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# ***Interactive comment on “P-wave velocity changes in freezing hard low-porosity rocks: a laboratory-based time-average model” by D. Draebing and M. Krautblatter***

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Review of the manuscript “P-wave velocity changes in freezing hard low-porosity rocks: a laboratory-based time-average model” by D. Draebing and M. Krautblatter submitted for consideration to Cryosphere

This manuscript presents laboratory experiments exploring the effect of freezing on the elastic wave velocity in low porosity rocks. The authors investigate the behaviour of various rocks sample, more or less anisotropic, as function of their surface temperature and compare these experimental observations with previously proposed models. This topic is of particular interest for understanding the effect of freezing on rock properties

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and also as a mean for imaging the frozen zone using seismic prospecting technique. The major result is that there is a considerable increase of the p-wave velocity when the water enclosed in the porosity freezes. The amplitude of the velocity change appears to be dependent of the rock type and also of the direction when considering anisotropic rocks. The experimental results are significant and robust. The comparison with previous model of the velocity reveals that such observations are not well captured and the authors propose another model for explaining the velocity change they observed. Unfortunately the authors do not directly compared their model with the data so the relevance of this new model is not clearly shown. An interesting point is that the authors observed an increase larger than the one explained by the water phase change. This excess of velocity change is explained by an increase of the matrix velocity associated with the freezing. This effect is well observed but not clearly explained in the manuscript. I suggest the following explanation based on laboratory observations in absence of freezing. It is commonly observed that the p-wave velocity increases when the confining pressure or the uniaxial stress increases (e.g. Wassermann et al 2009, Heap et al, 2010, Eslami et al 2010 and ref. herein) when the stress does not surpass the damage threshold. This is generally explained as the effect of the closure of crack parallel to the major stress. This is valid only when the stress is below the stress corresponding to the onset of damage after that the damage increase and the p-wave velocity decreases. As the authors indicate, the pores concerned by the water freezing porosity are only the ones hydraulically connected. So the non connected porosity only reacts to the changes of stress. So one may consider the following mechanism: when freezing, the pore pressure increases in the connected porosity inducing the increase of stress applied on the matrix (including the non connected porosity) and the closure of the non connected cracks imbedded in the matrix. In order to confirm the possibility of such mechanism it is suitable that the authors provide the partition between connected and non-connected porosity for the various rock types they examined and to plot it against the matrix velocity increase. In addition a direct confrontation between their model and their data should be added to convince the reader that their model

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is better explaining the data. If available the porosimetry (i.e. the distribution of pore size, obtained by mercury injection or other technics) could be also very helpful for understanding the differences between rocks. A more detailed description of rocks, in particular the nature of the anisotropy could be also suitable. An important question is the possible induce damage due to freezing. Does the velocity changes when comparing the unfrozen rocks before and after the freezing sequence? In other words, is there any damage or increase of porosity induced by the freezing? Another important remark concerns the building of the time average model (equation 1). It is important to indicate that this model consider an assembly of matrix and pores in series along the wave propagation direction. This is a good approximation for an anisotropic rock with waves propagating perpendicular to the anisotropy direction. But it is no more valid pour a random porous media or when the waves are propagating parallel to the anisotropy. This must be discussed in the introduction as it one of the reasons why such model does not apply to all the rock types.

My Overall opinion about this work is very good but the previous remarks should be addressed before publication. David Amitrano

Ref: Eslami, J., D. Grgic, et D. Hoxha (2010), Estimation of the damage of a porous limestone from continuous (P and S) wave velocity measurements under uniaxial loading and different hydrous conditions, *Geophysical Journal International*, 183(3), 1362–1375, doi:10.1111/j.1365-246X.2010.04801.x.

Heap, M. J., D. R. Faulkner, P. G. Meredith, et S. Vinciguerra (2010), Elastic moduli evolution and accompanying stress changes with increasing crack damage: implications for stress changes around fault zones and volcanoes during deformation RID C-7215-2011 RID F-7589-2011, *Geophys. J. Int.*, 183(1), 225–236, doi:10.1111/j.1365-246X.2010.04726.x.

Wassermann, J., G. Senfaute, D. Amitrano, et F. Homand (2009), Evidence of dilatant and non-dilatant damage processes in oolitic iron ore: P-wave velocity and

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Acoustic Emission analyses, *Geophysical Journal International*, 177, 1357–1365; doi: 10.1111/j.1365–246X.2008.04017.x.

Other technical remarks and typos are listed here after 1 Introduction

Page 2 lines 21-26: The S waves are generally considered to be more sensitive to pore change and liquid saturation than P waves.

Page 3 lines 16-19: The pore size is quite different when comparing laboratory and field data that could explain the observed discrepancies.

Page 4 line 8 : this equation should apply only for a very particular set of parameters, so it not a surprise that it does not work for all the rocks.

Page 4 lines 18-21: This is related to change of porosity induced by change of applied stress, e.g. crack closure observed in the laboratory. This supposed that the stress is transmitted to the matrix and should not be confused with pore pressure increase that leads to an increase of the pore size.

Page 5 line 16: more recent references show the increase of anisotropy during the loading of rocks eg Wasserman et al and Eslami et al, Heap et al.

## 2 Methodology

Please add a scheme showing the imposed temperature conditions and the geometry of the thermal gradient.

Page 6 line 6-8: this method of saturation is similar to natural condition but probably includes air bubbles within the pore water; this is more complicated to interpret.

Page 6 line 16: In addition to the concept of hydraulically linked pores, the ratio between linked and non-linked pores is probably useful for understanding the variety of rocks behavior.

Page 6 lines 26-29: why does the authors change the cooling rate before and after

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0°C. Is there any flank of the samples insulated or are they all directly in contact with the climatic chamber air.

Page 7 lines 11-13: there is a possible confusion between 'V' and 'nu' for the velocity, please clarify.

Page 8 lines 1-2: the difference between absolute porosity and effective porosity corresponds to the part of non-connected porosity and should be expressed explicitly.

Page 8 lines 27: Is the hysteresis related to supercooling or to the possible increase of porosity induced by pore pressure (i.e damage).

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Page 10 lines 11-12: Ok the model of McGinnis is not relevant here but this does not exclude that the porosity could be a relevant parameter.

Pages 10 lines 21-24: This sentence is not clear to me, please rephrase.

Page 11 line 5: The term 'alteration' is not appropriate here, 'variation', 'change', 'modification' are probably preferable.

Page 11 lines 18-19: please explain where this threshold value is coming from.

Page 11 lines 21-30: what about thermal dilation and its effect on porosity? Is the cubic geometry of the samples providing similar thermal gradient that natural conditions?

Page 12 lines 2-13: I suggest to plot DeltaV as a function of the nonconnected porosity ratio and to plot data vs model.

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Interactive comment on The Cryosphere Discuss., 6, 793, 2012.

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