  
44 uncertainties in the cut-bubble correction. The replication of the results estimated by  
45 repeated measurements in the same horizontal slice of an ice core has been confirmed  
46 to be better than 1%.

47 For  $\text{CO}_2$  measurements at the University of Bern, ice samples of about 7 g were  
48 pulverized in a cooled and evacuated vacuum chamber using a needle cracker  
49 principle. After this dry extraction process, the extracted air was expanded from the  
50 vacuum chamber into an infrared laser spectrometer which is used to derive the  $\text{CO}_2$   
51 concentration. At the LGGE about 40g of ice were pulverized in a cooled vacuum  
52 chamber using a ball mill principle. In this system the extracted air is transferred into a  
53 GC in order to derive the  $\text{CO}_2$  concentration. A more detailed description of the systems  
54 used in Bern and at the LGGE is found in Siegenthaler et al. (2005) and Barnola et al.  
55 (1987), respectively. The  $\text{CO}_2$  data set shown in this paper has a resolution of about 2.2  
56 m and a precision of 1.6 - 2 ppmv (corresponding to mean Bern and LGGE precision,  
57 respectively), whereas up to 8 replicate measurements were performed.

58 For  $\text{CH}_4$  and  $\text{N}_2\text{O}$  measurements, ice samples of about 40 g (University of Bern) or 50 g  
59 (LGGE) were melted in sealed and evacuated glass containers. After refreezing of the  
60 samples the extracted ancient air is injected into a sampling loop and analyzed by gas  
61 chromatography. The gas chromatographs are equipped with a thermal conductivity  
62 detector (TCD, for total air amount), a flame ionization detector (FID, for  $\text{CH}_4$ ), and an  
63 electron capture detector (ECD) for  $\text{N}_2\text{O}$  (University of Bern only). A detailed description  
64 of this melt-refreezing method and the measurement systems can be found in Flückiger  
65 et al. (2004) and Chappellaz et al. (1997). The precision of the  $\text{CH}_4$  and  $\text{N}_2\text{O}$   
66 measurements is 10 and 5.6 ppbV respectively. Note that the  $\text{N}_2\text{O}$  measurements are  
67 potentially affected by in-situ production in the ice leading to elevated values (see Schilt  
68 et al., 2010). The mean resolution of the  $\text{CH}_4$  and  $\text{N}_2\text{O}$  measurements for the depth  
69 interval 3191 to 3259 m is 1.4 and 2.1 m, respectively.

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

75 *S1.4 Crystal size*

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

84 *S1.5 Dust*

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

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

94 As discussed in section 3, we have chosen to compare the chemistry of the **Clean and**  
95 **Dispersed basal ice facies** to the one of the previous glacial climatic episodes, showing  
96 minimum  $\delta D$  values. To achieve this, we have selected these successive “full glacial”  
97 episodes by isolating in the  $\delta D$  data set the periods with minimal values, using locations  
98 of increasing  $\delta$ -gradients as cutting points on both sides. Table 1 shows that the  $\delta D$   
99 ranges obtained for the various selected periods are quite similar. However, these  
100 various glacial episodes obviously cover different depth and time intervals. Before we  
101 discuss and compare the mean values and the variability between those groups and the  
102 **Clean and Dispersed basal ice facies**, it is essential to show that no artificial “time  
103 smoothing” is induced by the methodology. For example, one might expect that,  
104 depending on the resolution of the data set, increasing the time window at a given  
105 resolution would damp the variability. In figure S1, we have plotted, for each chemical  
106 species considered and for each group of samples, their mean (Fig. S1a) and  $1\sigma$  (Fig.  
107 S1b) value as a function of the duration of the period, based on the EDC-3 time scale  
108 (Parrenin, 2007, extended for the basal ice layer). Although there is some variability, no  
109 clear trend of the chemical signals is seen with duration of the episodes. Furthermore, if  
110 “time smoothing” was to occur, it should result in a decrease of the variability, at a given

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111 resolution, as we go down the EDC core, which is the reverse of what is observed  
112 comparing the **Clean and Dispersed basal ice facies** to the “full glacial” episodes above.  
113 Finally, the contrast between the signature of different elements within **the Clean or**  
114 **within the Dispersed basal ice facies** concerns samples that are strictly from the same  
115 time window, at the same resolution, so that it is sound to discuss it.

Facies	Total gas Content		CO <sub>2</sub>		CH <sub>4</sub>		N <sub>2</sub> O		δ <sup>18</sup> O <sub>atm</sub>		δO <sub>2</sub> /N <sub>2</sub>		
	Depth (m)	Total gas content (ml <sub>air</sub> g <sub>ice</sub> <sup>-1</sup> )	Depth (m)	CO <sub>2</sub> (ppmV)	Depth (m)	CH <sub>4</sub> (ppbV)	Depth(m)	N <sub>2</sub> O(ppbV)	Depth(m)	δ <sup>18</sup> O <sub>atm</sub>	δO <sub>2</sub> /N <sub>2</sub>		
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. δO<sub>2</sub>/N<sub>2</sub> values are expressed wrt. atmospheric air and corrected for gravitational effects (Landais et al., 2012).