Interactive comment on **"Holocene climate change, permafrost, and cryogenic carbonate formation: insights from a recently deglaciated, high-elevation cave in the Austrian Alps"** *by* C. Spötl and H. Cheng

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General comments

The paper is very useful since it touches several general aspects of speleothem-based paleoclimatic studies requiring further research and detailed discussion (I will briefly discuss these general aspects below). The paper also represents a report on a new find of Holocene coarse-grained cryogenic cave carbonate (CCC_{coarse}) in a high-altitude Alpine cave, which are the facts justifying the publication. Nevertheless, the relationship between the outside climate and the cave microclimate under the present-day conditions, the importance of cave morphology on its microclimate, and especially the relationship between cave microclimate and surface climate during the transition from a permafrost setting to a non-permafrost setting in the past should be discussed in more detail. The morphology of the cave under study is quite different from caves hosting the CCC_{coarse} in lowlands and highlands of Germany, Czech Republic, Slovakia and Poland which makes such more detailed discussion crucial. The paper can be published after a wider discussion of these aspects and after reconsidering/modification of some formulations discussed below in the Specific comments.

General discussion: Contrasting response of different cave microclimatic types to surface climatic changes

Possible systematic differences between cave microclimate and surface climate are usually not discussed in sufficient detail in the speleothem-based paleoclimatic studies. The relationship between cave microclimate and the surface climate becomes more complex during the transitions from non-permafrost to permafrost settings and vice versa. Most of the traditional assumptions on cave microclimate usually considered as correct cannot be taken as valid any more during these important climatic transitions. Studies of the relationship between cave climate and present-day permafrost distribution are not frequent (e.g., Pulina, 2005; Mavlyudov, 2008). The response of cave climate to former permafrost formation and destruction was theoretically modelled by Pielsticker (2000).

To investigate the response of cave microclimate, especially temperature, during permafrost formation and destruction it is necessary to understand the processes governing the transmission of surface climatic changes into the cave. In general there are two mechanisms: heat advection, via moving air or water, and heat conduction through the soil and karst rock (in combination with the geothermal flux from below). An overview of cave climatology based on heat transfers was given by Badino (2010) or by Domínguez-Villar (2012).

For the discussion of paleo-microclimatology of caves it is useful to define theoretical climatic end-members of the caves, i.e. specific cave types, each with one dominant heat transfer mechanism: i) heat is transferred with the cave airflow; ii) heat is transferred with the underground water flow, and iii) heat is transferred by conduction within the rock. The response of the cave mean annual air temperature (C-MAAT) to the changes of surface mean annual air temperature (S-MAAT) can be different in each of these cave types. I suppose for this brief discussion caves which are located deeper than about 15 m below the surface. The effect of surface seasonal temperature changes transmitted to the cave by heat conduction through limestone is already negligible at this depth (Badino 2010). The theoretical cave end-member types are as follows:

Type 1: Caves or cave sections dominated by heat transfers related to cave airflow. In this cave type, air circulation is the dominant factor that controls C-MAAT. Cave air circulation can have several physical drivers, e.g., the pressure difference between the interior of the cave and the external air and density differences; a summary of different air circulation scenarios active under different cave morphologies was given by Badino (2010) or Domínguez-Villar (2012). Short caves with large open entrances, multi-entrance caves with large open entrances located at different elevations, or multi-entrance caves with a large open entrance in a rock face opened to strong exterior winds belong to this category. Under surface climatic changes the C-MAAT of these dynamically ventilated caves or cave sections is usually close to S-MAAT and rapidly follows the surface climate. These caves may even show seasonal variations in cave temperature, which are always strongly attenuated and usually delayed with respect to surface seasonal variations (Cropley, 1965). Latent heat related to water condensation and water evaporation in the cave can further enhance the heat transfers.

Subtypes of Type 1 caves: Within this cave type, there exist several specific sub-types whose C-MAAT strongly differs from the S-MAAT. Warm air masses circulating in upper sections and cool air masses circulating at the bottom can be trapped in chimneys or vaults and in deeper sections of a cave (Pflitsch and Piasecki, 2003; Luetscher et al., 2008). *Cold air-trap* or vertical *snow-trap caves* are typically caves without water streams, with one or several large open entrances located at a higher elevation than most of the cave. During winter, cold dense air sinks into inclined descending caves. Because of its higher density, it is trapped there year-round. Caves of this morphology show a high ventilation in winter (with cave temperature drops strongly below 0 °C) and a limited ventilation during the warmer part of the year, when the cave temperature is stable and generally close to 0 °C (the temperature is stabilized by melting of perennial ice accumulations; Perşoiu et al., 2011). These caves have the C-MAAT lower by several °C than the S-MAAT, and can host perennial ice accumulations even in areas of temperate climate (Yonge 2004). Empirical data show that the upper limit of the S-MAAT under which caves of this type can keep perennial ice accumulations is about 9 to 10 °C (evidenced by, e.g., Silická ladnica Cave in Southern Slovakia, Bella 2008; see also Karakostanoglou, 1989; Silvestru, 1999; Mavlyudov, 2008; Luetscher et al., 2008). Similarly, caves having a large open entrance at their lowermost point are *warm-air-trap caves*, with their C-MAAT higher than S-MAAT.

Type 2: Caves or cave sections dominated by heat transferred by flowing water. If the water flow or water dripping through the cave are sufficient (and the cave ventilation is limited), the cave air temperature is controlled dominantly by the thermal equilibrium between the cave air and water. In this case, flowing water controls also the rock temperature around the cave (Badino 2005). A good example is represented by deep chasmal caves of the mountain karst with permanent or temporary water flow, which do not follow the usual geothermal gradient (Badino 2010 and references therein). In deep caves the transformation of the water potential energy to heat, as it falls down, has also be taken into account (cf. thermal profile of the Krubera-Voronya Cave; Sendra and Reboleira 2012). While under non-permafrost settings, water flowing in the underground cools the deep subsurface environment (the geothermal gradient is much less steep than the undisturbed one), under permafrost conditions the circumstances are different. A cave with seasonal water flow can have its C-MAAT slightly above 0 °C and thus represents a talik in the permafrost. This relates to the fact that common low-mineralized water cannot flow at negative temperature. Seasonal summer water flow through these caves (of water with temperature slightly above 0 °C) transports the heat inside and keeps the cave unfrozen and hydrologically active (Ford and Williams, 2007). Another theoretical sub-type lies at the opposite end of the thermal spectrum: caves climatically fully controlled by the thermal groundwater inflow, whose C-MAAT markedly exceeds the S-MAAT.

Type 3: Caves or cave sections climatically dominated by heat conduction within the rock and by heat exchange between the rock and the cave air. If a cave is isolated from the heat transfers related to water flow or air circulation, this third factor becomes the most important one. These caves are typically inactive today (without water streams, with low quantity of drips), and have been usually formed under different morphological or climatic conditions in the past. Their entrances are usually narrow and can be partly or completely blocked by roof collapses and/or their corridors are sealed by sediment fill in some sections (or by temporary snow fields and/or ice plugs under glacial climates). These caves show barometric cave airflow (in relation to variations in external atmospheric pressure) in some cases, but air in their internal sections is little exchanged. With respect to usual ~100% air humidity, latent heat production/consumption related to water condensation/evaporation is negligible. Since the permafrost formation and destruction are very slow processes (which can be significantly delayed with respect to surface climatic change), any cave paleoclimatic data derived from Type 3 caves have to be evaluated with care when correlating them with surface climatic changes, especially in caves located deep under the surface. It should be noted here that relics of permafrost formed during the Last Glacial can locally still survive at depth in the lowlands of Central Europe, as documented by Szewczyk and Nawrocki (2011) in Poland. This clearly evidences the large “inertia” of the permafrost.

It should be noted that the above defined cave types (Type 1 with heat transferred by airflow, Type 2 with heat transferred by flowing or dripping water, and Type 3 with heat transferred via conduction within the rocks) are theoretical end-members. Under real circumstances the cave systems can be influenced by all types of the heat transfer. The conditions can also change temporarily, when an ice plug blocks the cave entrance, or if the stream flowing through the cave during an interglacial or interstadial disappears because of low precipitation quantity and restricted infiltration during a stadial. Transitions from one dominant heat transfer mechanism to another one can be considered as probable during the permafrost formation and destruction.

Cave types 1 and 2 can show (usually small, but measureable) negative and positive differences of the C-MAAT from S-MAAT. Under specific circumstances, they can form major thermal inhomogeneities in the subsurface environment, locally disturbing the geothermal depth gradient. They can form a talik in the permaforst (Type 2), or isolated permafrost occurrences (cold traps) in the area far behind the limits of sporadic permafrost (Type 1), as discussed above. Therefore, they are not well suited for the studies of distribution of the former permafrost. Only Type 3 caves are more suitable for such studies. Fortunately, it is this cave type that hosts majority of the accumulations of $\mathrm{CCC}_{\mathrm{coarse}}$ in lowlands and highlands, which are mostly absent in other cave types.

The reviewer hopes that the theoretical discussion above shed some light on possible complex relationships between cave microclimate and surface climatic changes – an aspect which should be discussed in more detail in the reviewed paper. The opinion of the reviewer is that the studied Mitterschneidkar Eishöhle (further MSK Cave) possibly changed its microclimate type several times. It could have functioned as a cold-air trap in periods of low precipitation and low snow quantity, or as Type 3 cave when the entrance was completely blocked by ice/snow or rock debris. One possibility is that the formation of $\mathrm{CCC}_{\mathrm{coarse}}$ was related cave microclimate at a transition from Type 3 to Type 2, i.e., a massive influx of infiltration water into an empty cavity, which was located in the permafrost zone. If this was the case, the formation of $\mathrm{CCC}_{\mathrm{coarse}}$ could have been generally related to a high-precipitation (rain) period rather than a high-temperature period.

Specific comments

Page 1494, Abstract, lines 5–7: Information contained at the end of the first paragraph of Abstract is partly misleading. The sentence seems to indicate that the CCC_{coarse} can form during ice melting, which is not correct. The published models of the CCC_{coarse} formation explain its precipitation during periods of permafrost destruction, but yet deep inside the permafrozen zone, **during progressive karst water freezing**. The rates of precipitation and infiltration are strongly reduced during the coldest glacial conditions and permafrost growth, usually preventing any speleothem formation. In contrast, warming periods are usually accompanied by higher precipitation and infiltration, more vegetation on the surface and thus higher CO_2 charge and higher mineralization of the infiltrating water. Penetration of such groundwater into still frozen cavity deeper inside the still permafrozen zone results in its slow freezing and CCC_{coarse} formation. The model is therefore based on a delay between the surface climatic changes and the permafrost destruction at depth. CCC_{coarse} formation models presented in Žák et al. (2004) or Žák et al. (2012) did not exploit repeated cycles of ice formation, i.e. melting and refreezing. In fact, during the complete water-freezing event, the dissolved carbonate species typically precipitate as cryogenic minerals (CO_2 escapes into the cave atmosphere and is ventilated out). Solid carbonate phase typically survives ice melting in the form of solid mineral particles, which reduces the mineralization of the meltwater. Formation of another portion of CCC_{coarse} by refreezing of this meltwater is therefore improbable. Observations of two or more stages of CCC_{coarse} formation in one cavity can be therefore much more readily explained by a repeated influx of a new portion of mineralized water from the suprapermafrost layer and its freezing deeper in the permafrozen zone.

Page 1494, Abstract, lines 13–14: Similarly, the formulation "...pools of water carved in ice..." seems to indicate that the formation of the pools was related to ice melting. The pools can be residual water bodies produced during progressive water freezing. It should be also mentioned here that the morphology of cave ice in a cave in the permafrost should be much different from the morphology of perennial ice in an iced cave (cold air traps) in a non-permafrost setting. The cavity walls are cold (below the freezing point) in the permafrost setting, ice is formed on the walls, and the residual (ice-covered) pool of the progressive freezing remains somewhere in the middle of the cavity. In contrast, cavity walls in ice caves located in a non-permafrost setting are warmer (above 0 °C), and ice is thawed close to the walls.

Page 1494, Abstract, line 17: With respect to the general discussion given above, the CCC_{coarse} formation in this specific cave could possibly reflect not only the permafrost destruction but more probably a period with higher precipitation, especially summer precipitation in the form of rain. In fact, this conclusion is contained in the Abstract below.

Page 1495, lines 20–21: Both types of CCC have been directly observed and sampled in caves. What was never done for the CCC_{coarse} is a direct observation of its crystallization. Please, modify the sentence to present this more clearly.

Page 1495, lines 26–27: I recommend to add the mentioned data (an attempt to date CCC_{fine}) in the paper or as a separate online-available supplement, even if the dating was not successful. This is better than referring to "unpublished data".

Page 1496, line 6: There is a fresh paper by Chaykovskyi et al. (2014) describing CCC_{coarse} from a cave in the Ural Mts., Russia, which is the first internationally published report on the occurrence of this type of speleothem outside Central Europe.

Page 1496, lines 14–17: The formation of CCC_{fine} is almost certainly much more widespread. The existence of CCC_{fine} has been reported from ice caves in the Carpathians, i.e. in the eastern part of the Alpine-Carpathian mountain chain (references are contained in Žák et al., 2012).

Page 1496, lines 26–27: It would be useful to know the dimensions and morphology of the cave entrance.

Page 1497, line 5: It would be useful to know whether the layering of ice was parallel to the corridor slope or rather horizontal.

Page 1497, lines 25–26: If I read Fig. 5 properly, summer temperatures recorded at the lower end of the MSK Cave reach quite high values of up to +6 or +8 °C during summer, which is rather surprising for a cave of this morphology. Is there any explanation for these temperatures? They indicate a rather dynamic behavior of the cave atmosphere in periods when the upper entrance is not sealed with snow. Are there any cave entrances on the western side of the range?

Page 1498, lines 5–6, a comment related to mineral X-ray diffraction: Metastable carbonate phases like ikaite can survive usually a few hours or days at usual laboratory temperatures, or a few minutes under the X-ray beam. They become converted to calcite thereafter. In a cave like this, providing a chance for a preservation of some metastable carbonates, the best practice is to transport the sample from the cave at temperature close to 0 °C and analyze it by X-ray diffraction using a rapid procedure (or under cooling). If this procedure is not followed, metastable carbonate phases cannot be detected. This comment relates also to page 1499, line 19.

Page 1499, lines 3–5: If I understand the circumstances well, there has been no significant frost-shattering event in the cavities hosting $\mathrm{CCC}_{\mathrm{coarse}}$ after $\mathrm{CCC}_{\mathrm{coarse}}$ precipitation, while a lot of frost-shattering before its precipitation. Such circumstances are quite typical for most $\mathrm{CCC}_{\mathrm{coarse}}$ sites.

Page 1501, lines 7–9: It would be useful to know what was the U content in the much older usual-type flowstone, which was also dated. Data are mentioned in the text but do not appear in any table.

Page 1502, line 1: I cannot fully agree with the statement that the MSK site shows many similarities with the previously reported $\mathrm{CCC}_{\mathrm{coarse}}$ localities. The studied sites in the MSK Cave are located about 100 and 140 m from the entrance but in a branch of a large-diameter corridor, which would certainly act as a cave with a dynamic behavior of cave atmosphere, if the entrance is opened. I fully agree with the interpretation contained in the discussion that the entrance was somehow blocked during the $\mathrm{CCC}_{\mathrm{coarse}}$ formation and that the heat transfer mechanism before the $\mathrm{CCC}_{\mathrm{coarse}}$ formation was most probably close to the Type 3 microclimate defined above. Most other sites located in the lowlands and highlands of Central Europe are of complex cave morphology. Their cooling as a cold-air trap was never possible. These caves show practically no seasonal temperature variations, which is a big difference from the temperature record of the MSK.

Page 1503, line 8: There is a lack of soil and vegetation above the MSK Cave now, but the present-day upper limit of grassy fields does not lie much lower. Under different climatic conditions in the past, grassy patches could have been present above the cave. In fact, it is not known from which direction did the groundwater penetrate into the cavities hosting the $\mathrm{CCC}_{\mathrm{coarse}}$.

Page 1505, lines 2–3: The conclusion is not correct since the isotope data indicate clearly that the studied $\mathrm{CCC}_{\mathrm{coarse}}$ formed during water freezing inside the cavity, not melting. Possible melting (permafrost destruction is perhaps a more suited term) can relate to the upper part of the permafrozen zone above the cave. The possibility of influx of mineralized water via an open channel was already discussed.

Page 1504, lines 8–13: See the earlier comments to the abstract regarding the concept of refreezing of meltwater and pools of meltwater on the ice surface.

Technical corrections

Page 1496 line 3: The paper by Orvošová et al. will be included in the 2014 journal volume. Please, cite it as year 2014 with DOI, or use full reference if the paper is already included in the volume.
Page 1503 line 15: there is a typo: properly ...slow freezing... instead of ...low freezing...
Page 1506 line 7: Perşoiu instead of Perôiu, the same typo is in the References.
Page 1516, caption of Table 1: Sample numbers should refer to Fig. 3, not to Fig. 1.
Page 1516, caption of Fig. 1: The word Cave should be with capital C in all cases.
Page 1518, caption of the Fig. 3: Please, state the names of the authors of cave mapping if different from the authors of the paper. The authors of cave mapping, which is the first step towards a scientific study of a cave, should always be cited.
Several references used in the paper are not contained in the reference list: Clark and Lauriol (1992), Fohlmeister et al. (2013), Luetscher et al. (2007).

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