

Response to comments: Monitoring the temperature dependent elastic and anelastic properties in isotropic polycrystalline ice using resonant ultrasound spectroscopy

Matthew J. Vaughan¹, Kasper van Wijk², David J. Prior¹, and M. Hamish Bowman¹

¹Department of Geology, University of Otago, 360 Leith Walk, Dunedin, New Zealand, 9054.

²Department of Physics, Building 303, University of Auckland, 38 Princes Street, Auckland, New Zealand, 92019

Correspondence to: Matthew Vaughan (mattvaughan902@gmail.com)

1 Introduction

The following provides responses to all comments received during the on-line discussion of this manuscript from reviewer Dr. Reid Cooper (RC2) entitled ‘The attenuation signature of pre-melting on grain boundaries in ice’.

2 Response To RC2: Dr. Reid Cooper

5 – **Comment:** ‘The significantly increased attenuation (decreased Q) noted exclusively for extensional (Youngs-modulus)- modes with increasing temperature, and its assignment to pre-melting at the grain boundaries is curious. I do not here argue against the idea – at least not directly; rather, I’ll point-out behaviour to which the current data might be compared. We’ve done low-frequency ($0.001 \leq (\text{Hz}) \leq 1$), high-temperature measurements of attenuation in silicate glass-ceramics and partial melts in both shear and (flexural) Youngs-modulus modes. In these materials, the quasi-equilibrium texture is to have melt (glass) confined to grain triple junctions (as a fully interconnected network, even at low volume

10 fractions of melt/glass) and melt-free (i.e., crystalline) grain boundaries. As a consequence, shear attenuation was only modestly affected by the melt phase but Youngs-modulus attenuation was significant. In the latter, the pressure wave promotes/produces the relative motion of the melt and crystalline phases, following what the geodynamics community describes as compaction theory, as augmented with interfacial energy thermodynamics.

15 I’m no expert on premelting in ice. But experience with ice, consistent with what’s seen in nature, is that water does not wet ice grain boundaries. A similar texture to silicate partial melts, rather, seems likely. Getting back to attenuation, if premelting in ice occurs at grain boundaries (or is uniquely associated with grain boundaries), would it not have two mechanical effects: (a) making degenerate the structures (and energetics) of the boundaries and so (b) affecting (presumably increasing) the shear attenuation more than the Youngs-modulus attenuation? Question is, what would be

20 the thermodynamics and mechanics allowing premelting to be associated primarily with the extensional modes?

Perhaps this question is beyond the scope of the current manuscript. Nevertheless: The recent work out of the materials community by scholars at Lehigh (Martin Harmer) and MIT (Craig Carter) on grain boundary ‘complexions’ is perhaps the key. If premelting does not represent a single quasi-liquid state but rather a host of states bridging a crystalline grain boundary at one extreme and a water film at the other, then the transformation(s) amongst states (and their kinetics),
5 nicely described in the Harmer/Carter efforts, could be an (the?) important aspect of extensional-mode attenuation.’

Response: Thank you, Dr. Cooper for your thoughtful and insightful comments, and for taking the time to consider our manuscript carefully.

The distribution of melt on grain boundaries and triple junction lines in ice remains unconstrained, and maybe data such
10 as ours can be coupled with microstructural or atomic scale models to constrain this better. We must look elsewhere for an understanding of the nature and distribution of this ‘fluid-like’ phase. Your comments on complexions may provide insight here.

Recent work exploring grain boundary complexions (see Cantwell et al. (2014) for a review) suggest that in unary systems, grain boundaries can undergo first order, or continuous transitions which include prewetting / premelting at the highest
15 temperatures (Luo, 2008), resulting in discontinuous changes in interface properties such as mobility, and cohesive strength. These temperature dependent transitions in the thickness, structure, and level of disorder of grain boundaries could account for dramatic changes in the bulk characteristics of a poly-crystal, and show that grain boundary mobility can increase dramatically even at temperatures insufficient to cause boundary wetting. One important point raised in experiments conducted by Schumacher et al. (2016) is that complexion transitions are also time dependent, with the rate of change of temperature during an
20 experiment has influence on the stability of grain boundary complexions. The view of Luo (2008) was that the highest temperature grain boundary complexion is probably some kind of liquid-like melt film. In ceramics and metallurgy it is difficult to access this high temperature field, and ice might provide a great model material for work on this. In our experiments, we are able to achieve a homologous temperature of > 0.95 . While we feel that the considerations of grain boundary complexions goes beyond the scope of this manuscript, we believe that the results obtained in our experiments raise important questions
25 about the nature of grain boundary structures, and appreciate that this has been recognised by the reviewer. To this end, we have included some statements in the discussion directing readers to additional resources on complexions and the extensive work on low frequency measurements of attenuation in ice.

In the case of our experiments, we minimise the influence of dislocation related mechanisms, CPO, and second phases through a practised sample manufacturing process, performing ‘zero’ load experiments at frequencies between seismic and
30 ultrasonic, using low amplitude oscillations that do not induce non-recoverable deformation. For these reasons, we localise the most likely contributor to drastic changes in attenuation to pre-melting effects.

We would like to point to a few key differences between our experiments, and lower frequency experiments involving creeping ice, such as in McCarthy and Cooper (2016) for example. In plastically deforming ice, particularly at higher homologous temperatures, creep can introduce an alignment of crystal orientations or a ‘CPO’ at low strain, and introduces attenuation
35 mechanisms that depend on the generation, migration, and kinetics of defects in the lattice or grain boundaries. CPO in poly-

crystalline ice has been demonstrated to have a significant influence on Q^{-1} (Cole et al., 1998). This influence arises because single crystals of ice can be anisotropic in their attenuation. Dislocation processes including dislocation damping, and grain boundary relaxation have been explored in the work of Cole and co-authors on saline and freshwater ice (Cole et al., 1998; Cole and Durell, 1995; Cole, 1990). This effort resulted in a temperature dependent model (Figure 1) that accounts for multiple mechanisms to explain attenuation behaviour. Importantly, the magnitude of Q^{-1} in the dislocation damping regime in this model, likely depends on the amplitude of oscillations, and the location of the peak in grain-boundary dissipation likely depends on frequency of the oscillations.

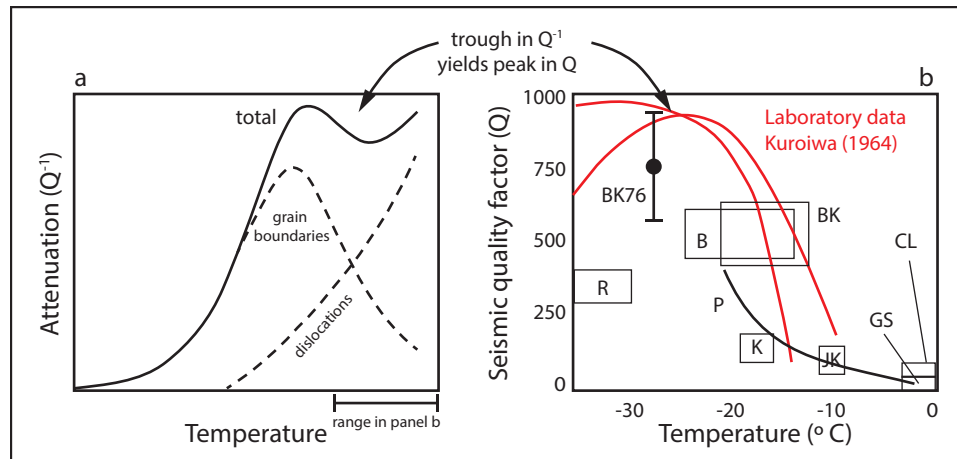


Figure 1. Examples of attenuation in ice. (a) Schematic depiction of attenuation resulting from different mechanisms, after Cole and Durell (1995). (b) Compilation of field-based measurements of attenuation in ice sheets compared to laboratory experiments of Kuroiwa (1964) conducted on natural ice from Antarctica and Greenland. Frequencies differ among studies and range from 60 Hz to 1000 Hz. Note the relatively poor constraints on temperature for a given value of Q . References are B, Bentley (1971), BK, Brockamp and Kohnen (1965), BK76, Bentley and Kohnen (1976), CL, Clee et al. (1969), GS, Gusmeroli et al. (2010), JK, Jarvis and King (1993), K, Kohnen (1969), P, Peters et al. (2012), R, Robin and Robin (1958)

– **Comment:** Here are the little points (again, based on the 04 Aug 16 version):

Page 1-Line 4: It's Q that decreases with increasing temperature, not “attenuation” (which is $1/Q$).

10 **Response:** This error has been corrected in the manuscript

– **Comment:** Page 3-Line 22: I do not understand “imperfections” in elasticity. The physics of elasticity do not change: you are measuring the stiffness of the bonds; it is by definition, perfect. Non-infinite Q means that the mechanical stimulus has sampled responses (anelastic +/- plastic) that dissipate, instead of store, strain energy.

Response: Thanks for pointing this out. We have edited this part of the manuscript to say ‘dissipative mechanisms’

– **Comment:** Page 3-Line 25: I am not sure exactly what you mean by ‘intrinsic attenuation’. ‘Intrinsic’ usually means that which is solely a function of temperature (\pm pressure), i.e., independent of chemical potentials and texture. There are intrinsic effects: adiabatic loss; proton reordering in ice; point defect motion – but RUS can also “see” losses associated with texture, e.g., the presence of non-equilibrium defects like dislocations, grain boundaries, heterophase boundaries, etc. My experience with RUS has been to look at the impact of a finely disbursed second phase in synthetic peridotite, for example.

Response: What we mean by intrinsic attenuation, is absorption or dissipation. In RUS, we measure in the frequency domain over a period of time and all scattered energy arriving at the receiver is included in the calculations of Q, thereby isolating intrinsic Q from the attenuation due to scattering (Watson and van Wijk, 2015). In this context, we define intrinsic attenuation as dissipative losses: energy that gets converted from elastic wave energy into something else, usually associated heat. We have edited the manuscript to include the following:

‘That is, intrinsic attenuation captures dissipative losses: energy that gets converted from elastic wave energy into heat or some other form.’

References

- Bentley, C. R.: Seismic anisotropy in the West Antarctic Ice Sheet, Wiley Online Library, 1971.
- Bentley, C. R. and Kohnen, H.: Seismic refraction measurements of internal-friction in Antarctic ice, *Journal of Geophysical Research*, 81, 1519–1526, doi:10.1029/JB081i008p01519, <GotoISI>://WOS:A1976BL02700008, 1976.
- 5 Brockamp, B. and Kohnen, H.: Ein Beitrag zu den seismischen Untersuchungen auf dem Grönlandischen Inlandeis, *Polarforschung*, 35, 2–12, 1965.
- Cantwell, P. R., Tang, M., Dillon, S. J., Luo, J., Rohrer, G. S., and Harmer, M. P.: Grain boundary complexions, *Acta Materialia*, 62, 1–48, 2014.
- Clee, T., Savage, J., and Neave, K.: Internal friction in ice near its melting point, *Journal of Geophysical Research*, 74, 973–980, 1969.
- 10 Cole, D., Johnson, R., and Durell, G.: Cyclic loading and creep response of aligned first-year sea ice, *Journal of Geophysical Research: Oceans*, 103, 21 751–21 758, 1998.
- Cole, D. M.: Reversed direct-stress testing of ice: Initial experimental results and analysis, *Cold regions science and technology*, 18, 303–321, 1990.
- Cole, D. M. and Durell, G. D.: The cyclic loading of saline ice, *Philosophical Magazine A*, 72, 209–229, 1995.
- 15 Gusmeroli, A., Clark, R. A., Murray, T., Booth, A. D., Kulesa, B., and Barrett, B. E.: Seismic wave attenuation in the uppermost glacier ice of Storglaciaren, Sweden, *Journal of Glaciology*, 56, 249–256, <GotoISI>://WOS:000280258200006, 2010.
- Jarvis, E. and King, E.: The seismic wavefield recorded on an Antarctic ice shelf, *Geophysical Press*, 1993.
- Kohnen, H.: Über die Absorption elastischer longitudinaler Wellen im Eis, *Polarforschung*, 39, 269–275, 1969.
- Kuroiwa, D.: Internal Friction of Ice. I: The Internal Friction of H₂O and D₂O Ice, and the Influence of Chemical Impurities on Mechanical Damping, *Contributions from the Institute of Low Temperature Science*, 18, 1–37, 1964.
- 20 Luo, J.: Liquid-like interface complexion: From activated sintering to grain boundary diagrams, *Current Opinion in Solid State and Materials Science*, 12, 81–88, 2008.
- McCarthy, C. and Cooper, R. F.: Tidal dissipation in creeping ice and the thermal evolution of Europa, *Earth and Planetary Science Letters*, 443, 185–194, 2016.
- 25 Peters, L. E., Anandakrishnan, S., Alley, R. B., and Voigt, D. E.: Seismic attenuation in glacial ice: A proxy for englacial temperature, *Journal of Geophysical Research-Earth Surface*, 117, doi:F02008 10.1029/2011jf002201, <GotoISI>://WOS:000302896500002, 2012.
- Robin, G. d. Q. and Robin, G.: *Glaciology III: Seismic shooting and related investigations*, Norsk Polarinstitut, 1958.
- Schumacher, O., Marvel, C. J., Kelly, M. N., Cantwell, P. R., Vinci, R. P., Rickman, J. M., Rohrer, G. S., and Harmer, M. P.: Complexion time-temperature-transformation (TTT) diagrams: Opportunities and challenges, *Current Opinion in Solid State and Materials Science*, 30 2016.
- Watson, L. and van Wijk, K.: Resonant ultrasound spectroscopy of horizontal transversely isotropic samples, *Journal of Geophysical Research-Solid Earth*, 120, 4887–4897, <GotoISI>://WOS:000359746700013, 2015.