

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

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General comments

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

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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.

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.

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.

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

C922

provided. On 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.

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.

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.

Specific comments

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.

C923

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)

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"

C924

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"

C925

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. 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.

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.

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.

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

l16 What is trace mixing exactly? Stacking? Weighted averaging?

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

l18 How has surface elevation for static correction be obtained?

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

C926

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.

l22 differences

l26 "We show" -> "In the following we ..."

p1371

l7 "25 × 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.

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

l15 transitions -> transition. I would consider this only as a single transition surface in space.

l21 Delete "this issue".

l22 Do you mean saturated with carbonate?

l23 "transits" -> "transforms"

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?

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

p1372

l8 "left part of the ice cliff": Left and right only make sense if a specific picture is referred
C927

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)."

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)).

I26f "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?

p1375

I1 "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.

p1376

I14 I don't think that the conclusion is the right place to mention that changes in crystal-orientation 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.

I15/16 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).

C929

p1382

I3 "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

Fig 5b: Several events seem to be overmigrated (=smilies). Could the authors comment on this, please?

p1388

exhibit -> exhibits

(c) "The chaotic" -> "The incoherent"

last line: identified -> visible.

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