The Cryosphere Discuss., 4, C1642–C1648, 2011
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The Cryosphere Discussions

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4, C1642–C1648, 2011

Interactive Comment

Interactive comment on "A new model for quantifying subsurface ice content based on geophysical data sets" *by* C. Hauck et al.

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Received and published: 21 February 2011

The paper "A new model for quantifying subsurface ice content based on geophysical data sets" by C. Hauck, M. Böttcher and H. Maurer describes a 4 phase model for the description of the volumetric fraction of ice, water, air and rock on the basis of seismic refraction tomography and electrical resistivity tomography. In this novel approach, they combine the slowness averaging concept that has been developed by Wyllie et al. (1956/1958) and transferred to permafrost applications by Timur (1968) with Archie (1942)'s law, as has been anticipated by the effective medium theory by Sheng (1990). The 4-phase theory is convincingly developed in the paper and applied to two well-known case studies. Borehole data provides a general line of verification for calculated ice and solid content while they are less reliable for air content. The sensitivity to

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different initial porosity setting is demonstrated and perspectives and shortcomings are discussed in the final section.

General comments: This in, in general, an excellent and truly innovative paper, that provides a novel quantitative method for the geophysical interpretation of high-porosity permafrost systems. In my view, there are only some minor shortcomings in the present version: (i) The theoretical background could be explained with some more detail with respect to the premises behind Archie's law and Wyllie's / Timur's slowness averaging concept: I think, the reader needs a little bit more background why these concepts were chosen (Introduction) out of a number of possible representations of multiple phase systems (e.g. Carcione and Seriani, 1998) and how this choice affects the possible output of the four phase model (Discussion). (ii) This also applies for the statement that "Sheng 1990 justifies the empirical relations mentioned above for a wider parameter range" – please spend 3-4 sentences to explain the implications, restrictions and problems of the effective medium theory (both Intro and Discussion). (iii) Please check the stated volumetric contents of ice, rock and air with the Arenson and Springman (2005, Fig 4) paper – I have partly found different values. (iv) Perhaps this is a little bit meticulous, but one could facilitate the understanding of Equ. 6 and Equ. 7 by homogenising them (see spec. comments). (v) P801 "This confirms the above hypothesis, that the decreasing porosity at larger depths (including the occurrence of firm bedrock) is responsible for the inability of the porosity dependent model to find solutions are larger depths (Figs. 5 and 6)." – There could be another problem which is related to the fact that the slowness average model (Timur 1968 and Wyllie et al. 1958) systematically underestimates the velocity increase in freezing low-porosity rocks: (see specific comments) – please include a short statement on this topic in the discussion. (vi) P804 "Because the seismic velocities of ice and rock are comparatively similar (Table 1) and their electrical resistivities do not enter the set of equations used in the 4PM a differentiation between ice and 20 rock remains difficult without a priori information." - Please discuss in more detail – the first statement results from mathematical description of the phase change you apply for resistivity (Archie) and seismic velocities (slowness averaging) – please shortly discuss their shortcomings in the description of these phase changes (suggestions, see specific comments)

Otherwise a very nice paper. Good luck with the revisions.

Michael Krautblatter

Specific comments P 789 line 8 following: you could be a bit more specific about the deliverables of the 4-phase models and the scientific communities that will profit from the outcome.

P790, L10: "for the elastic properties such as the time-average equation for seismic P-wave velocities by Wyllie et al. (1958)" - I personally think that “slowness averaging” is the more intuitive and instructive term describing how Wyllie et al. (1956; 1958) derived their composite “measured” velocities. It could help the reader, who is not so familiar with these papers, if you shortly state the original formula of Archie and Wyllie et al. 1958 in the Introduction.

P 790, L11: "its extension to the frozen phase by Timur (1968). These relationships were originally only validated for a restricted range of materials (e.g. unconsolidated sediments, Zimmerman and King, 1986)." – I am not quite sure about the statement of validation for unconsolidated sediments, since Timur 1968 has used different types of clastic sedimentary, carbonate and metamorphic rocks to develop his theory.

P790, L12: "later studies theoretical concepts for simple pore geometries were developed including both electric and elastic properties of the material (e.g., Sheng, 1990), thereby justifying the empirical relations mentioned above for a wider parameter range" - The findings of Sheng 1990 on the application of the differential effective medium (DEM) theory for cemented consolidated materials are a key prerequisite for the development of the 4-phase model. You should consider spending 2-3 sentences on how he modified the existing DEM theory for the application in consolidated “cemented” material as this matches with your problem of transferring unfrozen unconsolidated material to frozen cemented material.

P792 L12-13: "Since ice is much stiffer than water, the wave velocity is tightly coupled to the ice-to-water ratio." – This is basically the point of Carcione and Seriani 1998 and Timur, 1968 which should be cited here.

P793 L10 "Combining Eqs. (1)–(5) and solving for the ice content." Insert Âń Volumetric Âż ice content

P793 L12 "Similarly, equations for the air content fa and the water content fw can be derived" - Insert Âń Volumetric Âż

P794 L10 : "The material constants can be taken from literature or can be estimated in the laboratory using field samples (e.g., Schön, 2004)." – Volumetric ice, air and solid content for both of your test sites have been published by Arenson and Springman (2005: Fig 4).

P792 L21: "For a porosity of 0.5 (characteristic for e.g. rock glaciers)" - Arenson and Springman (2005: Fig 4) indicate values raging from 0.4-0.8 for the Muragl – I think that is worth mentioning.

P793 Equ 7: perhaps this is a little bit meticulous, but you could facilitate the understanding of Equ. 6 and Equ. 7 by homogenising them a little: (SEE SUGGESTIONS IN EQU6AND7.JPG)

P796 L11: "meaning that the model can only determine the sum of ice and rock volumes" – replace volumes by fractions

P798 L18: "Arenson and Springman (2005) found volumetric solid contents between 40–60% within the upper most 15m of borehole BH 4/99 making 50% a reasonable assumption as a mean value." - Arenson and Springman (2005: Fig 4) indicate values ranging from ca. 20-56% for upper 15 m of the Muragl bore hole – please clarify

P799 L26 : "corresponding rock content of around 30–40%," - in (Arenson and Spring-

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man, 2005) I find values of 20-40% while the other fractions correspond to what you indicate in your paper please clarify

P801 L11: "This confirms the above hypothesis, that the decreasing porosity at larger depths (including the occurrence of firm bedrock) is responsible for the inability of the porosity dependent model to find solutions are larger depths (Figs. 5 and 6)." – There could be another problem which is related to the fact that the slowness average model (Timur 1968 and Wyllie et al. 1958) systematically underestimates the velocity increase in low-porosity rocks: see Timur (1968) black shale: 8.2% velocity increase, 3.5% porosity; also reproduced (and ignored) in McGinnis et al. (1973: Fig. 5).

P803 L 1: "distance 90 m, where high minimal rock contents indicate the presence of a large boulder within the rock glacier." – what about 130 m (x) and 50 m (y)?

P803 L5: "Finally, maximum ice contents (_100% saturation, Fig. 10a) are slightly higher for rock glacier Murt ' el than for rock glacier Muragl (_90%, Fig. 6a)" - in accordance with (Arenson and Springman, 2005)

P804 L18: "Because the seismic velocities of ice and rock are comparatively similar (Table 1) and their electrical resistivities do not enter the set of equations used in the 4PM a differentiation between ice and 20 rock remains difficult without a priori information." - Please discuss in more detail – the first statement results from mathematical description of the phase change you apply for resistivity (Archie) and seismic velocities (slowness averaging) – please shortly discuss their shortcomings in the description of these phase changes e.g. (Carcione and Seriani, 1998; Krautblatter et al., 2010: P12-13). AND Page 805 "An improved formulation of the 4PM, e.g. by using an electrical relationship that includes the resistivity of the bedrock, may overcome this problem." (see above)

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/4/C1642/2011/tcd-4-C1642-2011-

supplement.pdf

Interactive comment on The Cryosphere Discuss., 4, 787, 2010.

P793 L10 *Combining Eqs. (1)–(5) and solving for the ice content.* Insert « Volumetric » ice content

P793 L12 *Similarly, equations for the air content fa and the water content fw can be derived* Insert « Volumetric »

P794 L10 : *The material constants can be taken from literature or can be estimated in the laboratory using field samples (e.g., Schön, 2004).* – Volumetric ice, air and solid content for both of your test sites have been published by Arenson and Springman (2005: Fig 4).

P792 L21: *For a porosity of 0.5 (characteristic for e.g. rock glaciers)* - Arenson and Springman (2005: Fig 4) indicate values raging from 0.4-0.8 for the Muragl – I think that is worth mentioning.

P793 Equ 7: perhaps this is a little bit meticulous, but you could homogenise Equ7 and Equ6 and facilitate the understanding by changing:

Equ 7: $-\frac{1-f_r}{v_i}$ as stated analogously in Equ 6

Equ 6: $-\left(\frac{a\rho_w(1-f_r)^n}{\rho(1-f_r)^m}\right)^{1/n}\left(\frac{1}{v_w}-\frac{1}{v_a}\right)$ as stated analogously in Equ. 7

P796 L11: *meaning that the model can only determine the sum of ice and rock volumes* – replace volumes by fractions

P798 L18: Arenson and Springman (2005) found volumetric solid contents between 40–60% within the upper most 15m of borehole BH 4/99 making 50% a reasonable assumption as a

Fig. 1. Equations 6 and 7

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