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Directly imaging steeply-dipping fault zones in geothermal fields with multicomponent seismic data

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ABSTRACT

For characterizing geothermal systems, it is important to have clear images of steeply-dipping fault zones because they may confine the boundaries of geothermal reservoirs and influence hydrothermal flow. Elastic reverse-time migration (ERTM) is the most promising tool for subsurface imaging with multicomponent seismic data. However, conventional ERTM usually generates significant artifacts caused by the cross correlation of undesired wavefields and the polarity reversal of shear waves. In addition, it is difficult for conventional ERTM to directly image steeply-dipping fault zones. We develop a new ERTM imaging method in this paper to reduce these artifacts and directly image steeply-dipping fault zones. In our new ERTM method, forward-propagated source wavefields and backward-propagated receiver wavefields are decomposed into compressional (P) and shear (S) components. Each component of these wavefields is separated into left- and right-going, or downgoing and upgoing waves. The cross correlation imaging condition is applied to the separated wavefields along opposite propagation directions. For converted waves (P-to-S or S-to-P), the polarity correction is applied to the separated wavefields based on the analysis of Poynting vectors. Numerical imaging examples of synthetic seismic data demonstrate that our new ERTM method produces high-resolution images of steeply-dipping fault zones.

1. Introduction

Faults play an important role in geothermal fields. High-permeability faults provide preferential pathways for geothermal fluids, and are the primary control for efficient fluid flow and heat transfer (e.g., Goyal and Kassoy, 1980; López and Smith, 1995; Corbel et al., 2012). Faults may also act as barriers to fluid flow by juxtaposing impermeable lithologies against the reservoir rock (e.g., Knipe, 1992; Barnicoat et al., 2009). The existence of faults has a significant influence on the patterns of convection within the geothermal reservoir (e.g., Caine and Forster, 1999; Corbel et al., 2012). Faults can also produce earthquakes when the stress state in the field changes, causing damage to property and raising concerns of local communities (e.g., Megies and Wassermann, 2014; Wassing et al., 2014). Therefore, knowing the fault locations is crucial for understanding the hydrothermal flow in the geothermal system, conducting risk assessments, and planning geothermal operations.

Different techniques are available for detecting faults at depth in geothermal fields, including geological, gravity, magnetic, electromagnetic, and seismic surveys (Hatherton et al., 1966). Seismic methods are excellent tools for detecting faults because it could effectively map the locations and extension of buried faults both laterally and vertically.

As a standard data processing technique for seismic reflection data, conventional seismic migration methods, such as Kirchhoff migration, use primary reflection signals from subsurface interfaces to obtain images of impedance contrasts within geological structures. These conventional seismic migration methods can directly image horizontal layers and shallow-dipping faults. For steeply-dipping faults, as is usually found in geothermal fields (e.g., Huenges, 2010), none or only a very small portion of the primary reflection signals from these faults are recorded in surface seismic reflection data. Multiple reflections that illuminate these faults are much weaker than the primary reflections from stratigraphic layers. Therefore, it is a challenge to directly image steeply-dipping faults. The locations of steeply-dipping faults are, instead, usually inferred based on the offset of imaged stratigraphic layers. In many cases, because of the ambiguity in the offset of the stratigraphic layers, these inferences are subjective and inaccurate. Therefore,

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ERTM	elastic reverse-time migration
P	compressional wave
S	shear wave
$\mathbf{F}$	Poynting vector
$\mathbf{u}$	wavefield displacement or particle velocity
p	wavefield quantity
$s(\mathbf{x}, \tau)$	forward propagated source wavefield
$r(\mathbf{x}, t-\tau)$	backward propagated receiver wavefield
I	migration image
I^d	downward-looking migration image
I^u	upward-looking migration image
I^l	left-looking migration image
I^r	right-looking migration image
I_{PP}	migration image constructed using the compressional source wavefield and the compressional receiver wavefield
I_{PS}	migration image constructed using the compressional source wavefield and the shear receiver wavefield
I_{SP}	migration image constructed using the shear source wavefield and the compressional receiver wavefield
I_{SS}	migration image constructed using the shear source wavefield and the shear receiver wavefield

it is important and highly desirable to develop a seismic imaging method that is capable of directly imaging steeply-dipping fault zones in geothermal fields.

Reverse-time migration (RTM) is the most promising tool for high-resolution images of complex subsurface structures including steeply-dipping faults (e.g., Baysal et al., 1983; McMechan, 1983; Whitmore, 1983; Tan and Huang, 2014). RTM solves the full scalar-wave equation in heterogeneous media for forward propagation of source wavefields and backward propagation of recorded seismic reflection data from receivers. Thus it can handle complex wave phenomena including multiple reflections, and has no dip limitation. RTM is commonly employed for single-component seismic data. Multicomponent seismic surveys have developed rapidly during recent years (Gaiser et al., 2001). Multicomponent seismic data contain more complete information about seismic wavefields, and are useful in many applications that are not achievable with single-component data (Stewart et al., 2002, 2003). Performing elastic reverse-time migration (ERTM) rather than RTM is necessary to take full advantage of the additional information contained in multicomponent seismic data. ERTM solves the elastic-wave equation in heterogeneous media, and can properly handle the conversions between compressional (P) and shear (S) waves (Chang and McMechan, 1987). ERTM has been shown to provide better images of subsurface structures than conventional seismic migration and RTM (e.g., Lu et al., 2009; Huang and Albrecht, 2011; Huang et al., 2011).

Despite powerful imaging capabilities, ERTM faces some challenges (Yoon et al., 2004) for high-resolution imaging of complex subsurface structures. One of the challenges is the appearance of low-wavenumber artifacts in migration images (P-to-P or S-to-S) with the conventional full-wavefield zero-lag cross-correlation imaging condition (Claerbout, 1985). These artifacts are caused by the cross correlation of diving waves and their corresponding backscattered waves at locations other than the reflectors. Such artifacts are particularly strong in shallow layers or regions with large impedance contrasts, contaminating images of subsurface structures. Different approaches have been developed to suppress these low-wavenumber image artifacts. Filtering applied after imaging using filters such as bandpass, derivative, Laplacian, and more advanced least-square filters can reduce the low-wavenumber artifacts (Youn and Zhou, 2001; Mulder and Plessix, 2004; Guitton et al., 2007). However, the filtering may change the character of reflections such as phase and spectrum, increase high-wavenumber artifacts, or remove useful information. Reducing the reflections by smoothing the velocity model (Loewenthal et al., 1987) or using a nonreflecting wave equation (Baysal et al., 1984) can also suppress the artifacts, but introduce unrealistic wavefields. Modifying imaging conditions is another method to attenuate or remove the artifacts. Such methods include normalizing the conventional imaging condition by source or receiver illuminations (Kaelin et al., 2007), and separating or weighting wavefields traveling in different directions (e.g., Yoon et al., 2004; Costa et al., 2009; Liu et al., 2011).

Another challenge for ERTM is the polarity reversal problem for images obtained with converted waves (P-to-S or S-to-P). Because the polarity directions of S waves change across the normal incidence direction, when we stack migration images from different common-shot seismic data, mixed signs of polarity lead to destructive images. To obtain coherent images for the converted waves, we need to apply a polarity correction. Because the signs of polarity depend on the direction of the incident waves relative to a reflector, it is straightforward to correct for the polarity reversal by analyzing the propagation directions of the waves. Two popular methods can be used for this purpose. One applies the extended imaging condition to extract the angle information (Rickett and Sava, 2002; Sava and Fomel, 2006; Yan and Sava, 2008; Fomel, 2011), and the other uses Poynting vectors to obtain wave propagation directions (Dickens and Winbow, 2011; Vyas et al., 2011; Yoon et al., 2011; Du et al., 2012). The extended imaging condition method with the ability to handle multipathing is generally more accurate in complex geology, but it has lower angular resolution and is computationally expensive. The Poynting-vector method has high angular resolution and is computationally efficient, but cannot handle multipathing and is difficult to accurately estimate propagation directions for complicated wavefields (Patrikeeva and Sava, 2013).

We develop a new imaging condition for 2D ERTM by combining wavefield separation with the Poynting vector method. We separate the forward-propagated source wavefields and backward-propagated receiver wavefields along the vertical direction to obtain the downgoing and upgoing waves, and along the horizontal direction to obtain the left-going and right-going waves. ERTM with our new imaging condition can directly image steeply-dipping fault zones using multicomponent seismic data, while eliminating the low-wavenumber artifacts and correcting the polarity reversal efficiently and more accurately. We apply our method to synthetic elastic seismic reflection data for a geophysical model from the Soda Lake geothermal site containing several steeply-dipping fault zones, and demonstrate the capability of our new method for directly imaging steeply-dipping fault zones.

2. Methods

2.1. Elastic reverse-time migration

The first step of ERTM is elastic wavefield extrapolation. We compute elastic wavefields in an isotropic, non-attenuative medium using a staggered-grid high-order finite-difference scheme in the time domain. A perfectly matched layer (PML) approach is implemented as an absorbing boundary condition. The source wavefield is propagated forward in time, and the receiver wavefield is extrapolated backward in time using the recorded multicomponent seismic data as boundary values.