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

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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.

Keywords:

Steeply-dipping fault, seismic imaging, elastic reverse-time migration, wavefield separation, geothermal exploration, Poynting vector

Nomenclature

ERTM	elastic reverse-time migration
P	compressional wave
S	shear wave
F	Poynting vector
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
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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

26 a very small portion of the primary reflection signals from these faults are recorded
27 in surface seismic reflection data. Multiple reflections that illuminate these faults
28 are much weaker than the primary reflections from stratigraphic layers. There-
29 fore, it is a challenge to directly image steeply-dipping faults. The locations of
30 steeply-dipping faults are, instead, usually inferred based on the offset of imaged
31 stratigraphic layers. In many cases, because of the ambiguity in the offset of the
32 stratigraphic layers, these inferences are subjective and inaccurate. Therefore, it
33 is important and highly desirable to develop a seismic imaging method that is
34 capable of directly imaging steeply-dipping fault zones in geothermal fields.

35 Reverse-time migration (RTM) is the most promising tool for high-resolution
36 images of complex subsurface structures including steeply-dipping faults (e.g.,
37 Baysal et al., 1983; McMechan, 1983; Whitmore, 1983; Tan and Huang, 2014).
38 RTM solves the full scalar-wave equation in heterogeneous media for forward
39 propagation of source wavefields and backward propagation of recorded seis-
40 mic reflection data from receivers. Thus it can handle complex wave phenom-
41 ena including multiple reflections, and has no dip limitation. RTM is commonly
42 employed for single-component seismic data. Multicomponent seismic surveys
43 have developed rapidly during recent years (Gaiser et al., 2001). Multicompo-
44 nent seismic data contain more complete information about seismic wavefields,
45 and are useful in many applications that are not achievable with single-component
46 data (Stewart et al., 2002, 2003). Performing elastic reverse-time migration (ERTM)
47 rather than RTM is necessary to take full advantage of the additional information
48 contained in multicomponent seismic data. ERTM solves the elastic-wave equa-
49 tion in heterogeneous media, and can properly handle the conversions between
50 compressional (P) and shear (S) waves (Chang and McMechan, 1987). ERTM

51 has been shown to provide better images of subsurface structures than conven-
52 tional seismic migration and RTM (e.g., Lu et al., 2009; Huang and Albrecht,
53 2011; Huang et al., 2011).

54 Despite powerful imaging capabilities, ERTM faces some challenges (Yoon
55 et al., 2004) for high-resolution imaging of complex subsurface structures. One of
56 the challenges is the appearance of low-wavenumber artifacts in migration images
57 (P-to-P or S-to-S) with the conventional full-wavefield zero-lag cross-correlation
58 imaging condition (Claerbout, 1985). These artifacts are caused by the cross cor-
59 relation of diving waves and their corresponding backscattered waves at locations
60 other than the reflectors. Such artifacts are particularly strong in shallow lay-
61 ers or regions with large impedance contrasts, contaminating images of subsur-
62 face structures. Different approaches have been developed to suppress these low-
63 wavenumber image artifacts. Filtering applied after imaging using filters such as
64 bandpass, derivative, Laplacian, and more advanced least-square filters can re-
65 duce the low-wavenumber artifacts (Youn and Zhou, 2001; Mulder and Plessix,
66 2004; Guitton et al., 2007). However, the filtering may change the character of
67 reflections such as phase and spectrum, increase high-wavenumber artifacts, or
68 remove useful information. Reducing the reflections by smoothing the velocity
69 model (Loewenthal et al., 1987) or using a nonreflecting wave equation (Baysal
70 et al., 1984) can also suppress the artifacts, but introduce unrealistic wavefields.
71 Modifying imaging conditions is another method to attenuate or remove the arti-
72 facts. Such methods include normalizing the conventional imaging condition by
73 source or receiver illuminations (Kaelin et al., 2007), and separating or weighting
74 wavefields traveling in different directions (e.g., Yoon et al., 2004; Costa et al.,
75 2009; Liu et al., 2011).

76 Another challenge for ERTM is the polarity reversal problem for images ob-
77 tained with converted waves (P-to-S or S-to-P). Because the polarity directions of
78 S waves change across the normal incidence direction, when we stack migration
79 images from different common-shot seismic data, mixed signs of polarity lead to
80 destructive images. To obtain coherent images for the converted waves, we need
81 to apply a polarity correction. Because the signs of polarity depend on the direc-
82 tion of the incident waves relative to a reflector, it is straightforward to correct for
83 the polarity reversal by analyzing the propagation directions of the waves. Two
84 popular methods can be used for this purpose. One applies the extended imag-
85 ing condition to extract the angle information (Rickett and Sava, 2002; Sava and
86 Fomel, 2006; Yan and Sava, 2008; Fomel, 2011), and the other uses Poynting
87 vectors to obtain wave propagation directions (Dickens and Winbow, 2011; Vyas
88 et al., 2011; Yoon et al., 2011; Du et al., 2012). The extended imaging condi-
89 tion method with the ability to handle multipathing is generally more accurate
90 in complex geology, but it has lower angular resolution and is computationally
91 expensive. The Poynting-vector method has high angular resolution and is com-
92 putationally efficient, but cannot handle multipathing and is difficult to accurately
93 estimate propagation directions for complicated wavefields (Patrikeeva and Sava,
94 2013).

95 We develop a new imaging condition for 2D ERTM by combining wavefield
96 separation with the Poynting vector method. We separate the forward-propagated
97 source wavefields and backward-propagated receiver wavefields along the vertical
98 direction to obtain the downgoing and upgoing waves, and along the horizontal di-
99 rection to obtain the left-going and right-going waves. ERTM with our new imag-
100 ing condition can directly image steeply-dipping fault zones using multicompo-

101 nent seismic data, while eliminating the low-wavenumber artifacts and correcting
 102 the polarity reversal efficiently and more accurately. We apply our method to syn-
 103 thetic elastic seismic reflection data for a geophysical model from the Soda Lake
 104 geothermal site containing several steeply-dipping fault zones, and demonstrate
 105 the capability of our new method for directly imaging steeply-dipping fault zones.

106 **2. Method**

107 *2.1. Elastic reverse-time migration*

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

115 After the wavefield extrapolation (forward or backward propagation), we de-
 116 compose both the source and receiver wavefields into compressional (P) and shear
 117 (S) components based on Helmholtz decomposition (Dellinger and Etgen, 1990):

118

$$P = \nabla \cdot \mathbf{u}, \quad (1)$$

119

$$\mathbf{S} = \nabla \times \mathbf{u}, \quad (2)$$

120 where $\mathbf{u}$ is the extrapolated elastic wavefield. It can be the vector field of either
 121 displacement or particle velocity in practice. The scalar P represents the curl-
 122 free part of the wavefield. The vector $\mathbf{S}$ describes the divergence-free part of the

123 wavefield. In two dimensions, the vector $\mathbf{S}$ has only one non-zero component and
 124 can also be treated as a scalar.

125 The conventional imaging condition in ERTM is implemented as

$$I(\mathbf{x}) = \int_0^t s(\mathbf{x}, \tau) r(\mathbf{x}, t - \tau) d\tau, \quad (3)$$

126 where $s(\mathbf{x}, \tau)$ is the forward propagated source wavefield at location $\mathbf{x}$ and time τ ,
 127 $r(\mathbf{x}, t - \tau)$ denotes the backward propagated receiver wavefield, and t represents
 128 the maximum record time in seismic traces. By cross correlating different wave
 129 modes (P or S) of the source and receiver wavefields, we can obtain four differ-
 130 ent images: compressional-to-compressional (I_{PP}), compressional-to-shear (I_{PS}),
 131 shear-to-compressional (I_{SP}), and shear-to-shear (I_{SS}) images. Comparing with
 132 simple cross correlation of Cartesian components of the wavefields, the images
 133 formed with cross correlation of decomposed P and S components are free of ar-
 134 tifacts caused by the crosstalk between different wave modes, and are easier to
 135 interpret in a physical sense (Yan and Sava, 2008).

136 2.2. *Wavefield separation*

137 If we use the conventional imaging condition in Eq. (3), the resulting images
 138 I_{PP} and I_{SS} will have large low-wavenumber artifacts. These artifacts are caused
 139 by the undesired cross correlation between diving waves and backscattered waves.

140 To remove these low-wavenumber artifacts, we can modify the imaging con-
 141 ditions with separated wavefields (Denli and Huang, 2008; Liu et al., 2011). After
 142 wave-mode decomposition, we use a frequency-wavenumber (f-k) filter to sepa-
 143 rate P and S components from both the source and receiver wavefields along hor-
 144 izontal and vertical directions, and then use the separated downgoing, upgoing,

145 left-going, and right-going wavefields to form multiple images. The downward-
 146 looking (I^d), upward-looking (I^u), left-looking (I^l), and right-looking (I^r) images
 147 are constructed using the cross correlations of the separated wavefields propagat-
 148 ing in the opposite directions:

$$\begin{aligned}
 I^d(\mathbf{x}) &= \int_0^t s^{+z}(\mathbf{x}, \tau) r^{-z}(\mathbf{x}, t - \tau) d\tau, \\
 I^u(\mathbf{x}) &= \int_0^t s^{-z}(\mathbf{x}, \tau) r^{+z}(\mathbf{x}, t - \tau) d\tau, \\
 I^l(\mathbf{x}) &= \int_0^t s^{-x}(\mathbf{x}, \tau) r^{+x}(\mathbf{x}, t - \tau) d\tau, \\
 I^r(\mathbf{x}) &= \int_0^t s^{+x}(\mathbf{x}, \tau) r^{-x}(\mathbf{x}, t - \tau) d\tau,
 \end{aligned} \tag{4}$$

149 where “+ z ”, “- z ”, “- x ”, and “+ x ” designate downgoing, upgoing, left-going, and
 150 right-going wavefields, respectively. The wavefields s and r can represent either
 151 the P or S component, forming PP (I_{PP}), PS (I_{PS}), SP (I_{SP}), and SS (I_{SS}) images.
 152 I^d and I^u provide images of horizontal or shallow-dipping reflectors, while I^l and
 153 I^r show vertical or steeply-dipping reflectors, such as steep faults. For surface
 154 seismic surveys, seismic sources are located at the Earth’s surface, or above the
 155 subsurface structures, and the most useful source wave signals are downgoing
 156 instead of upgoing, so we use the combination of I^d , I^l , and I^r to form the complete
 157 images.

158 Since diving waves and time-reversed backscattered waves have the same
 159 propagation directions, using only the separated waves along opposite directions
 160 instead of the full wavefields to form migration images, we can eliminate the un-
 161 desired cross correlation between source and receiver wavefields and remove the
 162 low-wavenumber artifacts. The separation of wavefields along both horizontal
 163 and vertical directions and the imaging condition with only waves along oppo-

164 site propagation directions also enable us to directly image steep faults, because
 165 steeply-dipping reflectors are illuminated mostly by weak multiple reflections,
 166 which are likely buried in other strong primary reflection signals without wave-
 167 field separation.

168 2.3. *Polarity correction*

169 Images I_{PS} and I_{SP} , constructed using converted waves, do not contain low-
 170 wavenumber artifacts, because the diving waves and their corresponding backscat-
 171 tered waves are not in phase as a result of the different velocities of P and S waves.
 172 However, I_{PS} and I_{SP} may suffer from polarity issues.

173 Because of the polarity reversal of S waves, the S-wave component (Eq. (2))
 174 has different directions on the opposite sides of the normal incidence point. Since
 175 we treat the S-wave component as a scalar in the imaging condition, the different
 176 directions of the S-wave component are shown with different signs in Eqs. (3)
 177 and (4). For I_{SS} , that does not matter because both source (s) and receiver (r)
 178 wavefields change signs. For I_{PS} and I_{SP} , the polarity reversal of S waves re-
 179 sults in flipped signs on opposite sides of normal incidence points for each of the
 180 common-shot images. Because seismic incident waves from different shots have
 181 different normal incidence points, when we stack migration images from multiple
 182 common-shot gathers, the images become destructive rather than constructive or
 183 coherent.

184 To correct for the polarity reversal, we may first compute Poynting vectors for
 185 both source and receiver wavefields. The Poynting vector $\mathbf{F}$ describes the energy
 186 flux density, and can be calculated using

$$\mathbf{F} = -\dot{p} \nabla p, \quad (5)$$

187 where p is the wavefield quantity for P or S waves (Eqs. (1), (2)). The Poynt-
 188 ing vectors calculated using Eq. (5) is more accurate than those obtained using
 189 the multiplication of stress and velocity (Du et al., 2012). The sign of the cross
 190 product between the Poynting vectors of the source and receiver wavefield $\mathbf{F}_s \times \mathbf{F}_r$
 191 changes with the polarity distribution of S waves, and can be used to correct for
 192 polarity reversal as (Du et al., 2012)

$$I(\mathbf{x}) = \int_0^t s(\mathbf{x}, \tau) r(\mathbf{x}, t - \tau) \text{sgn}(\mathbf{F}_s \times \mathbf{F}_r) d\tau. \quad (6)$$

193 The Poynting vector analysis is a very attractive approach for correcting the
 194 polarity reversal because of its computational efficiency. This is crucial for large-
 195 scale 3D migration imaging. However, it is difficult to accurately estimate Poynt-
 196 ing vectors for complicated wavefields. In addition, because the Poynting vector
 197 assumes only one propagation direction at any time for a given point, it cannot
 198 handle multipathing. To alleviate these limitations, rather than directly using the
 199 imaging condition in Eq. (6), we estimate Poynting vectors for separated wave-
 200 fields, and then apply the polarity correction to the separated wavefields to obtain
 201 downward-looking, upward-looking, left-looking, and right-looking images for
 202 I_{PS} and I_{SP} as:

$$\begin{aligned} I^d(\mathbf{x}) &= \int_0^t s^{+z}(\mathbf{x}, \tau) r^{-z}(\mathbf{x}, t - \tau) \text{sgn}(\mathbf{F}_s^{+z} \times \mathbf{F}_r^{-z}) d\tau, \\ I^u(\mathbf{x}) &= \int_0^t s^{-z}(\mathbf{x}, \tau) r^{+z}(\mathbf{x}, t - \tau) \text{sgn}(\mathbf{F}_s^{-z} \times \mathbf{F}_r^{+z}) d\tau, \\ I^l(\mathbf{x}) &= \int_0^t s^{-x}(\mathbf{x}, \tau) r^{+x}(\mathbf{x}, t - \tau) \text{sgn}(\mathbf{F}_s^{-x} \times \mathbf{F}_r^{+x}) d\tau, \\ I^r(\mathbf{x}) &= \int_0^t s^{+x}(\mathbf{x}, \tau) r^{-x}(\mathbf{x}, t - \tau) \text{sgn}(\mathbf{F}_s^{+x} \times \mathbf{F}_r^{-x}) d\tau. \end{aligned} \quad (7)$$

203 Because separated wavefields become simpler than the full wavefields, we
 204 are able to improve the accuracy of the computed Poynting vectors and enhance

205 polarity-corrected images using Eq. (7). Computing Poynting vectors after wave-
206 field separation can also help distinguish some multipathing with different propa-
207 gating directions. Therefore, ERTM with the imaging condition shown in Eq. (7)
208 is an efficient and effective method for directly imaging steep-dipping faults using
209 multicomponent seismic data.

210 While we develop our new ERTM method for improving imaging of steeply-
211 dipping faults that are difficult for conventional migration to map, our new method
212 can also image reflectors with any dip angles and faults with any thicknesses.

213 **3. Numerical examples**

214 Our focus is to directly image steeply-dipping fault zones in geothermal fields
215 using multicomponent seismic data. First, we validate the effectiveness of our
216 ERTM method for imaging faults using a simple 2D layered model with one ver-
217 tical fault. Then we apply our method to image a 2D geophysical model for the
218 Soda Lake geothermal site in Nevada.

219 *3.1. Vertical fault model*

220 We consider a four-layer model with an embedded vertical fault zone (Fig. 1).
221 The middle two layers are displaced approximately 5 m vertically along the fault.
222 The fault zone has a thickness of 20 m. The P-wave velocity of the fault zone is
223 10% lower than that of the surrounding regions. S-wave velocities have similar
224 structure to the P-wave velocities with a constant ratio of $V_P/V_S = 1.73$. Such
225 a fault with a dip angle as large as 90 degrees and small displacement is partic-
226 ularly difficult to image using conventional seismic migration methods that use
227 only primary reflections for imaging.

228 We use a high-order finite-difference scheme to solve the elastic-wave equa-
 229 tion to generate synthetic elastic reflection data for a surface seismic survey. A
 230 total of 34 explosive shots with an even spacing of 30 m are located on the top
 231 surface of the model. The source signal is a Ricker wavelet with a center fre-
 232 quency of 20 Hz. The grid size of the model is 5 m.

233 We apply our new ERTM method to the synthetic seismic data to perform
 234 migration imaging using the true velocity model. We then compare our migration
 235 images with those obtained using the conventional migration imaging condition.
 236 Fig. 2 shows a comparison of PP images within a region around the vertical fault
 237 zone. The image in Fig. 2a obtained using the conventional ERTM (Eq. (3)) is
 238 contaminated by high-amplitude background artifacts, which mask a large part
 239 of the structures. The artifacts overwhelm the images of reflectors so the image
 240 appears all blue with a symmetric red-white-blue colorbar.

241 If we separate the source and receiver wavefields into downgoing and upgoing
 242 components, and perform cross correlation only between the downgoing source

Fig. 1. A model with a vertical fault. (a) P-wave velocity and (b) S-wave velocity.

Fig. 2. PP images of a section of the fault model in Fig. 1. (a) The conventional ERTM image, (b) downward-looking image I_{PP}^d , (c) horizontal-looking image ($I_{PP}^l + I_{PP}^r$), and (d) our new ERTM image ($I_{PP}^d + I_{PP}^l + I_{PP}^r$).

243 wavefield and upgoing receiver wavefield, the resulting downward-looking image
 244 (Fig. 2b) is free of background artifacts and clearly shows the horizontal reflectors.
 245 Note that the offset at the location of the fault is very small. Thus it is a challenge
 246 to infer the geometry of the fault based on the displacement of the horizontal
 247 layers, as is usually performed for conventional seismic migration methods that
 248 use only primary reflections.

249 If we separate the source and receiver wavefields into left-going and right-
 250 going components, the cross correlation between the separated right-going source

Fig. 3. PS images of a section of the fault model in Fig. 1. (a) The conventional ERTM image using Eq. (3), (b) the polarity corrected image using Eq. (6), and (c) our new ERTM image using Eq. (7).

251 wavefield and left-going receiver wavefield provides a right-looking view of the
 252 vertical or steeply-dipping reflectors, i.e., the fault. Similarly, the cross correla-
 253 tion between the left-going source wavefield and right-going receiver wavefield
 254 provides a left-looking view of the fault. The combination of the right-looking
 255 and left-looking images yields a horizontal-looking image (Fig. 2c), which clearly
 256 shows the fault without the background artifacts.

257 Since the shots are on the surface, the upward-looking image contains more
 258 artifacts than real structures. We thus combine only the downward-looking and

horizontal-looking images to form our final image (Fig. 2d). Our new ERTM produces a greatly improved image (Fig. 2d) when compared to the conventional ERTM (Fig. 2a), clearly revealing both the horizontal layers and the vertical fault without the contamination from low-wavenumber background artifacts.

PS images of ERTM are shown in Fig. 3. There is no background artifact problem in the PS images, but the interfaces in the image obtained using the conventional imaging condition (Fig. 3a) are not coherent because of the polarity reversal. With the polarity correction using Poynting vectors for the full wavefields (Eq. (6)), the coherency of the imaged horizontal reflectors is improved (Fig. 3b), but the fault is still not well mapped. This demonstrates that, for ERTM with full wavefields, the usefulness of the polarity correction using Poynting vectors for imaging the vertical fault is much less significant than that for horizontal reflectors. Using our ERTM method that computes Poynting vectors and employs the imaging condition based on separated wavefields (Eq. (7)), we obtain a much improved image of the fault and horizontal layers (Fig. 3c). Note that the resolution of the PS image (Fig. 3b) is higher than that of the PP image (Fig. 2d) because of the shorter wavelengths of S waves compared to P waves.

Because we use explosive sources in the simulation, we only show PP and PS images for illustration. If the sources generate enough S components using shear-wave sources, we can also produce SP and SS images in a similar approach. The SP and SS images are supposed to have features similar to the PS and PP images, respectively, except that the SS image has higher resolution than the PP image. However, if the sources contain S components, the wavefields become more complicated, and more artifacts may be expected in the resulting images compared to the case of explosive sources.

284 3.2. Soda Lake geothermal model

285 We next apply our ERTM method to a velocity model from the Soda Lake
 286 geothermal site to demonstrate the capability of our method for directly imag-
 287 ing steep faults in a complex structure environment representative of geothermal
 288 fields. The Soda Lake geothermal site is located about 10 km northwest of Fal-
 289 lon, Nevada. The velocity model is constructed by integrating well logs, gravity,
 290 seismic reflection data, and geological interpretation results. The model contains
 291 multiple stratigraphic layers and six steeply-dipping fault zones with a width of
 292 25 m (Fig. 4). A high-velocity basaltic unit is intruded from the bottom to a depth
 293 of around 0.7 km (Magma Energy (U.S.) Corp., 2011). S-wave velocities have a
 294 structure similar to that of P-wave velocities with a constant ratio of $V_P/V_S = 1.73$.
 295 The velocity values of the fault zones are 15% lower than those of the surround-
 296 ings.

Fig. 4. The velocity model for the Soda Lake geothermal site. (a) P-wave velocity and (b) S-wave velocity.

297 We simulate elastic wave propagation for 113 explosive sources located along
 298 the top surface of the model. The sources have an even space interval of 10 m.

299 The source function is a Ricker wavelet with a central frequency of 20 Hz. The
 300 grid size of the model is 6 m. We apply ERTM to the synthetic seismic data to
 301 perform migration using the true velocity model to produce PP and PS images.

Fig. 5. PP images of the model in Fig. 4. (a) The conventional ERTM image, (b) downward-looking image I_{PP}^d , (c) horizontal-looking image ($I_{PP}^l + I_{PP}^r$), and (d) our new ERTM image ($I_{PP}^d + I_{PP}^l + I_{PP}^r$).

302 For the PP images, ERTM with the conventional imaging condition (Eq. (3))
 303 produces high-amplitude, low-wavenumber image artifacts throughout the image,
 304 particularly above the high-contrast basaltic unit (Fig. 5a). These low-wavenumber
 305 artifacts contaminate the image so that some structures, especially the shallow
 306 ones above the high-velocity basaltic unit, are almost invisible. Using our new
 307 ERTM imaging condition with separated wavefields (Eq. (4)), the low-wavenumber
 308 artifacts are eliminated and many previously masked structures are clearly re-

309 vealed (Figs. 5b-d). Horizontal or gently-dipping discontinuities are shown in
310 the downward-looking image (Fig. 5b), while steeply-dipping faults are shown in
311 the horizontal-looking image (Fig. 5c). Note that not only the location but also the
312 end points of the faults are well imaged. For example, the images clearly show
313 that the fourth and fifth faults from the left do not reach the surface (blind faults).
314 Locating fault terminations is important for characterizing the hydrothermal flow
315 in a geothermal field, but they cannot be determined using the offset of imaged
316 horizontal layers in conventional seismic migration images. The top interfaces
317 of the basaltic unit are faintly seen in the horizontal-looking image because of
318 numerical diffraction of the discretized model. Comparing Figs. 5a with 5d, our
319 new ERTM method produces an improved image with clear visualization of both
320 horizontal layers as well as the steep-dipping fault zones.

321 The PS images shown in Fig. 6 do not contain low-wavenumber artifacts like
322 those in the conventional PP images. However, the mixed polarity signs of con-
323 verted shear waves result in a destructive image using the conventional imaging
324 condition (Fig. 6a). Polarity reversal correction using Poynting vectors computed
325 with the full wavefields (Eq. (6)) leads to an improved image (Fig. 6b). How-
326 ever, the faults and some of the deep layers are still not well imaged. Our ERTM
327 method computes Poynting vectors and employs the imaging conditions based on
328 the separated wavefields (Eq. (7)), and produces a much more coherent image of
329 both the horizontal layers and steeply-dipping faults (Fig. 6c). The PS image in
330 Fig. 6c has higher resolution than that of the PP image in Fig. 5d because of the
331 shorter wavelengths of the S waves compared to P waves. Some interfaces that are
332 too close to be separated in the PP image may be distinguishable in the PS image.
333 For example, the image of the top of the basaltic unit is merged with the image of

Fig. 6. PS images of the model in Fig. 4. (a) The conventional ERTM image using Eq. (3), (b) the polarity corrected image using Eq. (6), and (c) our new ERTM image using Eq. (7).

the interface above the basaltic unit in the PP image, whereas these two interfaces are well separated in the PS image.

The computational costs for our numerical examples are approximately a couple of hours on a modern 50-CPU-core cluster.

4. Conclusions

We have developed a new ERTM method for directly imaging steeply-dipping fault zones in geothermal fields using multicomponent seismic data. In our new method, we first separate the forward-propagated source wavefields and the backward-propagated receiver wavefields along the vertical direction to obtain downgoing and upgoing waves, and along the horizontal direction to obtain the left-

344 going and right-going waves. We then use the separated wavefields propagating
345 along opposite directions to produce compressional-to-compressional (or shear-
346 to-shear) images. For imaging with converted waves, we correct the polarity re-
347 versal of the shear waves using Poynting vectors computed with the separated
348 wavefields to alleviate the multipathing issue and improve the accuracy of the
349 estimated propagation directions. The new method has several advantages; (1)
350 it enables us to directly image steep faults using multicomponent seismic data;
351 (2) it eliminates the low-wavenumber background artifacts for compressional-to-
352 compressional (or shear-to-shear) images; and (3) it is computationally efficient
353 for polarity corrections, which is particularly important for large-scale 3D imag-
354 ing. We have applied our new ERTM method to synthetic elastic seismic data
355 generated for a Soda Lake geothermal model, and demonstrated that our method
356 directly images steep faults as well as horizontal layers. For imaging with con-
357 verted waves, our new method produces much clearer images of steeply-dipping
358 fault zones and horizontal layers compared to those obtained using Poynting vec-
359 tors and an imaging condition based on unseparated wavefields.

360 In our numerical examples, we use noise-free synthetic seismic data and true
361 velocity models to perform migration and demonstrate the effectiveness of our
362 new ERTM imaging condition. For practical application, the velocity models used
363 for ERTM can be obtained using velocity analysis and high-resolution seismic-
364 waveform inversion. Velocity uncertainties and noise in seismic data could de-
365 grade migration images. Nevertheless, our method can still produce better imag-
366 ing results than the conventional ERTM.

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