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The Cryosphere Discussions

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?

- 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 Saarhalle" (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) In this study the authors present terrific geophysical data sets, which could help to elucidate the formation and evolution of ice bodies formed in caves. Observable intra ice stratigraphy has the potential to assist interpretation of ice-core properties in terms of climate change as recorded in the cave, as has been the case for glaciers. The presentation of ground-penetrating radar data acquired in four different caves indicates differences in the internal structure as well as at the boundary characteristics between ice and the underlying bed. As ice bodies in caves often have accessible sides of considerable length (as demonstrated here) they moreover provide a terrific opportunity to directly relate observed GPR features with interfacial properties. In this respect this study with its suit of different reflection characteristics is also of interest to a wider readership dealing with other ice bodies, as it could serve as reference for interpreting interfacial characteristics within or underneath glaciers, where otherwise only small diameter ice cores (if at all) are available. Especially as the ice bodies in caves basically do not show any dynamic behaviour the interpretation can thus be simplified.

(Reviewer) Although the data itself is worthwhile presenting, the study has the potential to provide further interpretations and move from a basically descriptive account on what was observed to quantitative interpretations of wider interest. Unfortunately, in its current form it falls somewhat short of providing sufficient evidence and discussion. Given TCD's evaluation criteria, I think the MS has the potential for excellent scientific significance, with the potential to improve both scientific and presentation quality easily further, with encouragement of the authors to do so.

(Reviewer) The authors focus on describing the observed stratigraphy and only marginally refer to other studies which provide more detailed insights into the physical properties of the ice as e.g. available from two ice cores. With the data available from GPR and ice-core measurements it is easily possible to perform more quantitative analyses. More quantitative information should be provided on the background conductivity and maximum peak heights as well as density from ice cores.

(Author) Until the submission of the MS profiles on the permittivity and conductivity were not available from the two ice cores. For the DMH ice core the samples were not cooled during the transport since the aim was to investigate the isotopic composition. Conductivity measurements have been done for the meltwater of both cores and can thus be not directly related to the GPR measurements. We will mention the average electrolytic conductivities in both caves (ERW: 10 – 50 yS/m; DMH: 100 – 200 yS/m) in the revised MS, but we think that a detailed discussion of these conductivities is beyond the scope of the MS. We will refer in more detail to the density (ERW) in the

forthcoming Discussion section.

(Reviewer) In the abstract it is speculated that the observed layers are isochrones. The only other mentioning of isochrones is in the conclusions, where it is stated that "Accumulated layers of particles ... must represent isochrones". I agree with the latter statement. However, what I really miss is a thorough discussion of this issue in a respective "Discussion" section (which is missing). Even if the observed layers at sides of the ice bodies are isochrones it is not obvious that the internal layering observed with GPR is actually caused by the visible bands (although likely). Although the comparison of the picture in Figure 2g and the radargram in Fig. 3d is mentioned in the text, it is not possible for the reader to verify this comparison. Neither scales nor accuracies are provided. One possibility would be to overlay the radargram on a scaled version of the picture (i.e. provide approximate metric scale on right) or present them face to face. An error analysis is missing concerning the accuracy of the conversion to depth, which is important when it comes to comparison and identification of the reflection mechanisms.

(Author) An estimate of depth the error will be provided. A discussion section will be added.

(Reviewer) In this context the provided structure of the paper is somewhat misleading. Section 4 presents "Measurements and data processing" followed by the section 5 "Results". However, a number of results are already presented in section 4. An actual discussion of the interpretation of GPR data, which leads to the final interpretation results seems to be missing.

(Author) We split up the measurements section and moved all results into the results section as well as to move the data processing to the shortened method section. Further we introduced a chapter discussion where the interpretation of GPR data leading to the final interpretation results is discussed.

(Reviewer) The authors mention that calcite minerals could be the cause for the observed internal structure. However, a thorough discussion is missing and more quantitative results could be provided, e.g. the potential change in dielectric permittivity based on dielectric mixing formulae (e.g. Looyenga) by adding some calcite or other impurities and comparing those to the reflectivity of layers with different air-bubble or liquid water content.

(Author) The results from the introduction of Looyenga's mixing formula will be included in the Discussion section.

Specific comments (Reviewer) The paragraph presenting the data processing is too sparse but easy to fix. Detailed questions follow below. The authors use terms like sub-surface parallel, bed-parallel and alike several times in the text and in Table 1. The readers, especially those not dealing with radar or geophysical methods in general, would benefit from a sketch which could schematically show all of these different features, in addition to "large" and "small" hyperbolae. The authors use "ground" to separate it from "ice". However, given the terminology of ground-penetrating radar (which means that ice is considered as the ground), I suggest to use the term "bed" or "base" instead, implying either a bed/base made up of sediments or solid bedrock. This should be fixed at numerous instances in the MS.

(Author) We will avoid inaccurate phrases (e.g. "large hyperbolae"). The term "base" will be used.

(Reviewer) The authors write Eisriesenwelt-Cave and alike, sometimes Dachstein-Mammuthöhle. First, this should be consistent throughout the MS. Second, I consider Eisriesenwelthöhle the actual name, so "Höhle" should not be translated into English. As a prominent example, everybody talks about "Eyjafjallajökull", but nobody translated it into "Eyja-Mountain-Glacier" or even "Island-Mountain-Glacier". The authors use the term multitude and multiples interchangeably (e.g. p1373). Whereas multitude is ok, the term multiple has a fixed meaning in geophysics: not the one used here. Multiple is used to define multiple reflections, e.g. a wave being reflected at an interface, travelling to the surface, being reflected there once more, moving down and up again.

This is definitely not the meaning here and causes irritation, as true multiples could definitely be possible with shallow ice as presented in this study. The authors should take care to get their terminology unambiguously right. ground penetrating radar -> ground-penetrating radar (all instances)

(Author) We will follow these suggestions.

p1366 Delete "(GPR)" in the title l12 "can result": very unspecific and hypothetical. Could be rewritten more specifically in a revised version of the manuscript, given that discussion of evidence is extended. l24 "ice caves potential" -> "ice caves' potential" p1367 l5 "real- or complex-valued" l9 operates -> operate l21 delete comma after therefore l23 heavy -> dense l24 "light cave air" -> "cave air of lower density" l24 "into cave" -> "into the cave" p1368 l2 delete "out" l4 rocks -> rock l7 MAAT not defined. l16/17 Rewrite to "We only deal with the latter permafrost feature ..." l14 delete "out" l25 "in the actual study" Do you mean this study? Clarify. p1369 l2 "is a geophysical" l3 impulse -> pulse l5 A discontinuity is not required, a gradient is enough! Gradients appear as discontinuities when sampled at discrete intervals. Rewrite. l7 It should be mentioned that a radargram is made up of several traces. l7 radar velocity -> electromagnetic wave speed. Non-geophysicists could mistake radar velocity as the speed at which the radar device is pulled along the surface. Although at other instances. l23 "The radar velocity is mainly controlled": For electromagnetic wave in a low-loss medium, as is the case here, only density and liquid water content can be considered as main factors. All other properties (conductivity, dust, ...) are negligible in comparison to these two factors. l25 ... 0.167 m/ns for ice" -> "... around 0.167 m/ns for pure ice" p1370 l1 ice thickness measurements -> ice-thickness measurements l7 "from a shielded antenna with a center" -> "with shielded antennae at a center" l11 Unclear whether 64 scans per second were vertically stacked or if you obtain 64 independent traces over the area you move within 1 s.

(Reviewer) What does continuous record mode mean? Continuous or quasi-continuous? Please provide information on how you determined the trace interval and its accuracy (obviously, GPS is not available). This is a crucial part of the migration to get velocities right.

(Author) We used the time-based (continuous) mode in combination with a reel and a marker interval of 2 m to define the survey geometry. Profiles were selected on flat areas to facilitate steady moving of the antenna. We estimate the accuracy of the collected traces with a value of $\pm$ 0.02 m per marker interval. Based on these values, we will add an error analysis of the velocities. The procedure of the continuous mode will be described in more detail.

(Reviewer) l11/12 Does this mean you used different record length for different surveys? Or do you mean the range of data you're interested in? In the first case the sample interval likely changed, please provide numbers.

(Author) Depending on the record length the sample interval varies from 0.04 to 0.09 ns for the 500 MHz antenna and is 0.19 ns for the 200 MHz antenna. In all cases this sample interval is sufficient to satisfy the Nyquist condition. Will be added.

(Reviewer) l14 It is actually not the wavelength but the bandwidth which limits the resolution for GPR (i.e. the actual length of the source wavelet). Usually the bandwidth is approximately the nominal frequency. Whether this is the case for the utilized GSSI I do not know but can easily be checked by looking at the direct waves. I would expect one seldomly obtains a resolution of less than half the wavelength.

(Reviewer) l15 Provide numbers on how large the first Fresnel zone is at typical ice thicknesses obtained in this study.

(Author) For a 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) and 1.45 m (200 MHz). Will be added.

(Reviewer) l16 What is trace mixing exactly? Stacking? Weighted averaging?

(Author) Trace mixing is horizontal averaging, where a median average over 71 traces

is used. This horizontal average is removed from each trace. The whole procedure aims at removing horizontal antenna noise.

(Reviewer) l17 Bandpass filter: do the numbers indicate a linear ramp on either side of the actual center window?

(Author) The applied bandpass filter is a trapeze filter. The values define the four corner frequencies of the trapeze and thus control the slope of the linear ramp.

(Reviewer) l18 How has surface elevation for static correction be obtained?

(Author) Almost all profiles were conducted on planar surfaces. However, for profile "Feenpalast 2" (ice cliff) we surveyed the position of significant changes in the profile height using simple geodetic methods (measuring distances and inclination to points along the profile and calculating relative elevations).

(Reviewer) l15-20 Did you perform any stacking (see above) e.g. during acquisition or during postprocessing? Which migration algorithm was used?

(Author)No. For the migration we applied the Steep Dip Explicit FD Time Migration algorithm with a maximum dip of 50 $^\circ$.

(Reviewer) l21 What is the actual uncertainty in the velocity from this analysis and how does this translate into depth uncertainty? This information is especially important for the reader in regard of the comparison of certain visible features with the internal GPR layering as indicated in Fig 2g and 3d.

(Author) To estimate the actual uncertainty of the velocity determination we applied the analytical error propagation law to the equation for diffraction hyperbolas. We analysed three representative hyperbolas using standard deviations of $\pm$ 0.02 m for errors in the geometry and $\pm$ 1 ns for errors in the time domain. The identification of individual hyperbolas result in an error of $\pm$ 0.006 m/ns. Adding a picking accuracy of 1 ns, the error of the depth conversion amounts to $\pm$ 0.35 m.

l22 differences l26 "We show" -> "In the following we ..." p1371 l7 "25 âU° Ł 10m wide": Either one writes "25 m x 10 m wide" or "25 x 10 m2 wide" or "25 m by 10 m wide" etc. The authors mix "x" and "by" in the manuscript. Please be consistent at this and all other occurrences in the MS.

(Reviewer) l9 How has the variable content of bubbles and the embedded particles been determined? Simply by eye in the exposed ice?

(Author) At places where ice was exposed we made visible stratigraphy - simply by eye and a reel.

l15 transitions -> transition. I would consider this only as a single transition surface in space. l21 Delete "this issue". (Reviewer) l22 Do you mean saturated with carbonate?

(Author) Yes

l23 "transits" -> "transforms" (Reviewer) l25 How has the depth been matched, i.e. how has the depth of the visible stratigraphy been determined? What is the error of this comparison on either side, visible stratigraphy and GPR layer depth?

(Author) For the location "Eispalast" (Eisriesenwelt) we derived depths of 7.3 $\pm$ 0.35 m from GPR and 7.12 m from the ice core. Since the GPR profiles were carried out prior to the ice core extraction (to find the deepest part of Feenpalast) the location of the core is about 1 m beside the closest GPR profile. The undulating base topography makes it difficult to compare these two values. For the location "Saarhalle" depths of 5.6 $\pm$ 0.25 m (GPR) and 5.3 m (ice core) were detected. In Feenpalast 1 values for the depth were 3.2 $\pm$ 0.20 m (GPR), and 3.4 m (visual stratigraphy with tape and plumb).

(Reviewer) l25-7 Unclear, rewrite. How would calcite minerals change the electric properties of the ice-with-impurities mixture?

(Author) This misleading sentence will be deleted. The main point is that the strong stratification is both recognized in the visual inspection and in the GPR data.

p1372 l8 "left part of the ice cliff": Left and right only make sense if a specific picture is referred to next to this specification. Where ever possible it would be better to exactly define the horizontal position in terms of profile distance. Also at other locations of the MS. p1373 l3 ice part -> ice-covered part l6 lie -> range l6 sharply: I would not consider this sharply, rather suddenly or steeply. l6/7 "southern" does not make sense as no indication of north-south-east-west is provided in the figures. Please add geographical directions, usage of which could also replace the usage of "left" and "right" as mentioned above. l7 "reflecting horizon": Do the authors mean the reflection from the ice-bed interface? Specify. l15 NCA is used only once, so I think that abbreviation is not needed. l16 "Opposed" -> "In contrast" l17 heavy -> dense l21 right part: see comment above, use profile distance instead. l22 Please specify "it is known from surface observation": In this study or do you refer to another one? p1374 l4 involves l5 "... several meters in diameter)."

(Reviewer) l9/10 Can you quantify how much larger permittivity? Provide reference. Are the ice bodies frozen to the bed or is the bed at the pressure melting point and some melting occurs? In that case the reflectivity increases also because of liquid water. Add some statement on the temperature of the ice (i.e. all temperate or some polytherm (unlikely)).

(Author) We will state literature values for the permittivity. (Author) For "Eispalast" (Eisriesenwelt) ice temperatures vary from -1.5 °C (winter) to -0.3 °C (summer) close to the surface and have values about -0.4 ° C in a depth of 3 m (Obleitner and Spötl, 2010). Near to the surface temperature measurements (in 8 cm depth) along a vertical profile at Feenpalast also indicate similar bed temperatures indicating ice close to the melting point. Liquid water could be observed at the surface of all ice locations (in autumn). However, at Feenpalast refrozen water was found near the base. Liquid water was also observed at a sample during the ice core drilling at Saarhalle.

(Reviewer) l26f "Voids": If one can observe them it should also be possible to determine their filling. "The infill could be" sounds very speculative, but is it also meant this way?

(Author) As the voids are very small, and our field work focussed on the GPR, we were not able to determine the filling.

p1375

(Reviewer) l1 "water or air": This could be determined by the wave speed. Liquid water reduces the wave speed whereas air bubbles increase it. That's why I consider it important to provide error estimates of the em wave speed and discussion if the observed speeds rather indicate liquid water or air.

(Author) This is an important point and will be addressed in the discussion.

p1376 (Reviewer) l14 I don't think that the conclusion is the right place to mention that changes in crystalorientation fabric (COF) are not part of the game here. This is something which belongs to the discussion (which basically did not take place). Moreover, post-depositional changes in COF can be excluded a priori as stresses are much too low to cause significant changes from isotropic COF distributions. The only other potential origin could be a formation mechanism which causes anisotropic accumulation at the surface, which I am not aware of and would also doubt.

(Author) If "anisotropic accumulation“ means creation of COF during freezing of water (syn-depositional), a possible mechanism may be a slow run-off on a sligthly tilted surface.

l15/16 Likewise, a discussion of the interesting sediment layer (and implications of its sudden termination) is missing. The statement here needs to be discussed much earlier, not just in the Conclusions.

p1380 This table would benefit from the velocity error and maybe also used radar frequencies. Riesen-Eis-Cave: "Not clear" -> "Not clearly visible". Is this what you mean? Eisriesenwelt and Beilstein: "end of the profile: either provide geographic direction or profile distance (see comment above). p1382 l3 "of a fine-grained" -> "of fine-grained" p1384 "in inside" -> "inside" "shallow sediment layer": although marked

at the top it would be good to add the specific depth range. How do you explain that it does not continue beyond profile distance 7 m suddenly? p1385 (Reviewer) Fig 5b: Several events seem to be overmigrated (=smilies). Could the authors comment on this, please?

(Author) Please find attached a migration analyses of the profile using the 200 MHz antenna. If rough velocity steps of 0.10 m/ns are used the hyperbola (at 82 ns) collapses at $0.15 < v < 0.16$ m/ns. Using finer steps one get a value of 0.158 m/ns (or 0.16 if rounded). We think that these similes are artefacts due to migration of “parts of” hyperbolas.

p1388 exhibit -> exhibits (c) "The chaotic" -> "The incoherent" last line: identified -> visible.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/4/C1078/2010/tcd-4-C1078-2010-supplement.zip

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

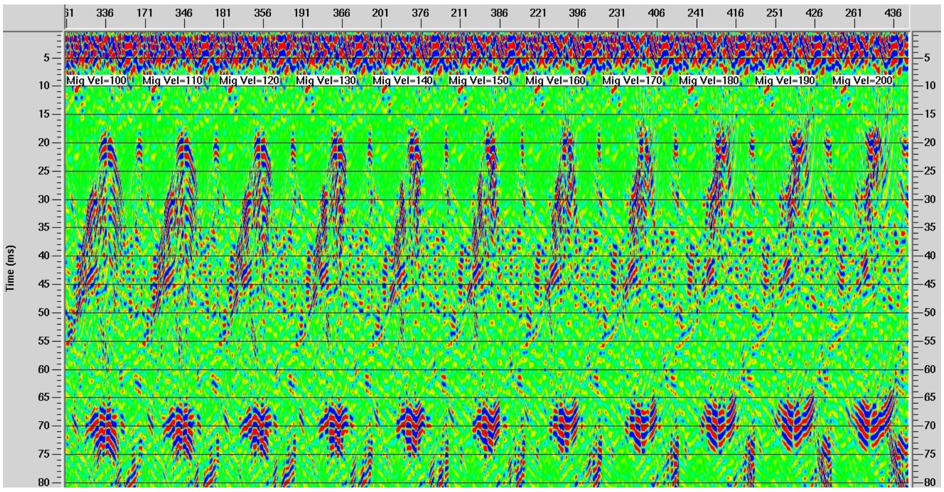
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Fig. 1.