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An excitation potential imaging condition for elastic reverse time migration

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ABSTRACT

Elastic reverse time migration (ERTM) has been demonstrated to be more accurate than scalar RTM. However, low efficiency (large storage and heavy calculated amount) and strong artifacts caused by the crosstalk between different wave modes are the two primary barriers to the application of the ERTM during the processing of real data. The scalar (P) and vector (S) potentials of the elastic wavefield and the arrival times corresponding to the first energy extremum of the wavefield are saved at each grid point during the forward modeling of the source wavefield. The angle-dependent reflection coefficient images are subsequently obtained by dividing the scalar and vector potentials of the backward extrapolated receiver wavefield by the saved scalar and vector potentials at the grid points that satisfy the image time at each time step, respectively. The proposed imaging condition does not need to store the snapshots of the source wavefield, while it can considerably improve the computational efficiency and decrease the amount of storage and Input/Output manipulation (compared with the cross-correlation imaging condition) in addition to suppressing the crosstalk between compressive and shear wave modes. Compared with the excitation time imaging condition, the proposed imaging condition reduces the energy loss caused by the opposite polarity of the horizontal component at opposite sides of the source in stacked images. Numerical tests with synthetic data of the Sigsbee2a model have demonstrated that this imaging condition is a cost-effective and practical imaging condition for use in prestack ERTM.

1. Introduction

All prestack migration algorithms involve an imaging principle that uses specific information from the propagating source and receiver wavefields (the imaging condition) to image a desired attribute (ideally, the angle-dependent reflection coefficient at the target) (Filhocunha, 1992). Many advanced prestack migration approaches have been developed in recent years. Ray-based migration techniques are based on the high-frequency approximation of the wave equation. However, because of multipathing, ray-based methods tend to break down in complex models with sharp impedance contrasts (Zhu et al., 2009). Generally, the results of one-way wave equation migrations are superior to the ray-based migrations when multipathing occurs (Operto et al., 2000), but they do not provide correct amplitudes for the reflector (Zhang et al., 2003), as the one-way propagator does not accurately model the wave amplitudes (Mulder and Plessix, 2004).

In contrast, full wave-equation-based migration techniques can handle all types of events (reflection, refraction and diffraction) without any approximation. Among these approaches, the prestack RTM (Baysal et al., 1983; McMechan, 1983) is the most accurate and can promise better imaging of steep dip and shadow zones compared with the Kirchhoff and one-way wave-equation-based algorithms (Chattopadhyay and McMechan, 2008). This improvement arises because the prestack RTM can use the comprehensive information of kinematics and dynamics.

The idea of the RTM was proposed early in 1978 (Hemon, 1978). Whitmore (1983) then formally proposed the RTM technique at the 53th SEG Annual Meeting. In the same year, other researchers discussed and applied the RTM to the stacked sections (Baysal et al., 1983; Loewenthal and Mufti, 1983; McMechan, 1983). Soon after, Chang and McMechan (1986, 1990) developed and applied the RTM to the prestack sections. However, the conventional RTM is usually based on the acoustic wave equation (Baysal et al., 1983; Liu et al., 2011) and is simply an approximation of the elastic wave equation. It ignores the shear-wave mode, which often leads to the incorrect characterization of wave propagation, incomplete illumination of the subsurface, and poor amplitude characterization (Yan and Sava, 2008). Although useful in practice, the assumption which it is based on is not theoretically valid.

On the other hand, the full elastic wave equation takes the compressive (P-) and shear (S-) wave propagation on the subsurface into account (Wapenaar et al., 1987). This is more consistent with actual earth materials. Thus, the use of the combinations of P- and S-wave data rather than P-wave data alone can yield previously unavailable information about the targets and better constrain the physical properties

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of the subsurface (Yan and Sava, 2008). In addition, the S-wave can also (in some cases) image structures that the P-wave cannot adequately portray, such as those beneath the high-velocity bodies (Yan and Xie, 2012). Therefore, based on the acoustic RTM, ERTM was first proposed by Sun and McMechan (1986) for elastic multicomponent data. Chang and McMechan (1987, 1994) carried out 2D and 3D elastic reverse-time migrations using a full-wave finite-difference method. Zhe and Greenhalgh (1997) used the potential instead of the displacement to propagate P- and S-waves. Sun and McMechan (2001) proposed the scalar reverse time migration for elastic multicomponent data by first using calculations of divergence and curl to separate the multicomponent data into pure P and S components. Sun et al. (2006) extended this method to 3D elastic data. Yan and Sava (2008) proposed an imaging method with scalar and vector potentials for elastic multicomponent seismic data.

Compared with the conventional acoustic RTM, the ERTM can better preserve the kinematic and dynamic features of elastic waves in complex models and gain more accurate seismic images of the subsurface (Yan and Xie, 2012). Many researchers have previously explored this aspect (e.g., Baysal et al., 1983; Chang and McMechan, 1986, 1987, 1994; Du and Qin, 2009; Levin, 1984; Sun and McMechan, 2001; Sun et al., 2006; Wapenaar et al., 1987; Yan and Sava, 2008, 2009; Yan and Xie, 2012; Yoon and Marfurt, 2006; Zhe and Greenhalgh, 1997). However, some problems still remained. The most important problem is the imaging condition, which affects both the results of the migration profile and the efficiency of the migration algorithm (Chattopadhyay and McMechan, 2008). Generally, the conventional crosscorrelation-based imaging conditions used in ERTM has the following three drawbacks: (a) they require a very large secondary storage capacity and afford a large Input/Output (I/O) burden because a priori knowledge of the full source wavefield is implied before applying the imaging condition (Nguyen and McMechan, 2013); (b) all of the amplitudes are imaged at each time, and all of multipaths are automatically included (at the expense of increased noise), which would lead to a low signal to noise ratio (SNR) in stacked images; and (c) the imaging ability of the horizontal component is comparatively weak. The excitation time imaging condition used by Chang and McMechan (1986, 1994) is extremely efficient, but it is not scaled by the correct normalization factor to obtain accurate reflection coefficients in the migrated domain (Nguyen and McMechan, 2013). In addition, the polarity-reversal of the horizontal component of the wavefield can lead to the destructive summation of wavefield energy in the migration domain and severely affect the migration quality and accuracy.

Another problem is that the crosstalk between P- and S-wave modes could result in severe image artifact (Yan and Sava, 2008). For example, when imaging with the vector displacement, a simple component-by-component operation (e.g., the cross-correlation operation under the cross-correlation imaging condition for vector wavefields) between source and receiver wavefields could lead to artifacts caused by crosstalk between the unseparated wave modes (Yan and Sava, 2008). However, this problem may be mostly alleviated by using the scalar and vector potentials of the elastic wavefield (Sun and McMechan, 2001; Sun et al., 2006; Yan and Sava, 2008, 2009; Zhe and Greenhalgh, 1997).

Nevertheless, the large storage and calculated amount as well as the strong artifact have remained a problem in all of the proposed approaches mentioned above. Here, we propose an excitation potential imaging condition for the ERTM that not only considers and capitalizes on the excitation time and the cross-correlation imaging conditions but also fully utilizes the Helmholtz decomposition theorem to solve these problems. Compared with the cross-correlation imaging condition, this imaging condition does not need to store the snapshot of the source wavefield, which could greatly improve the computational efficiency and decrease the amount of storage and I/O manipulation while suppressing the crosstalk between the compressive and shear wave modes. When compared with the excitation time imaging condition, this approach could reduce the energy loss caused by the opposite polarity of the horizontal component of the source. Perhaps, our successful application of the imaging condition to a set of 2-D synthetic data may help to demonstrate the value of this approach.

2. Theory

2.1. Theoretical background

Prestack elastic reverse-time migration mainly consists of three parts (Chang and McMechan, 1986): (a) the source wavefield is modeled by using a source at a given physical source location; (b) the extrapolation of the recorded multicomponent wavefields propagating backwards in time; and (c) the application of the imaging condition to the propagating wavefields for every grid point at each time step during the extrapolation.

Here, we define the arrival time corresponding to the first energy extremum of the wavefield at each grid point (instead of the maximum amplitude of the horizontal or vertical displacement components) as its excitation time (imaging time). We define the corresponding wavefield's

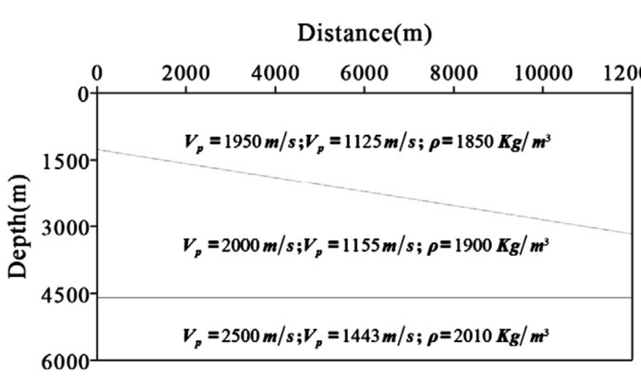

Fig. 1. P- and S-velocity and density of a three-layer model with slant and horizontal interfaces used in elastic wavefield forward modeling.

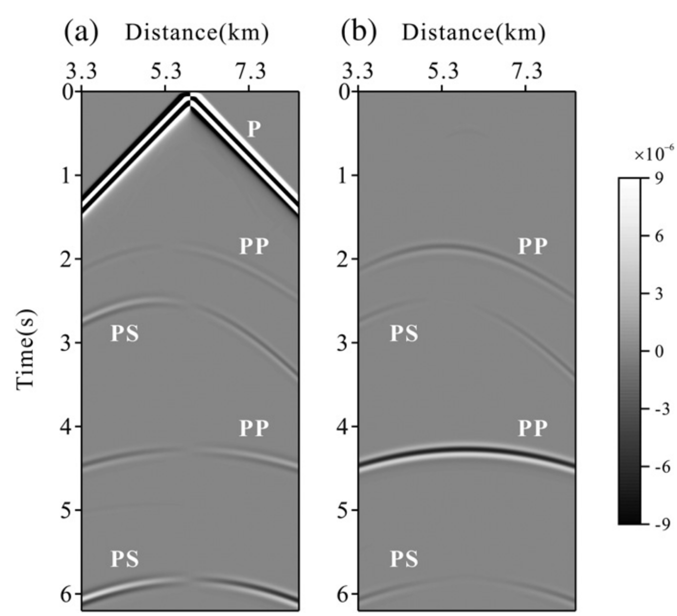

Fig. 2. A common shot gather modeling on the model in Fig. 1, with a source at $x = 5.8$ km and $z = 0.4$ km and receiver at $z = 0.4$ km. The vertical (a) and horizontal (b) components contain a mix of P- and S-modes.