Space-time boundary reflections in elastic media

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ABSTRACT

In 2017 potential monitoring applications of an unusual but perfectly real type of seismic reflection, namely that from time-boundaries (and mixed space-time boundaries), were discussed. The idea is simply that reflections occur from jumps in medium properties, and this holds for jumps along the time coordinate axis just as surely as for jumps along one of the space coordinate axes. Time boundary reflections are intrinsically "normal incidence" scattering events. Analysis was carried out in order to plausibly discuss oblique time-boundary reflections; these were argued to be possible only if the boundary had both space and time components. In this short note we further this interpretation by demonstrating that if elastic waves (P- or S-) encounter pure time boundaries, no conversion occurs. However, if the boundary includes spatial variations as will as time variations, becoming, as it were, oblique time reflections, conversions do occur.

INTRODUCTION

In a 2017 CREWES report, it was pointed out that seismic reflections, and in general scattering interactions, can take place as the consequence of perturbations in medium properties along time as well as space coordinate axes (Innanen, 2017). In the latter case, a homogeneous medium is suddenly perturbed into a second homogeneous medium, with different properties. This has been discussed in the context of wave control and imaging in three papers (Mendonça and Shukla, 2002; Bacot et al., 2016; Fink and Fort, 2017), but is otherwise an essentially unremarked upon subject. This is likely because time-boundaries are difficult to imagine being created in practical situations; however, Innanen (2018) further point out that as the "smart reservoir", involving a range of nanofluids, some of which may be designed with magnetorheological properties, comes online, the creation of time boundaries for the purpose of reservoir monitoring may well become feasible.

In all previously published accounts of reflections from time boundaries, "pure" time boundaries were considered, in which the medium property perturbations occurred through out the volume being considered. The novel aspect of the work described by includes extending the discussion to incorporate space components in addition to time. Including one or more spatial aspects to the medium property variations allows the concept of oblique reflections to be considered, in the same way that in order to discuss an oblique reflection across a standard space coordinate axis one must introduce at least one additional space coordinate axis.

Thus far all examples considered have been scalar-acoustic. In this short note we extend the idea to elastic media and present an example which further underscores the connection between space-time boundaries and oblique reflection. When an elastic wave (P or S) encounters a homogeneous and pure time boundary, no conversion (to S or P respectively) takes place; however, when a space component is included in the time-boundary, conversions occur. Thus pure time boundaries, in producing no conversions, continue to motivate a "normal incidence" interpretation, and space-time boundaries continue to invite an "oblique incidence" interpretation.

ELASTIC INTERACTIONS WITH SPACE-TIME BOUNDARIES

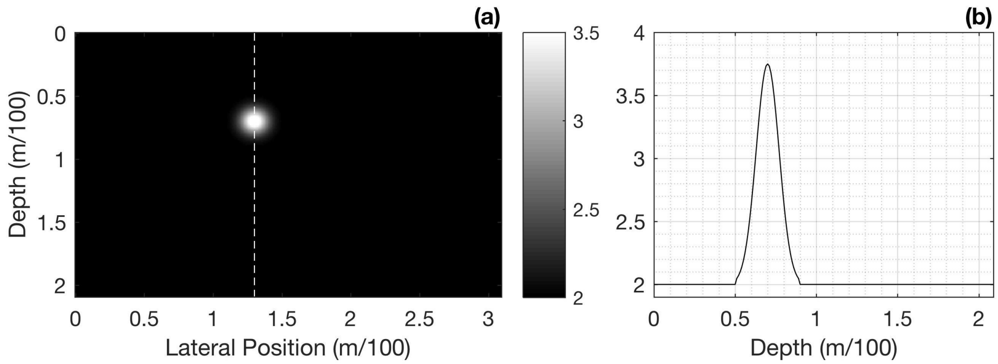

FIG. 1. Space-time boundary. (a) 2D form of the medium after the boundary has been encountered (beforehand it is homogeneous); (b) vertical profile through the Gaussian blob.

Model

In Figure 1a, the V_P part of the 2D background computational volume we use in this paper is illustrated; it is a homogeneous isotropic elastic medium with properties V_P=2000m/s, and:

$$\begin{aligned} V_S &= \frac{1}{2}V_P = 1000\text{m/s}, \\ \rho &= 310 \times V_P^{1/4} = 2073\text{kg/m}^3. \end{aligned} \tag{1}$$

We will consider two possible second media to act as perturbations on this background. First, a homogeneous perturbation from V_P of 2000m/s to 3500m/s (and with V_S and ρ also changing in accordance with equation (1). When the medium undergoes this variation the elastic wavefield will have impinged on a pure time boundary. Second, a heterogeneous perturbation in the form of a small Gaussian "blob" is introduced (see Figure 1b), which will, when it appears, create a space-time boundary for the wave to encounter obliquely.

Elastic time boundary

In Figure 2a-c three snapshots of the wave as it impinges on the pure time boundary are plotted. The left edge produces some edge artifacts, but within the computational domain the main observation is that there is a total lack of conversion. The larger-radius wavefront (P-wave) and the smaller radius wavefront (S-wave) both produce mode-conserved wavefronts which propagate back in the direction of the source (yellow).

Elastic space-time boundary

In Figure 3 the small Gaussian perturbation appears suddenly, interrupting the propagation of the S-wave. The P-wave has by this time propagated beyond the influence of

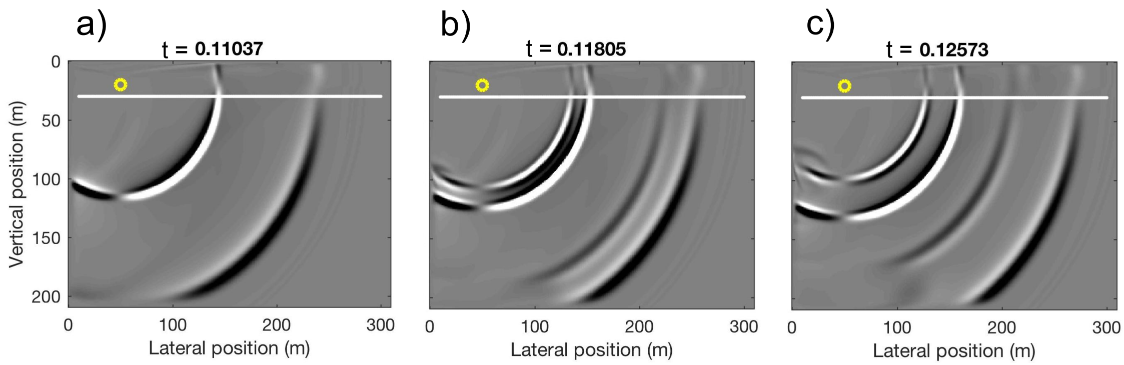

FIG. 2. (a)-(c) Three snapshots of the elastic wavefield after encountering the pure time boundary.

the perturbation; we will focus only on the S-wave reflection from this mixed space-time boundary. After it as impinged on the boundary, the S-wave continues to propagate away from the source, and the reflected S-wave front propagates back towards the source. However, with sufficient time, it becomes possible to observe that two waveforms were reflected from the perturbation: a fast P-wave can be seen outpacing the S-wave, both the front propagating back and the front continuing away from the source.

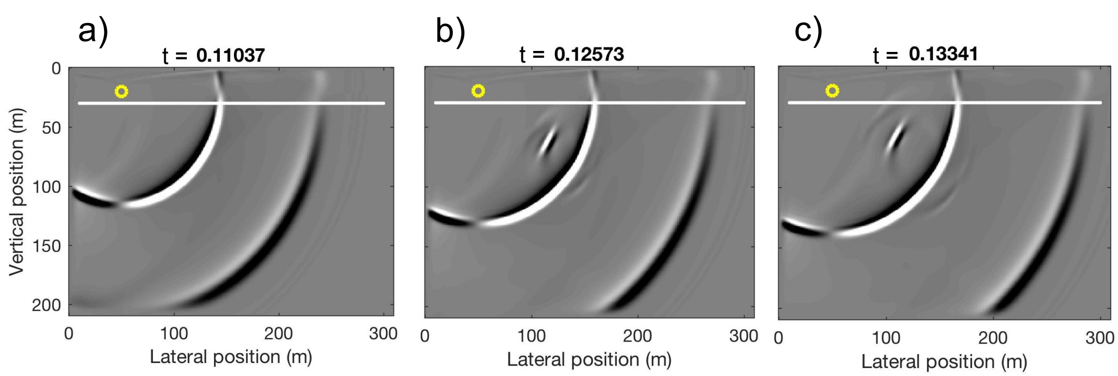

FIG. 3. (a)-(c) Three snapshots of the elastic wavefield after encountering the mixed space-time boundary.

Evidently a conversion has taken place. For more detail, see Figure 4.

CONCLUSIONS

We have commented on the possible applications of time-boundaries, which could in principle be created in reservoirs if nanofluids with magnetorheological properties were injected; in fact, reflections from these time boundaries might very accurately delineate regions into which the injection fluids had successfully penetrated. In any practical application, it is very unlikely that a pure time boundary could be arranged – i.e., a medium in which a large volume had been totally permeated such that a homogeneous change was created. We have discussed mixed space-time boundaries as acting effectively like time boundaries which are approached obliquely: in this paper further motivation for this view is presented, taking the form of the observation that elastic conversions happen for mixed but not for pure boundaries.

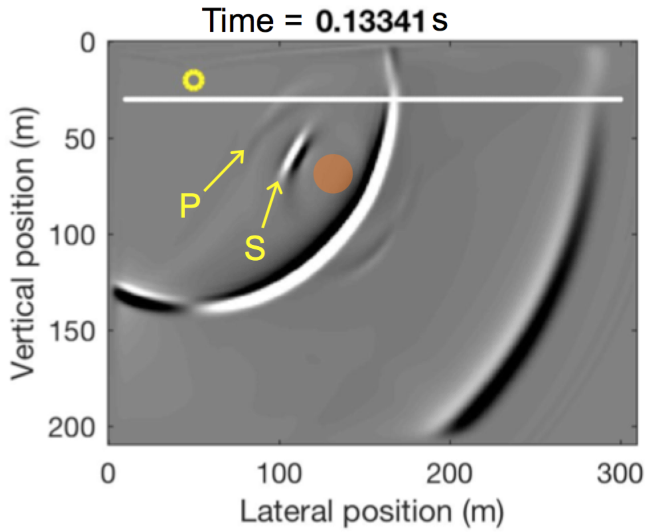

FIG. 4. Wavefront plot with key events labelled. Orange: the approximate size of the perturbing Gaussian blob.

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