Transition from elastic to inelastic deformation identified by seismic attenuation, not seismic velocity

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The transition from elastic to inelastic deformation occurs at the yield point in a stress-strain diagram. This yield point expresses the moment permanent deformation occurs and is marked by the onset of fracturing in the brittle field at relatively low pressures and temperatures or the onset of dislocation and/or diffusional creep processes in the ductile field at higher temperatures and pressures. Detection of this transition in materials under stress using an indirect measurement technique is crucial to predict imminent failure, loss of material integrity, or of approaching release of energy by seismic rupture.

Here we use a pulse transmission method at ultrasonic frequencies to record the change in acoustic wave form across the transition from elastic to inelastic deformation in a rock-fracturing experiment. In particular, we measure both the acoustic wave velocity (Figure 1B) and attenuation (Figure 1C) with increasing strain from the elastic regime all the way to macroscopic failure.

Our results (Figure 1) show that the transition from elastic to inelastic deformation coincides with a minimum in attenuation (Figure 1C). At the same time, the acoustic wave velocity continues to increase across the transition from elastic to inelastic deformation (Figure 1B). Therefore, the acoustic velocity is not a valid indicator for this elastic-to-inelastic transition. However, we observe a minimum in attenuation for a range of different rock types (Barnhoorn et al., submitted) and this seems to be an almost universal feature. Therefore, the change in attenuation is a valid indicator for the onset of permanent deformation and fracturing.

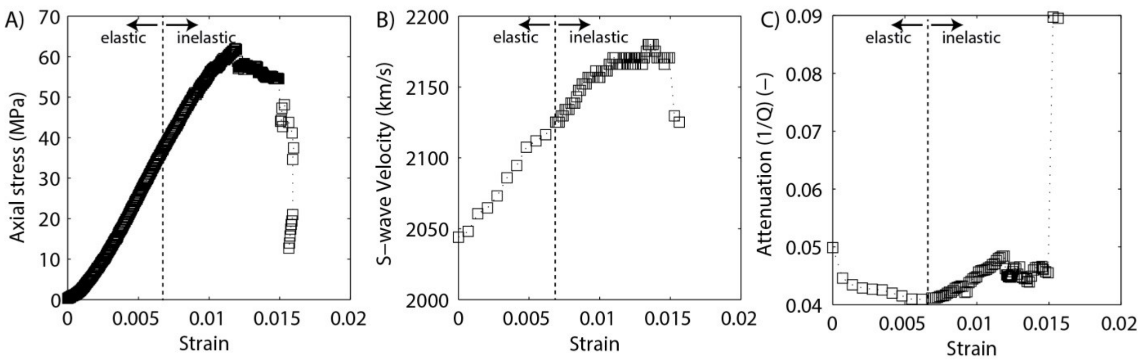

Figure 1: Example of mechanical and acoustic data for Whitby shale. A) Axial stress-strain data with shear wave velocity with strain (B) and shear wave attenuation with strain (C), both measured during the uniaxial compression experiment. The strain at which the transition from elastic to inelastic deformation behavior occurs is indicated with the dashed vertical line.

In Figure 2 we propose a conceptual model to explain our observations. Below the minimum in attenuation, pre-existing microfractures close, leading to a reduction of attenuation. Above this minimum, formation of new microfractures occurs and attenuation increases. In other words, attenuation is a function of the fracture density.

That the acoustic velocity does not react in the same way to the change in fracture density (Figure 1B) may be explained by the fracture orientation. For randomly oriented pre-existing microfractures, the fractures perpendicular to the uniaxial compression direction close preferentially. This leads to a preferred fracture orientation parallel to the sample axis at the onset of permanent deformation. New microfractures also preferentially form parallel to the sample axis, accentuating this preferred fracture orientation. This leads to a seismic anisotropy with the fast direction parallel to the sample axis, which increases throughout the experiment (i.e., crossing the elastic-to-inelastic transition).

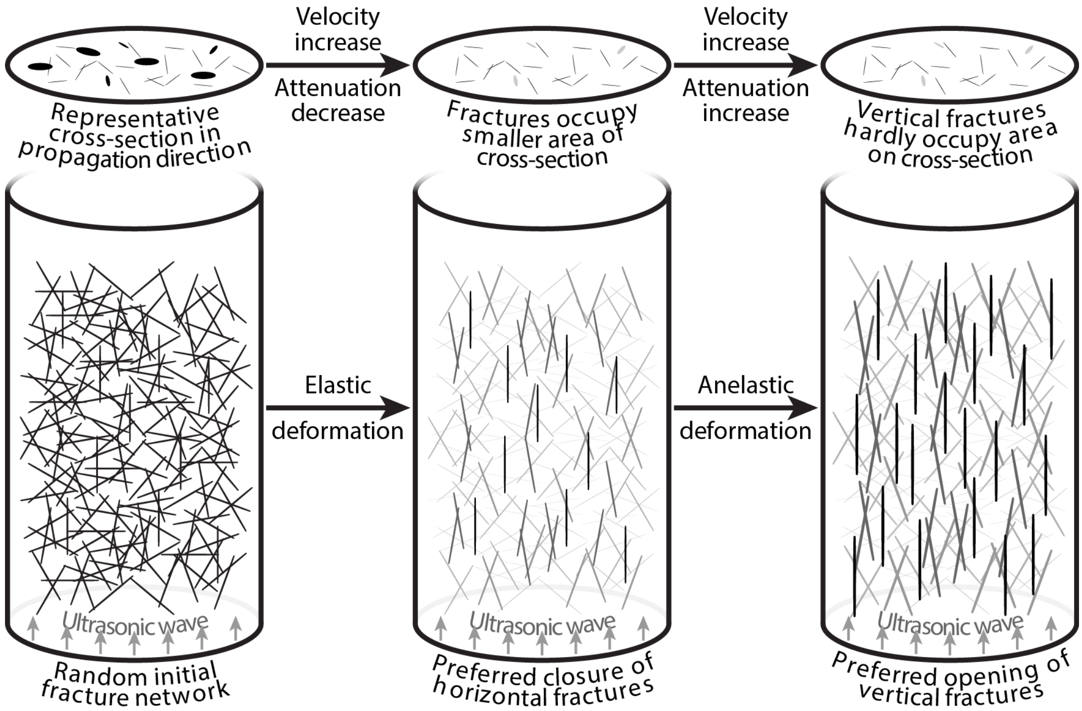

Figure 2: Conceptual model of fracture closure and opening of new fractures during a uniaxial compression experiment. The uniaxial compression results in a change in fracture density, but also in a change in fracture orientation from random to preferentially vertically oriented.

We propose that analysis of attenuation, not velocity, of acoustic waves through stressed materials may be used, for example, to detect imminent failure in materials, onset of crack formation in pipes or the cement casing in boreholes, or onset of fracturing in the near wellbore area. On a larger scale, attenuation monitoring may help predict the imminent release of energy by seismic rupture.

REFERENCE

Barnhoorn, A., Verheij, J., Frehner, M., Zhubayev, A. and Houben, M. submitted: Identification of the transition from elasticity to inelasticity from seismic attenuation analyses, Geophysical Research Letters.