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Climate of the Past Discussions

Interactive comment on "Cryogenic cave carbonate – a new tool for estimation of the Last Glacial permafrost depth of the Central Europe" *by* K. Žák et al.

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We are grateful for the detailed comments of referee 2, which helped to substantially improve the manuscript. We accept all recommendations for rephrasing and technical corrections as well as the recommended changes in the list of references. Our comments to those points of referee 2 requiring a more detailed discussion are given below:

Comment: Section 2.1. Most of the paper and all the U/Th dates refer to coarse-crystalline Cryogenic Cave Carbonate (CCCCC) and not more generally to CCC. I would suggest, therefore, to confine the paper to this kind of carbonate and insert

coarse-crystalline in the title and the notation (CCCCC) in the main text. The fine-crystalline powdery type of CCC can be mentioned in the introduction, in part 2, as well as in the stable isotope part (including Fig. 1). Reply: The information on fine-grained cryogenic cave carbonate is not relevant for the topic discussed in the manuscript and has been reduced in the revised version. The abbreviation CCC was already used in about 50 published papers. We therefore prefer not to modify this abbreviation. In the main text of the revised manuscript, we will systematically use the term "coarse-crystalline CCC" for coarse-crystalline Cryogenic Cave Carbonate.

Comment: Page 2151 line 16: "The size of these crystals varies from several tenths of micrometers to several millimeters." Do you mean TENS of micrometers, or maybe tenths of MILLIMETRES? Reply: In the final manuscript, we revised this inconsistency – it is meant "tens of micrometres".

Comment: Page 2152 line 1-2: I would insert one composite table with the most common CCCCC morphologies in the main text, and leave the supplement for more complex morphologies and CCC. Reply: A detailed description/characterization of the particular morphological types of coarse-crystalline CCC is not the topic of this manuscript and will only be included as an electronic supplement including the most typical morphologies. A detailed description/characterization of the morphology of CCC would require a paper on its own. The articles cited in the manuscript contain abundant photo and micro-photo documentation of these morphologies, and we think that information contained in the supplement is sufficient for the general reader.

Comment: Page 2152 line 13: Have you analyses about the fact that the CCC are made of low-Mg calcite? This can be a useful data to insert. Otherwise, you should have to remove the sentence. Reply: These data are not available for all studied localities. Thus, the information about the Mg content of CCC will be removed in the revised manuscript. Data on carbonate chemistry of coarse-crystalline CCC are available only for several of the studied localities, and are contained in the cited papers. The low Mg content of the CCC results from the nature of the cryogenic process. Since the ionic radii of Ca^{2+}, Mg^{2+}, Mn^{2+}, and Sr^{2+} differ, their segregation coefficients between ice and bulk initial water differ as well. Based on experiments of Killawee et al. (1998, Geochimica et Cosmochimica Acta 62: 3637-3655) it can be concluded that smaller ions (e.g., Mg^{2+}) are less effectively segregated into the residual (yet unfrozen) water than the larger ions (e.g., Ca^{2+}). The proportion of magnesium trapped directly in the ice is therefore slightly higher compared to calcium. As a result of this, the Mg content in the cryogenic carbonate is reduced and it is usually lower than in the limestone hosting the cave). The CCC samples from the German caves were analyzed by XRD with quartz as an internal standard. All CCC are formed by nearly stoichiometric calcite (d104 = 3.034 – 3.036 Å).

Comment: Evidence for cryogenic origin of the CCC. This is an important part of the paper and should have not to be treated in just 9 lines, especially if you want to expand the growth mechanism part (for example, is not state clearly which kind of crystals developed at the pool bottom and which one, or which side, at the water/air interface. As stated above, I would restrict this discussion to CCCCC. Otherwise you should have to discuss why the fine-powdery CCC cannot be partially related to evaporative phenomena, being their isotopic composition (Fig. 1). Reply: The information about cryogenic origin of CCC will be expanded as proposed. So far, the formation of coarse-crystalline CCC has not been directly observed in caves. Thus, the exact position of each type of crystals and crystal aggregates within the freezing pools is not available. Several models were published and their summary is contained in Fig. 5. After melting of the ice fill of the cavity, all coarse-crystalline CCC aggregates are mixed together and deposited together on the bottom of the cavity. We only know the chronological sequence of crystallization of the individual morphological types based on the stable isotope systematics of CCC. The information on these aspects will be extended in the final paper.

Comment: Page 2157 line 24: “or origin by disintegration of the host limestone is excluded”: I think that no one would ever consider this possibility! Reply: This statement

has been removed from the revised manuscript. However, this possibility was considered by Skřivánek (1954) in a local Czech journal. More detailed modern studies do not consider this possibility anymore.

Comment: Section 2.3. In the description of the different caves there are several information about the speleogenesis and the evolution of some cave systems. Being a kind of review paper I presume that all these information are available in the original papers and, anyway, they are not essential to the presented topic: I would suggest to remove them. On the other hand there are scattered and incomplete information about the host rock lithology. In some part of the paper is suggested the importance of the limestone host-rock for the development of CCCCC, but this hint is not further investigated. The information about the host rock lithology and porosity can be added in the “Basic cave description” column in Table 1. Reply: Characterization of the speleogenetic types of the studied caves was included in the table because each speleogenetic process produces typical cave morphologies. These typical morphologies provide information on the typical ventilation regimes of the caves. For instance, the phreatic maze cave systems formed by injection of river flood-water are frequently characterized by a combination of halls and narrow passages, and remote parts of them show very limited ventilation. In contrast, chasmal Alpine caves commonly consist of vertical or steep-sloped voluminous shafts and show a much higher degree of ventilation. These aspects led us to include this information in the manuscript. Since this information is provided in the table and does, thus, not require any extra space, we propose to the leave it in the manuscript. The information on the host rock lithology will be added to the Table 1. Most of the porosity important for groundwater flux in the studied caves is represented by fractures and faults, not by limestone porosity.

Comment: Section 4.2 Ventilation of the studied caves. To properly evaluate this part more data about the MAAT and in cave MAT at the CCCCC sites are needed. I would suggest to insert two new columns in Tab. 1 with these data (when available) in order to give to the reader the tool to properly comprehend the subject. Reply: The data will be provided in Table 1 where available. For the surface MAAT, the data from the nearest stations will be used because there are usually no weather stations close to the cave entrances. For the interior of the caves, typically only single temperature measurements are available because none of the studied caves is equipped with data-loggers recording continuous cave air temperature data-series.

Comment: Section 4.3 Age and model of formation of the studied CCC. This part of the discussion and the followings are the most important ones, but the paleoclimatic implications of the CCCCC ages are suggested but not completely exploited. Being the specific target of Climate of the Past I would recommend to investigate and discuss in more detail this part: 1. How the age distribution compare with the growth periods and growth frequency variations of "usual" speleothems (cfr. Baker et al., 1993) and stable isotopes speleothem records (cfr. Genty et al., 2003; Boch et al., 2011 and ref. therein)? (If you modify Fig.4 with a growth histogram (see below) you can comment more precisely on this point). Reply: Figure 4 will be modified as suggested in the revised version of the manuscript. However, comparison of the occurrence of CCC and speleothems for the same time period but for different areas is not straightforward. This is mainly due to the fact that growth of CCC and speleothems is caused by different mechanisms. The growth of CCC requires the formation of ice inside the cavity where CCC is formed. In contrast, the formation of speleothems requires an ice-free cavity and biological activity above the cave in order to maintain higher pCO2 within the soil zone than in the free atmosphere. Therefore, in different regions, the conditions may be suitable for both CCC and speleothem formation at the same time. Furthermore, the permafrost-melting propagates down very slowly. This may cause the occurrence of speleothems and CCC within the same cave system because speleothems may grow in those parts of the cave system, which are closer to the surface and, thus, already ice-free, and CCC may be formed in deeper parts of the cave system, which are lying within the 0 °C zone. As discussed in the paper, permafrost melting at depth can be significantly delayed with respect to surface climate as is clearly evidenced by local permafrost lenses surviving from the Last Glacial until today in NE Poland (cited

in the paper). The circumstances are, therefore, rather complex. Nevertheless, the discussion of CCC formation vs. speleothems growth will be extended in the revised manuscript.

Comment: 2. Can you explain in more detail the CCCCC formation in the 50-58 and 80-85 ka intervals during which "usual" speleothems commonly growth in Europe (cfr. Baker et al., 1993, Boch et al., 2011)? Reply: Part of the reply is already contained in the point above. These ages were obtained from caves, which are located near the northern limit of the zone containing coarse-grained CCC in Europe, or at higher elevations. Of course there is growth of "usual" speleothems possible during interstadial phases of the Weichselian, when the permafrost thickness was thinner or absent compared to stadial phases. Simultaneously the data indicate that the formation of CCC was possible in the relic permafrost lenses in the northernmost part of the studied area, or in mountain locations.

Comment: 3. The concepts of the Dansgaard-Oeschger (D-O) events with Greenland Interstadials and Greenland Stadials has to be introduced (cfr. Lowe et al., 2008) and discussed. Reply: Revised as suggested.

Comment: Section 4.4 Estimation of past permafrost thickness. As stated above, the information about present-day MAAT and MAT at the CCCCC sites should have to be incorporated in specific columns in Tab.1 to allow the reader to evaluate the temperature difference with respect to permafrost conditions. Reply: The air temperature data (MAAT, cave air temperature) will be included in Table 1 in the revised manuscript (see also above).

Comment: Section 4.5 Further interpretation possibilities for CCC data. The part on d18Owater calculation is rather an appendix than do not present any new insights with respect to the data presented in Fig.1. For the d18Owater calculation the less negative (initial) values plotted in Fig. 1 vary between -7 and -13 ‰ PDB for the lowlands caves. By using the Kim & O'Neil (1997) eq. (the more commonly used in speleothem studies) the corresponding d18Owater should vary between -10 and -16 ‰ SMOW and not -15 ‰ as stated in the paper. Anyway, it is not possible with the presented data to properly test these values and their implications. I would suggest to remove this part completely (preferable) or rather present and discuss in a more proper and detailed manner. Also the part about the possible calibrations of "clumped isotope thermometry" at low temperatures is rather speculative, by the fact that has to be tested a priori the equilibrium isotope fractionation of these calcite crystals. I would suggest to remove it, at least in the conclusions. Reply: Revised as suggested.

Technical corrections. Practically, all proposed technical corrections have been accepted. Two points require a more detailed reply:

Comment: Fig.3: The cave sections are really small to read. The plate should be possibly assembled in a more square proportion in order to enlarge the final scale. Reply: The figure was prepared as a whole-page figure for the printed journal version (with the figure caption printed on the opposite side). In the CPD on-line version it was reduced by the publisher to approximately one third of the real size. Since it can be easily enlarged to readable size in the PDF version of CPD, we accepted this size reduction. We hope that it will be much larger in the final printed paper.

Comment: Fig.4: Substitute the age data line with a histogram. Possibly highlight in different color /shading in the histogram the data relatives to high-elevation (and/or low presentday temperature) caves. Remove the vertical gridlines and substitute them with the boundaries of the relevant MIS or GI stages. Add VPDB and VSMOW respectively to the axis titles. Reply: Revised as suggested.

Interactive comment on Clim. Past Discuss., 8, 2145, 2012.