

Depth Imaging Enhancement Using Reverse Time Migration

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Abstract. Imaging the subsurface with complex structures and steeply dipping salt boundaries is a challenging task in seismic exploration. Between two main categories of seismic migration, wavefield-continuation methods have been more successful than ray-based ones. Wavefield-continuation migration constructs source and reflection wavefields as a function of depth or time by directly solving one-way or two-way wave equations. Consequently, this technique has two benefits. First, compared to Kirchhoff migration, it does not use high-frequency approximation and can more accurately propagate wavefields in shallow depths. Secondly, it can naturally handle multi-paths or multi-arrivals. Reverse time migration (RTM) is a wavefield-continuation method which is accepted as the best migration method currently available for imaging complicated geology. The main objective of this research is to improve imaging of complex structures by utilizing the RTM technique. Two models, involving anticlines, faults, etc., are employed to test the technique. The imaging results demonstrated that the RTM method succeeded to image the flanks, remove noises and improve the resolution.

1. Introduction

Migration is a seismic processing method aiming to move dipping reflections to their true subsurface positions and collapse diffractions, hence resulting in an image of the subsurface geology and increasing spatial resolution. For conventional Kirchhoff migration, the Green's function is extracted from asymptotic ray theory, which is a high frequency approximation to the true Green's function. Therefore, the asymptotic approximation of the Green's function involves errors. Another type of migration is known as wavefield-continuation migration which constructs source and reflection wavefields as a function of depth or time by directly solving one-way or two-way wave equation. Consequently, wavefield-continuation migration techniques have two benefits. First of all, these methods do not use high-frequency approximation and can more accurately propagate wavefields in shallow depths [1]. Secondly, they can naturally handle multi-paths or multi-arrivals [2, 3].

Wavefield-continuation migration includes two main categories: downward continuation and reverse time methods [4]. The main advantage of downward continuation techniques is that they can deal with lateral velocity variations because it extrapolates wavefields in the space domain. However, since it uses the one-way wave equation, it still has inaccuracy for steep dips [5]. The limitation of all mentioned imaging methods can be handled using the most powerful migration method which is called reverse time migration (RTM). RTM is based on two-way wave equation, and it can involve all frequencies and dip angles and adapts to any type of velocity variations [6]. RTM was first introduced



by Whitmore [6], McMechan [7], and Levin [8]. Two main feature of RTM are: constructing wavefields along the time axis instead of depth, and extrapolating the wavefield with a two-way wave equation. These features make RTM able to be executed for any type of velocity variation, migrates all frequencies, deals with all dips, and handles all types of waves such as prismatic reflections and turning waves [3, 9, 10]. Despite its advantages listed above, RTM was extremely expensive in both computing resources and computational time. The increase of computer speed and decrease in the cost of computer facilities, especially pc-clusters, have allowed RTM to be utilized as a principal prestack seismic imaging technique.

This paper presents the application of RTM, and its comparison with Kirchhoff imaging. A simple layered model with an anticline structure, and the Marmousi model, as a complex model, are used to investigate the strengths and limitations of RTM. The RTM results demonstrate that flanks and steep dips are imaged properly, noises are remove and the resolution is improved.

2. Methodology

Similar to all wavefield-continuation migration methods, RTM includes two steps: wavefield extrapolation followed by application of an imaging condition. For poststack zero-offset RTM, wavefield extrapolation is applied as a back propagation of the stacked data. For prestack RTM, however, wavefield extrapolation is divided into two substeps. One is forward extrapolation to construct the source wavefield at each time sample, and the other is back propagation of surface recorded data to reconstruct the reflected wavefield at each time sample. Figure 1 illustrates the workflow of RTM which comprises three key steps:

1. The source wavefield u_s is extrapolated forward in time using the source location, the source wavelet and the velocity model.
2. The receiver wavefield u_r is propagated backward in time, from all receiver positions using the recorded data as well as the velocity model.
3. Applying an imaging condition to calculate the zero lag cross-correlation between the two simulated wavefields u_s and u_r at all model grid points to locate the subsurface reflectors.

For the acoustic wave equation, the forward extrapolation can be expressed as [11]:

$$\left[\nabla^2 - \frac{1}{v^2} \frac{\partial^2}{\partial t^2} \right] u_s(\mathbf{x}, t) = f(\mathbf{x}, t) \quad , \quad (1)$$

where u_s is the source wavefield, v is the acoustic velocity of the medium, and for a point force of arbitrary orientation located at a point $\mathbf{x}_s$, $f(\mathbf{x}, t)$ is the body force distribution which is defined by

$$f(\mathbf{x}, t) = \mathbf{f}s(t)\delta(\mathbf{x} - \mathbf{x}_s) \quad , \quad (2)$$

in which $s(t)$ is the source time function, the variation of the amplitude of the force as a function of time, and $\delta(\mathbf{x} - \mathbf{x}_s)$ is the Kronecker delta. $\mathbf{f}$ is a unit vector in the direction of the point force, and $\mathbf{x}_s$ is the source position vector.

Likewise, the backward extrapolation can be written as

$$\left[\nabla^2 - \frac{1}{v^2} \frac{\partial^2}{\partial t^2} \right] u_r(\mathbf{x}, t) = 0 \quad , \quad u_r(\mathbf{x}_0, t) = d(\mathbf{x}_0, t) \quad (3)$$

where u_r is the reflected wavefield and d is recorded data on the surface which is used as a boundary condition. The boundary condition keeps the wavefront shape of the back-propagated wavefield the same as the record. However, the wavefront shape of the back-propagated wavefield is the same as the

integral of the record. In equations 1 and 3, u_s and u_r represent the vertical component of particle velocity for geophone-recorded data or pressure for hydrophone-recorded data.

Besides solving the acoustic wavefield, it is also significant to eliminate artificial reflections from the model boundary. This is because seismic waves propagate into the whole earth, while in practice the computations are restricted to a limited area. This generates artificial boundaries which in turn cause artificial reflections. In order to suppress these unwanted reflections, a suitable boundary condition should be included in the numerical simulation; otherwise, these artifacts will contaminate the simulated wavefields. We employ a sponge absorbing boundary condition (ABC) for constructing a nonreflecting boundary condition. It is based on gradual reduction of the amplitudes in a strip of nodes along the boundaries of the mesh [12].

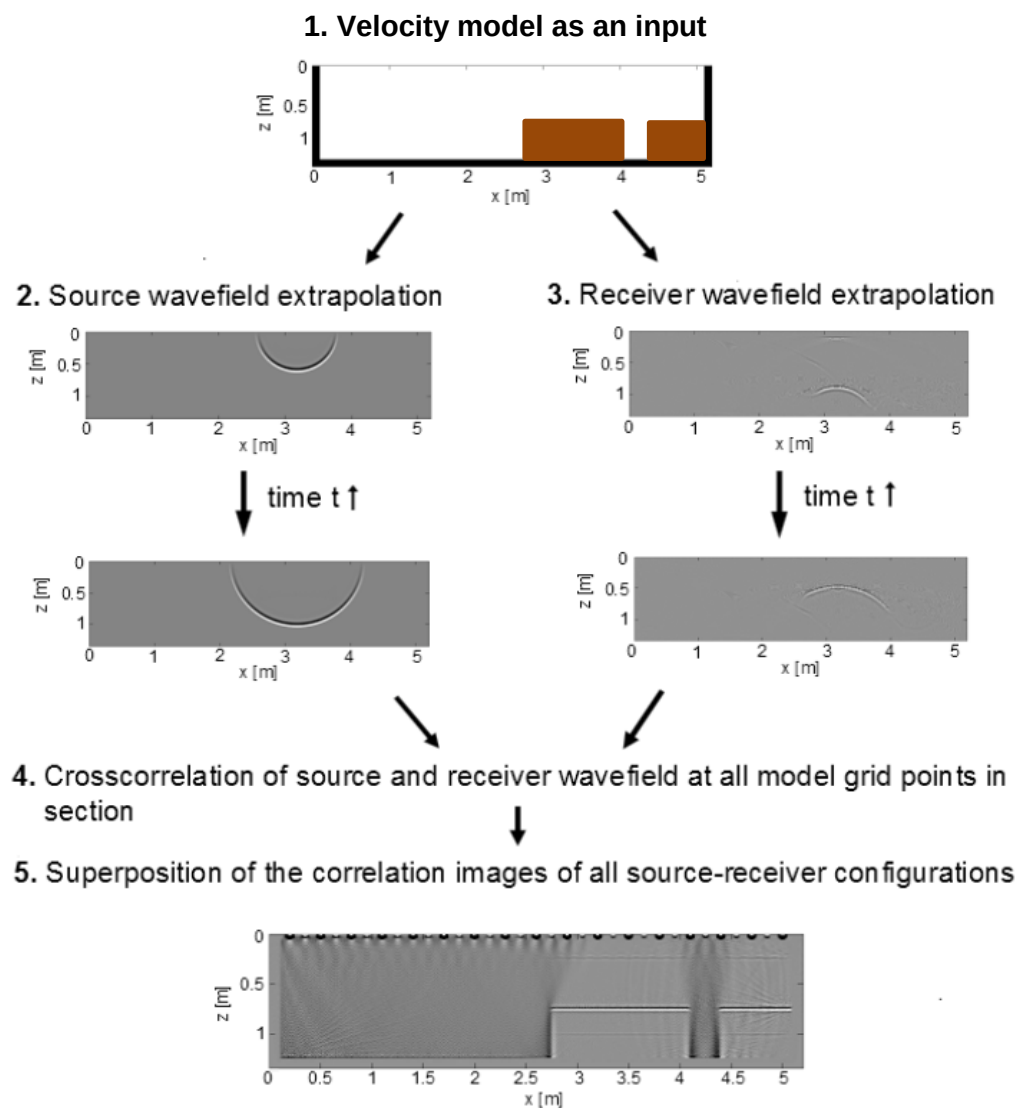


Figure 1: Flowchart of RTM [13].

The last key step of RTM is the imaging condition to extract the image from the constructed wavefields. In this research, the zero-lag cross-correlation imaging condition is used which is given by [14]:

$$I(\mathbf{x}) = \int u_s(\mathbf{x}, t)u_r(\mathbf{x}, t)dt. \quad (4)$$

where $I(\mathbf{x})$ is the migration image value at point $\mathbf{x}$. It can be carried out by cross-correlating the modelled source and backward-continued wavefields, and then extracting the value of the zero-lag (the sample at $t = 0$ in the cross-correlation signal). If the two wavefields are similar to each other, after cross-correlation, the zero-lag will be the biggest value in the cross-correlation. On the other hand, if the two wavefields are different, for example if the wavefields have different arrival times, the zero-lag cross-correlation value is normally small.

3. Numerical examples

The result of RTM on different models are investigated in this section. A simple layered model with an anticline structure is used to study the behavior of RTM to image a simple layering media. Next, the Marmousi model is chosen because it contains thin layers, steep faults, anticlines, pinch-out and other structures. This model is a complex model and more realistic, thus it can assist to find the strengths and limitations of RTM algorithm. Finally, we compare the RTM results with the Kirchhoff images.

3.1 Simple Layered Model with Anticline

The model contains three layers with velocities from 2 to 3 km/s. An anticline with steep dip flanks is embedded in the model. The depth of model is 2 km and the lateral distance is 8km. Forward modeling conducted by using a source signature corresponding to a 30 Hz Ricker wavelet with 800 receivers with 10 m spacing interval on the surface. An isotropic finite difference method is employed to generate the records. The direct arrivals are muted from the gathers since they do not comprise any reflector information (Figure 2).

Figure 3 illustrates the dataset of the simple model including an anticline with 82° dip for the left flank and 75° dip for the right flank, and its results of Kirchhoff depth imaging, and RTM. The data comprises diffractions in sharp points, and events in wrong positions. Although Kirchhoff migration has imaged the flat interfaces correctly, it is obvious that it is not able to image the steep dips, and its image contains distortions. However, the RTM method has succeeded to image the flanks, remove noises and improve the resolution. It can provide more detail about corners and wrinkles.

In RTM image (Figure 3c), red arrays show that flank imaging has executed much more better than the Kirchhoff result, and the yellow circles demonstrate how RTM is able to image more details. It is also obvious that the reflectors in RTM image are even, whereas reflectors in the Kirchhoff image are wavier specially those parts below the anticline. Overall, by conducting different depth imaging algorithms on the anticline model, it is proved that the RTM outcome, regarding to image steep dips, is better than the Kirchhoff migration, and it can produce excellent results.

3.2 Marmousi Model

Marmousi model is utilized to show how RTM works for a model with several challenging features. A 20 Hz Ricker wavelet is used as the source signature. Figure 4 displays Marmousi model and two shot gathers. The result of RTM on Marmousi model is showed in Figure 5. The RTM result provides an accurate image of dip reflectors and the pinch-out. Comparing the RTM and Kirchhoff images demonstrates a considerable improvement. RTM adds more detail to the image, and the resolution is enhanced. By considering two pinch-outs at the bottom of the images, it can be clearly find out that RTM has boosted their amplitude, and they can be detected better than in the Kirchhoff image. Furthermore, the anticline, which is located at the middle and bottom of the model, are imaged perfectly in RTM, while in the Kirchhoff image, only some features of anticline can be seen.

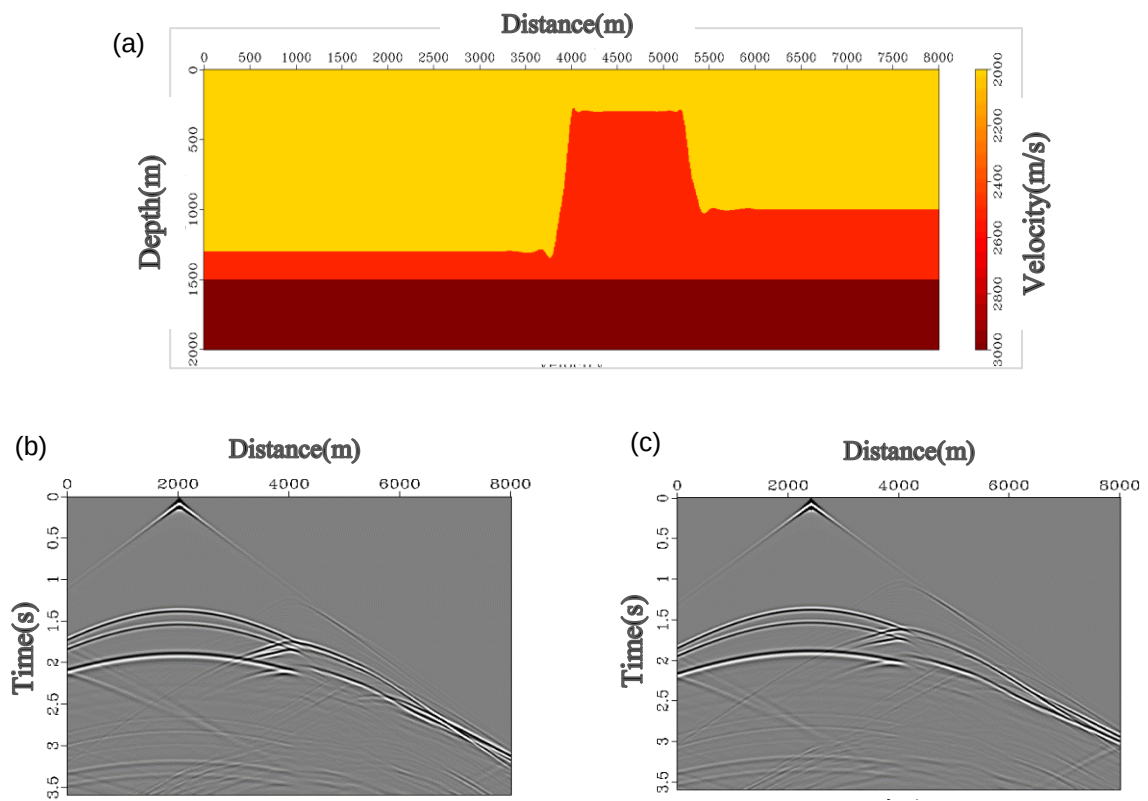


Figure 2: (a) Simple three-layer model with an anticline. (b) Shot gather of a source at 2 km and (c) shot gather of a source at 2.2 km.

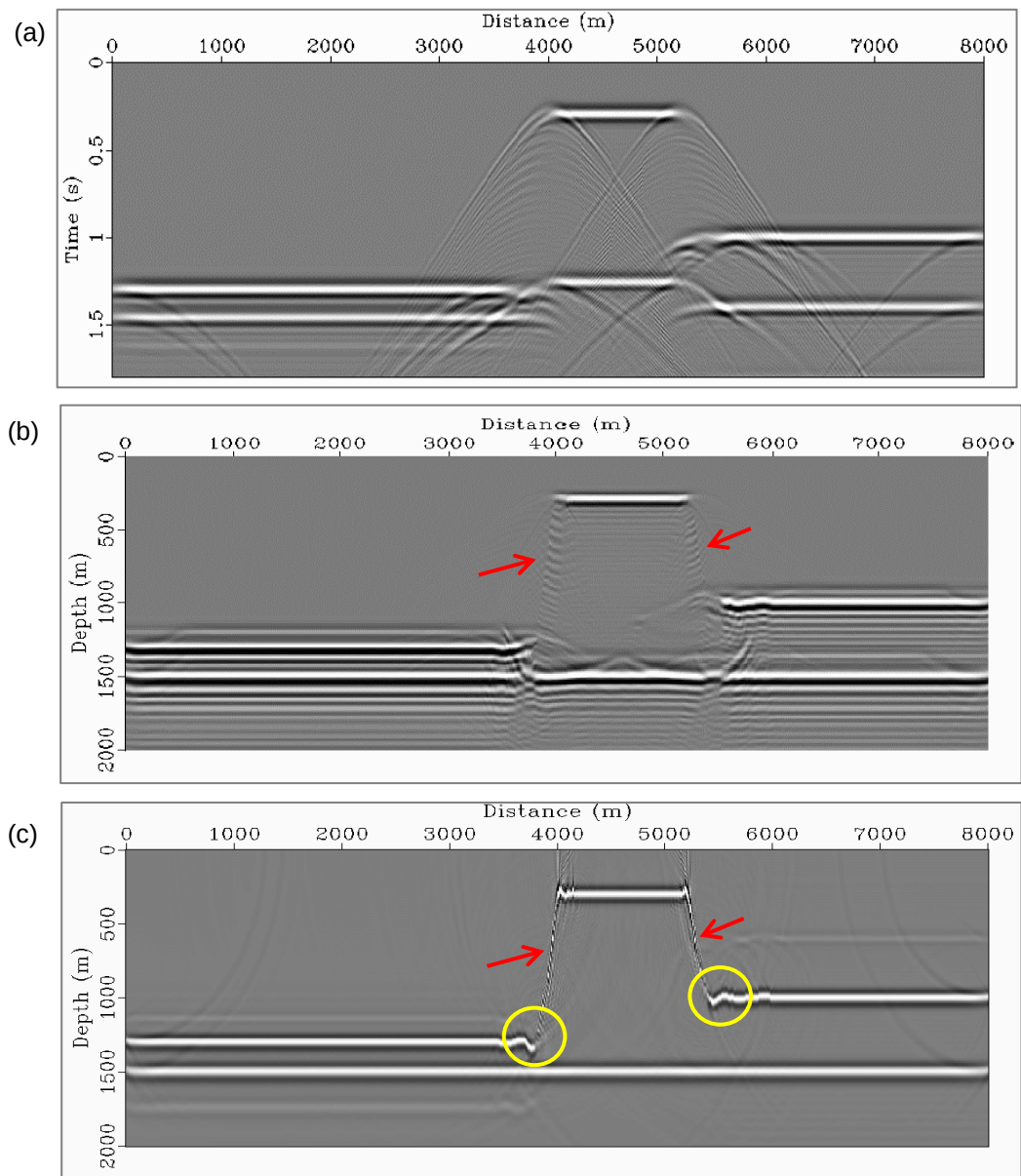


Figure 3: (a) Stack dataset of simple anticline model, and comparison of its images obtained by (b) Kirchhoff migration and (c) RTM.

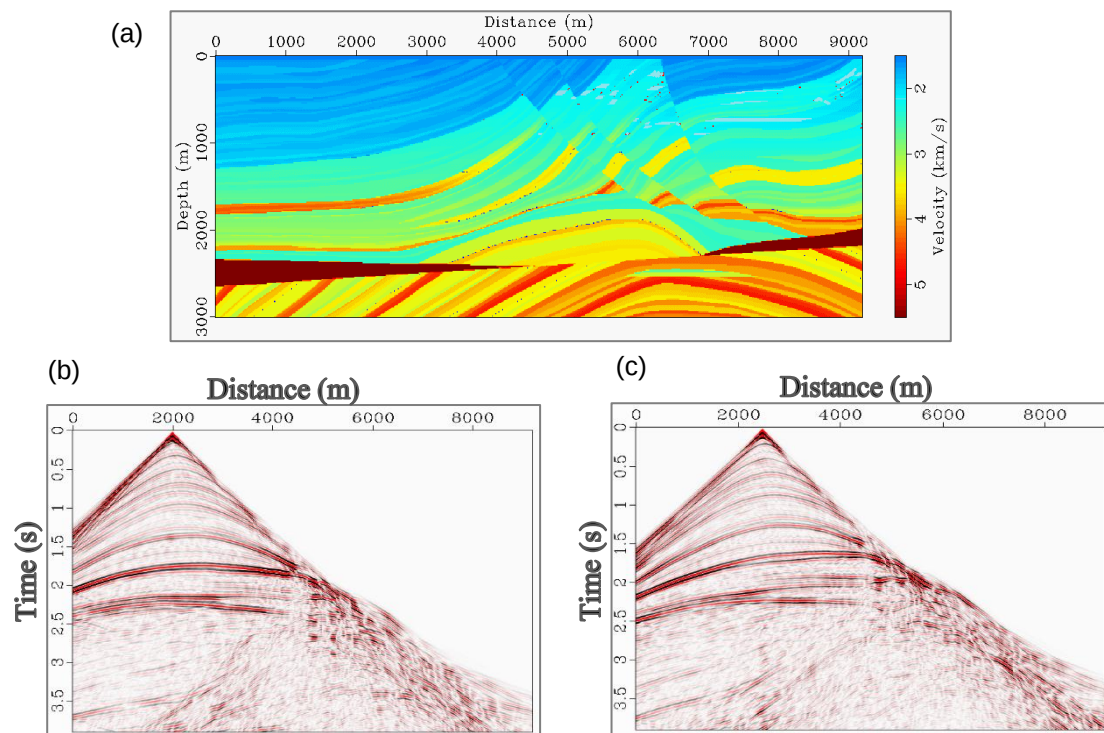
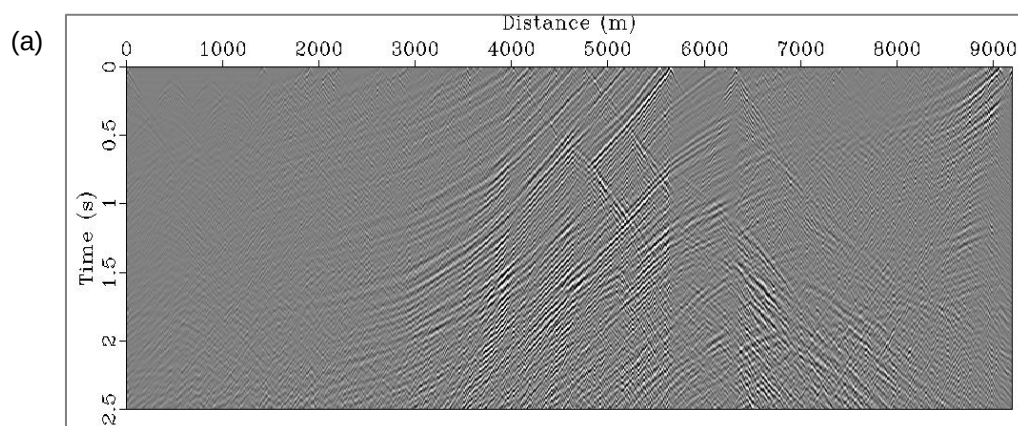


Figure 4: (a) Marmousi model involving complex structures. (b) Shot gather for a source at 2 km, and (c) shot gather for a source at 2.2 km.



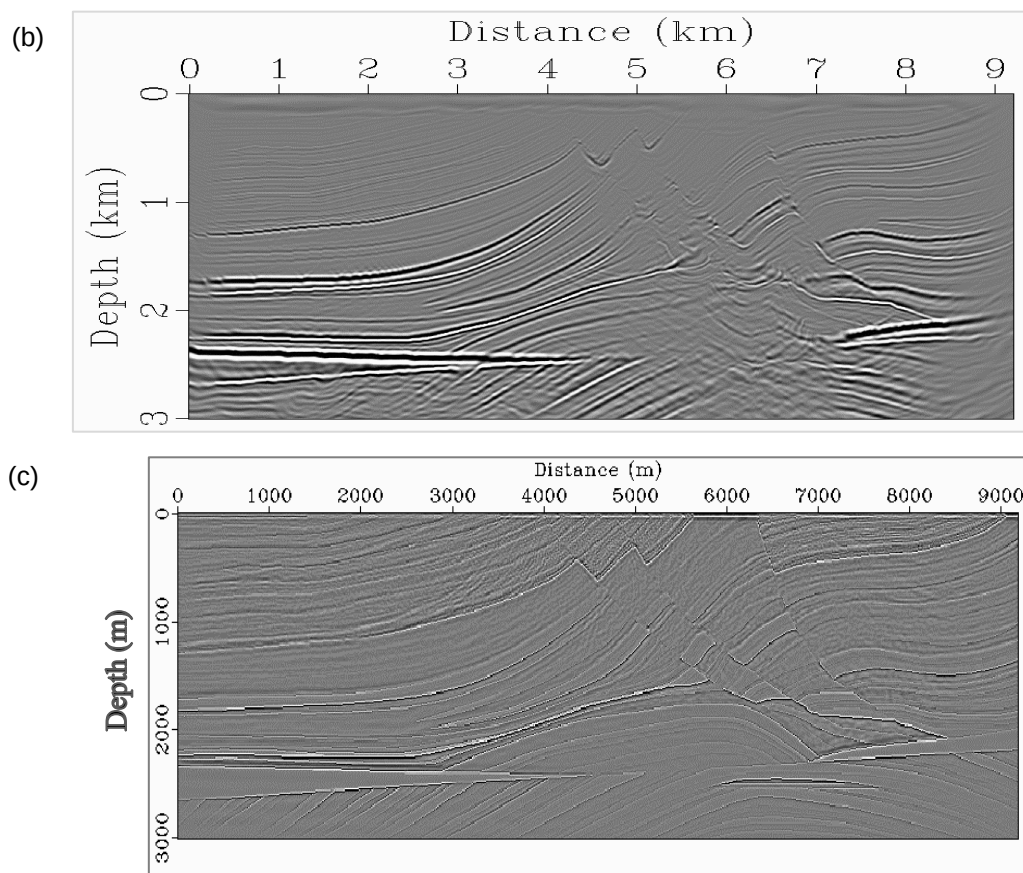


Figure 5: (a) Marmousi stack data and its images acquired using (b) Kirchhoff, and (c) RTM.

4. Conclusions

In this research, an RTM approach was studied. Although Kirchhoff migration has imaged the flat interfaces correctly, it is obvious that it is not able to image the steep dips, and its image contains distortions. However, the RTM method has succeeded to image the flanks, remove noises and improve the resolution. RTM could provide more details about corners and wrinkles. Overall, despite that RTM is an expensive method for imaging subsurface, it is crucial to employ when the structure is complex. The proposed RTM is appropriate for isotropic media. It can be modified for anisotropic imaging by using anisotropic wave propagator.

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