

## ***Interactive comment on “Application of ground penetrating radar (GPR) in Alpine ice caves” by H. Hausmann and M. Behm***

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(Author) General: We thank both reviewers for their in-depth discussion of the MS. We see that a main point of criticism derives from the absence of a profound discussion/interpretation section. Based on detailed suggestions of both reviews, we will add this section in the revised MS, and it will include the following issues:

1) Discussion of EM velocities With regard to an uncertainty analyses, the discussion of the EM velocities and the density data (from the Eisriesenwelt ice core) should help to address the following questions:

- Based on the observed low average density, how much air could be present in the ice?

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- Subsequently, how much liquid water would be needed to explain the overall low EM velocities?

2) Discussion of the observed layering in the radargrams

- Correlate these layers with the visual inspection of the stratification (again, uncertainty analysis is needed)?

- Could the accumulation of calcite minerals cause the internal layers?

- Possible mechanisms for the formation of the layers? Are they isochrones?

Major changes will encompass the refinement of the MS structure as well as the use of clear phrases to describe the reflections or the cave ice itself. We will shorten the section “method” and integrate the description of the data processing found in the section “measurement and data processing”. We further will follow the reviewer comments to move all results to the section “results”. To show how the observed layering in the radargrams correlate with layers from the visual inspection of the stratification we will introduce a new figure from the location “before Saarahalle” (Feenpalast, ice cliff).

The comment from the anonymous reviewer lead to a new title of the MS: “Imaging the Structure of Cave Ice by Ground-Penetrating Radar”.

In the following Authors comments, we try to answer some specific questions. We also outline the major changes in the structure and style of the MS. Minor issues (e.g. style of language) will be addressed in the revised MS.

(Reviewer) This paper describes the collection of ground penetrating radar (GPR) profiles over ice deposited in caves beneath the Austrian Alps. The study of these deposits is of importance as the cave ice sequences might contain valuable climate information. The application of GPR to imaging the cave ice is a novel and appropriate approach and should provide ice volume data, information on the basal interface and internal ice structure. Unfortunately, in its current form, this paper lacks a clear aim and findings and firm scientific conclusions that add to our knowledge of cave ice deposits. My initial

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general points are: The data is important, well collected and is generally well displayed. Integration of photographs with the radar profiles, rather than a separation of the image sets would make it easier to follow the labels and commentary.

(Author) In the MS we decided to first present photographs showing the visual outcrop of layers within the ice and to provide an impression of the diversity of the investigated ice. Secondly, we present the radargrams. Since scale and geometry of the photographs are quite different to that of the radargrams, and can't be easily distorted, we prefer to keep the existing separation of photographs and radargrams.

(Reviewer) There is also only limited need to display unmigrated profiles as they add little to the descriptions.

(Author) Since many publications still show unmigrated sections, we decide also to keep the unmigrated data. Further, a comparison between unmigrated and migrated data makes it possible to discover possible errors or inaccuracies in the migration.

(Reviewer) The title of the article does not indicate any real results – applying a tool, i.e. GPR is insufficient – there needs to be a scientific outcome for a paper in the Cryosphere. I am unsure what the aims of the paper really are. In places there seems to be a suggestion that the paper will characterise the internal structure of the ice. There are also comments regarding the subsurface reflection signature, which is described and discussed.

(Author) We will change the MS title to 'Imaging the Structure of Cave Ice by Ground-Penetrating Radar'. More importantly, we will restructure the paper such that a clear distinction between the description of the radargrams and the interpretation is made.

(Reviewer) More critically, there is a comment in the abstract and in the last paragraph of Section 1 about characterising ice thickness and extent, i.e. ice volume, though this is not done.

(Author) In general GPR profiles were conducted on locations where the ice had a flat

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surface topography. This was necessary to improve the antenna coupling as well as to move the antenna uniformly along the ice surface. At locations where the ice beside the GPR profiles showed huge undulations in their surface topography we could not calculate the ice volume without a 3D survey of the topography (e.g. laser scanning). Thus we will clarify the abstract, table 1 and add a calculation for the volume at Feenpalast.

(Reviewer) A number of terms are used somewhat interchangeably for the ice in the cave:- 'ice fillings', 'ice caves' and 'cave ice'. The term 'ice cave' is confusing in this context. These are caves with ice in them. I would prefer to see a distinction between the cave and the 'cave ice' within it and this later term used throughout to describe the deposit.

(Author) We agree that the term "ice cave" might also describe cavities found in glaciers or ice sheets. However, in central Europe we use the term "Eishöhle" (german) which literally translates to "ice cave". Since the TCD special issue uses the same term we still use it. Therefore we will consistently use "ice caves" to describe the caves and "ice" to describe the cave-ice (except for the title).

(Reviewer) The structure of the paper could be improved. Section 2 on ice caves is a general introduction that should come at the beginning of the paper.

(Author) Will be done.

(Reviewer) Towards the end of section 2 there is acknowledgement that detailed field descriptions and ice thickness results have already been presented in another paper, suggesting that internal structure is key to this paper. If so, state this from the beginning and integrate results into the abstract. The statement in the abstract with regards to internal structure is that 'internal structure.. is characterised by banded structures which are inclined or parallel to the subsurface topography'. This is not particularly helpful as it seems to cover most eventualities, so lacks relevance.

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(Author) We will address to this comment and will change the abstract.

(Reviewer) The methods section is a general background to GPR rather than a description of the measurements and data processing that come in the next section.

(Author) We will reduce the general background and will left only parts that describe internal structures such as layers within the ice. In addition we will move the parts describing the data processing to the section "methods".

(Reviewer) The measurements section has obvious error or omissions e.g. the band pass filter given would not work for the 200 MHz data, so must be the filter used for the higher frequency antennae. Clear filter parameters should be given for the data sets displayed in the paper. The Fresnel zone is mentioned, but not calculated for the different frequency of antennae or the ice depth.

(Author) We will add the description of the bandpass filter for the 200 MHz antenna (50-100-400-600) and an estimation for the Fresnel zone. For an investigation depth of 5 m and an electromagnetic wave speed of 0.167 m/ns the Fresnel zone has a radius of 0.9 m (500 MHz) or 1.45 m (200 MHz), respectively.

(Reviewer) Errors are also found in the interpretation of the GPR. Following seismic descriptions, a multiple would have a dip twice that of the first reflector. I doubt there are any true multiples here – possibly ghosts or ringing but not multiples. The phrase 'high reflective diffraction hyperbolae' is very confusing. They are high amplitude reflections. Are they hyperbolae? This phrase has a strict meaning, i.e. they are generated at a point. Are they diffractions? The GPR descriptions need care and attention throughout.

(Author) We will improve such phrases to avoid confusion.

(Reviewer) The descriptions of the 4 caves are a mix of field site descriptions as well as results and interpretation from the GPR surveys. I suspect a significant amount of this description is found in other papers. These field site descriptions should be shortened and all results moved to the results section. The results section is very

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short. Systematically describe all your reflections to explain your data.

(Author) We will split up the measurements section and move the results into the results section. In addition we will short the residual description of the caves.

(Reviewer) There then needs to be a clear interpretation section. Some of the interpretation, indeed some of the results are found in the conclusions, where new data is presented for the first time. Comparing GPR reflections with sediment bands should be done systematically in the results section.

(Author) We will introduce all data found in the conclusion for the first time in the previous section results. Instead of an interpretation section we introduced a chapter discussion where the interpretation of GPR data leading to the final interpretation results is discussed.

(Reviewer) Conclusions need to address the aims of the paper, once the aims of the GPR survey are clearly stated. I will happily send a list of corrections to the written English in the paper to assist with the Editorial process, but do not feel now is the appropriate time to do this as I believe the paper first needs restructuring to address the issue I raise above and there are a significant number of minor corrections to make. I agree with the posting by the first reviewer – 'great data, more discussion needed'

(Author) We will rewrite the conclusion section to focus on the aims of the paper. We appreciate to receive a list of corrections to further improve the MS.

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Interactive comment on The Cryosphere Discuss., 4, 1365, 2010.

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