Seismic reflections from space-, time- and mixed boundaries

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What is a "time boundary"?

Suppose a one-way wave is propagating in a homogeneous medium. Suppose we at some instant t_0 during its propagation, the entire medium has its elastic properties changed, i.e., at $t>t_0$, the medium remains homogeneous, but its properties are everywhere different from the ones prior to t_0. What would happen?

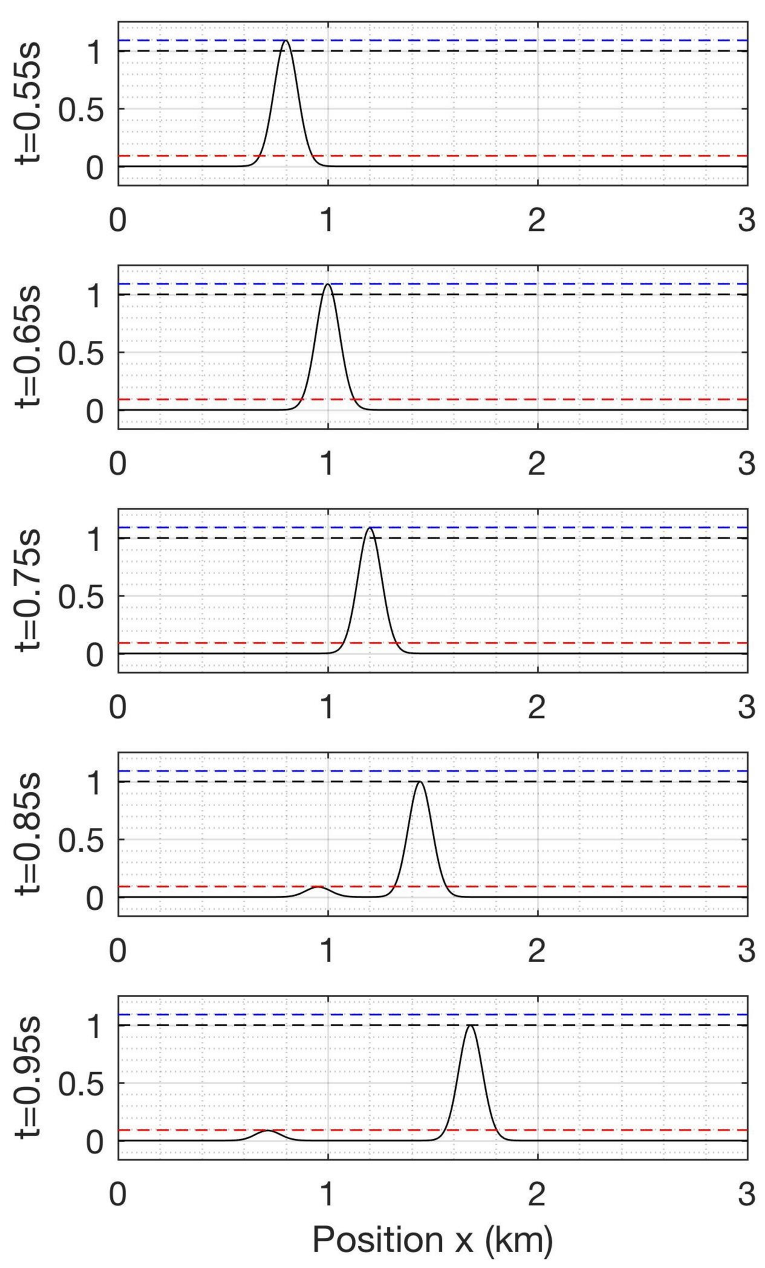

Fig. 1. Answer: a reflection! Because of the symmetry of the wave equation, a discontinuity in time is very similar to a discontinuity in space. In the Figure, a 1D pulse of height T propagates to the right. At t=0.75s, the medium properties change from v_0=2.0km/s to v_1=2.4km/s. The energy partitions into a right-going component of height 1, and a left-going component of height R. The values 1, $T=1.091$, and R=0.091 obey the rules $R = (v_1-v_0)/(v_1+v_0)$ and $T = 1 + R$. But, notice that it is the "incident" wave that has height T. The wave equation is not perfectly symmetric!

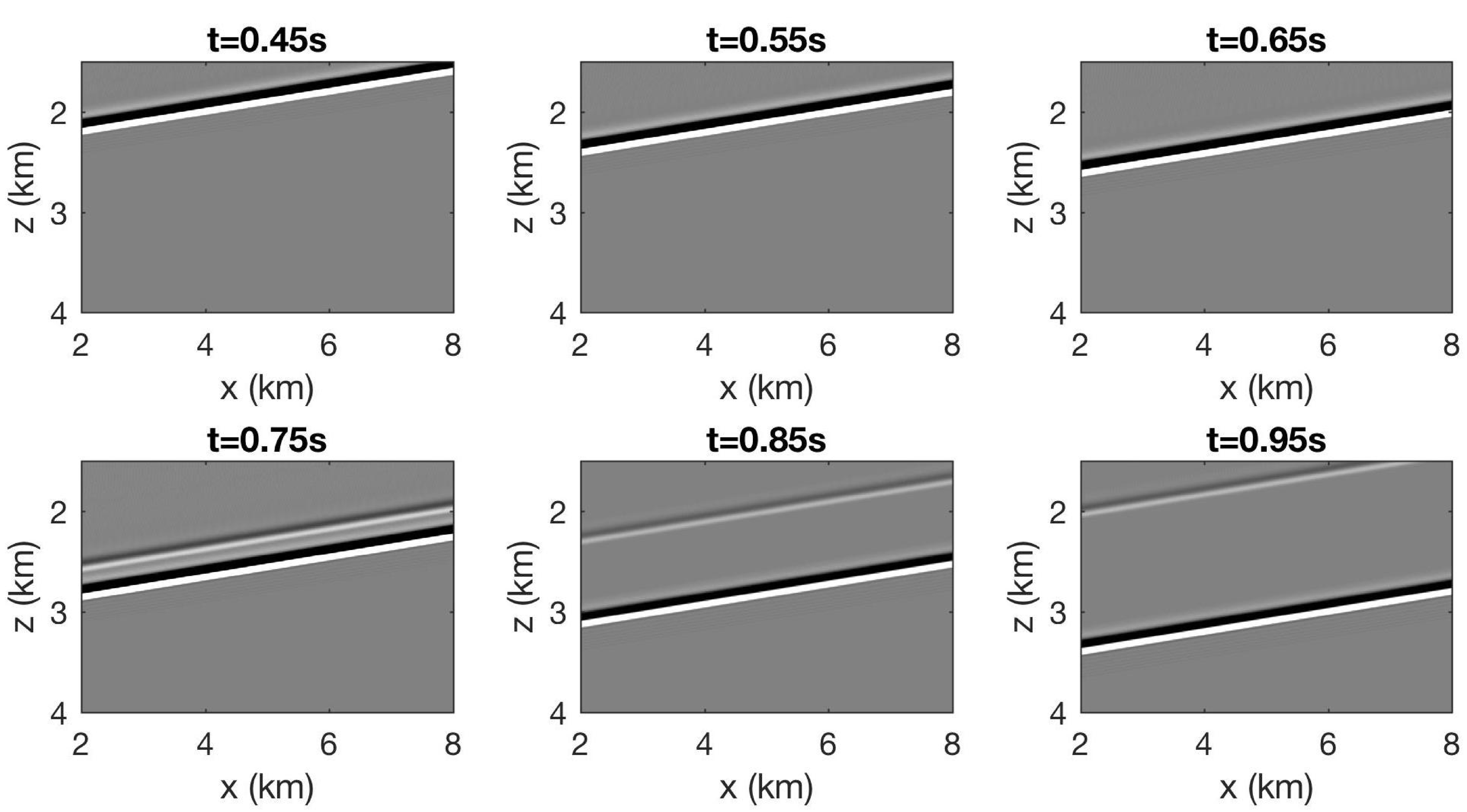

Fig. 2. Does it work in multiple dimensions? Yup. For plane waves upon hitting a "time boundary" a reflection normal to the incident wave is created. All current theory/results concerning time boundaries are inherently "normal incidence".

Wave "control" and AVO without an interface

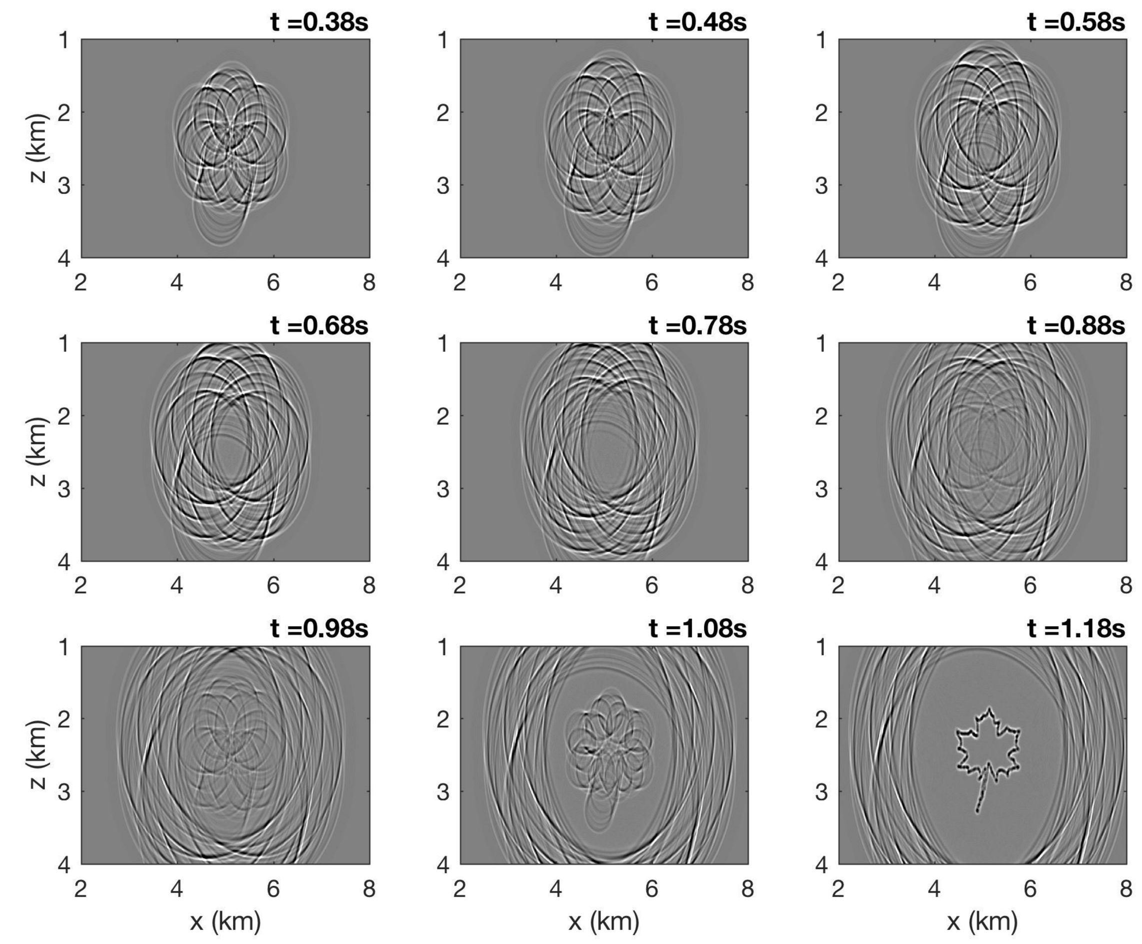

Fig. 3. Bacot et al. (2016) focus on time boundaries from the point of view of imaging and wave control. Suppose a maple leaf fell on the surface of a pool at time 0, exciting surface waves. By suddenly changing the wave velocity at0.7s, , each point on the complex waveform generated by the leaf acts as a Huygens' source, and at 1.18s the source is clearly imaged.

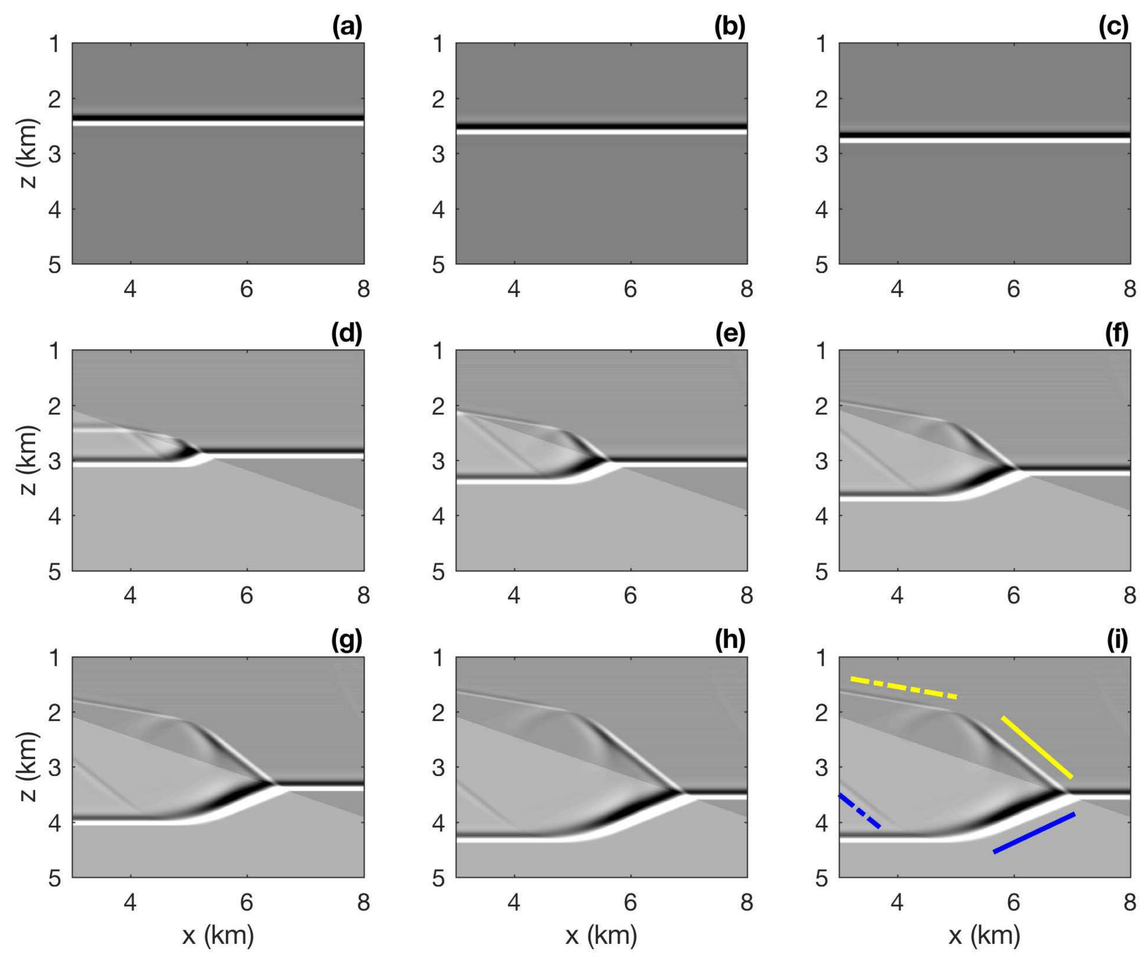

Fig. 4. Reflections and no spatial boundaries... so, can we do AVO without an interface? Surprisingly, it is not the "A" that is hard, it is the "O" – all time boundary reflections are normal. Our main contribution is to show that by mixing time-boundaries with normal space-boundaries we can generate oblique reflections (upgoing wavefront labelled with yellow dashed line).

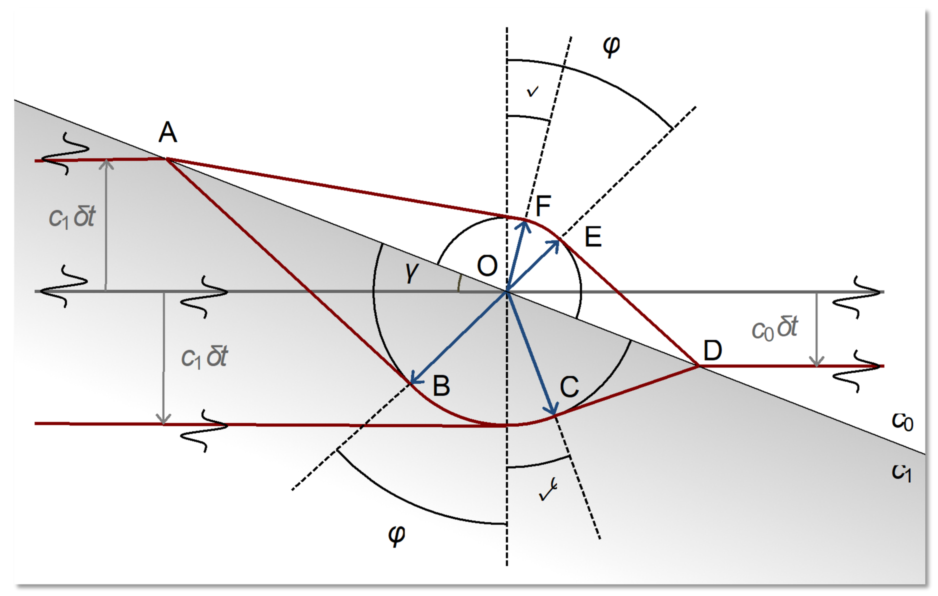

Fig. 5. The kite-shaped quadruplet of wavefronts arises when a time-boundary is introduced with space-boundary features. The "reflected" wavefront can be shown to have an angle θ, where θ = μ - γ, and where γ is the interface dip angle and μ satisfies

$$\sin \mu = (v_0/v_1) \sin \gamma$$

Applications?

Difficult to say: monitoring? Can we illuminate a reservoir target as a rapid process of pressuring up is occurring? If injection fluids have the right properties, could we apply a magnetic field and cause an illuminating seismic wave to scatter from sites of strong injection?