Imaging Steeply-Dipping Fault Zones Using
a Novel Least-Squares Reverse-Time Migration Method

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ABSTRACT
Imaging fault zones plays an important role in exploration for geothermal energy. It is very challenging for conventional seismic migration imaging using primary reflection data to obtain high-resolution images of steeply-dipping fault zones. We develop a new least-squares reverse-time migration for high-resolution imaging of steeply-dipping fault zones. Our method uses a field-division imaging condition and updated source wavefields during each iteration step of least-squares reverse-time migration. We validate the improved imaging capability of our new method using synthetic surface reflection data for a 2D geophysical model constructed using geologic features found at the Soda Lake geothermal field. The model contains several steeply-dipping fault zones. Our least-squares reverse-time migration method significantly improves the images of steeply-dipping fault zones compared with those obtained using conventional reverse-time migration or conventional least-squares reverse-time migration. Our method provides a promising tool for site characterization of geothermal fields.

1. INTRODUCTION
Seismic imaging of subsurface structures plays an important role in geothermal exploration. In particular, imaging faults can provide crucial information for site characterization, because fault zones may dominate the flow paths of hot water, or confine the boundaries of geothermal reservoirs. It is very challenging for conventional seismic migration method using primary reflection data to obtain high-resolution images of steeply-dipping fault zones. This is because seismic reflection data often contain few primary reflections from steeply-dipping fault zones. Reverse-time migration (RTM), on the other hand, uses the full-wave equation to propagate the recorded wavefield from the recording surface into the subsurface with time running backward (e.g., Baysal et al., 1983; Etgen et al., 2009). It can handle any spatial velocity variation with no limitation of dip-angles and thus is one of the most promising tools for imaging steeply-dipping fault zones. Recently, RTM is implemented with least-squares migration (Nemeth et al., 1999) and such methods are called least-squares reverse-time migration (LSRTM) (Tang, 2009; Wong et al., 2011; Dai et al., 2012; Dai and Schuster, 2013). It has been shown that LSRTM of surface seismic data can reduce artifacts in conventional RTM images and enhance the image resolution.

However, we find that RTM/LSRTM using the conventional cross-correlation imaging condition (henceforth conventional RTM/LSRTM) still produces poor images, if possible, of steeply-dipping fault zones, particularly when the data acquisition aperture is limited.

We develop a novel least-squares reverse-time migration method for high-resolution imaging of steeply-dipping fault zones. Our method employs a field-division imaging condition and updated source wavefields. The field-division imaging condition was first introduced to RTM for reducing low-wavenumber artifacts caused by cross-correlation between wavefields propagating along the same direction. The idea is that source and receiver wavefields are separated into upgoing- and downgoing-propagating wavefields. Only wavefields that propagate in opposite directions are cross-correlated to construct RTM images (Denli and Huang, 2008; Fei et al., 2010; Liu et al., 2011; Chen and Huang 2013). Denli and Huang (2008) separated the wavefields into left-going and right-going ones. It has been demonstrated that the resulting horizontal-looking images significantly enhance the features of fault zones (Denli and Huang, 2008; Huang et al., 2011; Chen and Huang 2013). We employ the field-division imaging condition into our LSRTM.

In conventional LSRTM, source wavefields are usually simulated using a smoothed migration velocity model and kept the same throughout iterative migration (Dai et al., 2012; Dai and Schuster, 2013). We find that it is crucial to update source wavefields at each iteration step in our LSRTM for imaging steeply-dipping fault zones. The updated source wavefields account for weak reflections from heterogeneities. This is particularly important for imaging fault zones because multiple reflections from faults are much weaker than primary reflections from sedimentary layers.

We demonstrate the improved imaging capability of our new method using synthetic surface reflection data for a geophysical model built using geologic features found at the Soda Lake geothermal field. The model contains several steeply-dipping fault zones. Our LSRTM method significantly improves the images of the steeply-dipping fault zones compared with those obtained using conventional RTM/LSRTM.

2. CONVENTIONAL LEAST-SQUARES REVERSE-TIME MIGRATION
We assume $L$ is the forward modeling operator using the full-wave equation. Seismic data $d$ is related to the reflectivity model $m$ via the Born approximation
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d = Lm. \tag{1}

The RTM operator is the adjoint operator of L

\[
m_{\text{mis}} = L^T d. \tag{2}
\]

The conventional common-shot imaging condition for RTM is a cross-correlation between the forward propagating wavefield \( S^{(0)}(x,t) \) from a source and the backward propagating wavefield \( R(x,t) \) from receivers, leading to a migration image given by

\[
m_{\text{mis}}(x) = \int S^{(0)}(x,t) R(x,t) dt. \tag{3}
\]

LSRTM aims to solve the reflectivity model by minimizing the least-squares function

\[
J(m) = \frac{1}{2} \| m - d \| \tag{4}
\]

We use a preconditioned conjugate gradient algorithm to find the minimizer iteratively. Each iteration comprises one RTM and one update of the reflectivity model. In conventional LSRTM, the source wavefield \( S^{(0)}(x,t) \) is calculated using the initial migration velocity model and is kept the same throughout all iterations.

3. LEAST-SQUARES REVERSE-TIME MIGRATION USING A WAVEFIELD-SEPARATION IMAGING CONDITION

The conventional cross-correlation imaging condition (3) produces images suffering from low-wavenumber artifacts and poor resolutions of steeply-dipping fault zones. This motivates the development of wavefield-separation imaging conditions for RTM.

3.1 Wavefield-separation imaging condition for RTM

The wavefields \( S^{(0)}(x,t) \) and \( R(x,t) \) contain waves propagating in all directions. We separate them into down-going, up-going, left-going and right-going waves:

\[
S^{(0)}(x,t) = S^{(0)}_{\downarrow}(x,t) + S^{(0)}_{\uparrow}(x,t),
\]

\[
R(x,t) = R_{\downarrow}(x,t) + R_{\uparrow}(x,t), \tag{5}
\]

The wavefield-separation imaging condition for RTM is the cross-correlation between the wavefields propagating in opposite directions (Denli and Huang, 2008; Fei et al., 2010; Liu et al., 2011; Chen and Huang, 2013). This gives us vertical- and horizontal-looking images:

\[
m_{\text{mis},v}(x) = \int S^{(0)}_{\downarrow}(x,t) \cdot R_{\downarrow}(x,t) + S^{(0)}_{\uparrow}(x,t) \cdot R_{\uparrow}(x,t) dt,
\]

\[
m_{\text{mis},h}(x) = \int S^{(0)}_{\downarrow}(x,t) \cdot R_{\downarrow}(x,t) + S^{(0)}_{\uparrow}(x,t) \cdot R_{\uparrow}(x,t) dt. \tag{6}
\]

The vertical-looking image \( m_{\text{mis},v}(x) \) eliminates the low-wavenumber artifacts seen in the conventional RTM image \( m_{\text{mis}}(x) \). The horizontal image \( m_{\text{mis},h}(x) \) mainly contains the images of steeply-dipping fault zones.

3.2 LSRTM with the wavefield-separation imaging condition and updated source wavefields

At the \( n^{th} \) iteration of LSRTM, we combine the vertical- and horizontal-looking images to approximate the gradient of the misfit function (4)

\[
L^T d = m_{\text{mis}}(x) - m_{\text{mis},v}(x) + m_{\text{mis},h}(x)

= \int [S^{(0)}_{\downarrow}(x,t) \cdot R_{\downarrow}(x,t) + S^{(0)}_{\uparrow}(x,t) \cdot R_{\uparrow}(x,t)] dt

+ \int [S^{(0)}_{\downarrow}(x,t) \cdot R_{\downarrow}(x,t) + S^{(0)}_{\uparrow}(x,t) \cdot R_{\uparrow}(x,t)] dt, \tag{7}
\]

where the superscript “(0)" denotes the source wavefield that is re-calculated using the updated migration velocity model at the current iteration step. As demonstrated in our numerical example in Section 4, employing updated source wavefields is crucial for enhancing the images of steeply-dipping fault zones.

The horizontal-looking image \( m_{\text{mis},h}(x) \), which contains mostly images of fault zones, is harder to be reconstructed than the vertical-looking image \( m_{\text{mis},v}(x) \). During LSRTM, to enhance the horizontal-looking image, we switch the imaging condition to

\[
L^T d = m_{\text{mis}}(x) - m_{\text{mis},h}(x) = \int [S^{(0)}_{\downarrow}(x,t) \cdot R_{\downarrow}(x,t) + S^{(0)}_{\uparrow}(x,t) \cdot R_{\uparrow}(x,t)] dt, \tag{8}
\]
when \( m_{\text{true}}(x) \) changes little after a certain number of iterations. Our experience based on synthetic data examples is that approximately 10 iterations are sufficient for reconstructing \( m_{\text{true}}(x) \). Therefore, we focus on updating the horizontal-looking image after 10 iterations of LSRTM.

4. IMAGING FAULTS FOR A SODA LAKE MODEL

We use a velocity model from the Soda Lake geothermal field in Nevada to validate the improved imaging capability of our LSRTM over conventional RTM/LSRTM.

The velocity model is constructed using the geologic interpretation result of a prestack migration image. There are five stratigraphic layers and six steeply-dipping fault zones in the model, as displayed in Fig. 1(a). For the fault zones from left to right in Figure 1(a), the dip angles are 57°, 69°, 71°, 68°, 66°, 73°, respectively. The fault zones are 24 m wide and their wave speeds are 15% lower than those of the surrounding layers. The model also contains high-contrast basalt units.

We generate synthetic reflection data with a fixed-spread acquisition geometry where 185 sources and 961 receivers are located on the top surface of the model. The source interval is 40 m and the receiver interval is 8 m. The source time function is a Ricker wavelet with a central frequency of 25 Hz. The initial migration velocity model is obtained using a one-wavelength smoother of the true velocity model (Fig. 1b).

![Velocity model](image)

(a) True velocity model

![Velocity model](image)

(b) Smoothed velocity model used as the initial model for LSRTM

Figure 1: A velocity model constructed using geologic features found the Soda Lake geothermal field, Nevada. (a) True velocity model for generating synthetic data; (b) Smoothed migration velocity model obtained using a one-wavelength smoother of the true model.
Figure 2: Migration images obtained using (a) conventional RTM and (b) conventional LSRTM. Although conventional LSRTM reduces low-wavenumber artifacts in the RTM image and improves the image resolution, the rightmost fault zone with the largest dip angle is not well imaged using the conventional imaging condition.

Figure 2(a) demonstrates the migration image obtained using conventional RTM. The image contains high-amplitude, low-wavenumber artifacts caused by the conventional imaging condition that cross-correlates the full source wavefield with the full receiver wavefield. The artifacts contaminate the image of the leftmost fault zone, and mask the images in the top layer. In addition, the deep part of the rightmost fault zone is hardly imaged. The conventional LSRTM image displayed in Fig. 2(b) improves image resolution and contains fewer low-wavenumber artifacts than the RTM image in Fig. 2(a). However, the resolution of the rightmost fault zone is still quite low, especially for the deep part of the fault zone.

Figure 3(a) shows the LSRTM image obtained using the wavefield-separation imaging condition but with the fixed source wavefield $S^0(x,t)$. The low-wavenumber artifacts in the RTM image displayed in Figs. 2(a) and 2(b) are eliminated by the wavefield-separation imaging condition. Compared with the conventional LSRTM image in Fig. 2(b), there is a slight improvement of the resolutions of the fault zones in Fig. 3(a).

We conduct LSRTM with the wavefield-separation imaging condition and updated source wavefields, and produce the image in Fig. 3(b). The images of the fault zones are clearer than those in Figs. 2(b) and 3(a), particularly for the rightmost fault zone with the largest dip angle. In the bottom layer, the fault zones are not completely imaged except for the leftmost one because of the few primary or multiple reflections in the data.

5. CONCLUSIONS
We have developed a least-squares reverse-time migration method for high-resolution imaging of steeply-dipping fault zones. Our method accounts for the propagation directions of the wavefields and updated source wavefields in each iteration. In particular, the horizontal-looking images obtained using cross-correlation between the left-going and right-going wavefields contain mostly images of steeply-dipping fault zones. We use synthetic seismic reflection data for a 2D velocity model constructed using the geologic features found at the Soda Lake geothermal field to validate the improved imaging capability of our method. Our least-
squares reverse-time migration method significantly improves the images of steeply-dipping fault zones compared with those obtained using conventional reverse-time migration or conventional least-squares reverse-time migration.

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Figure 3: Migration images obtained using LSRTM with the wavefield-separation imaging condition together with (a) the fixed source wavefields and (b) the updated source wavefields. The image in panel (a) reduces the low-wavenumber artifacts, but only slightly improves the resolutions of the fault zones. The image in panel (b) clearly shows all the fault zones except in the bottom layer.

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