Research Article

Application of Reverse Time Migration to Faults Imaging in Rakhine Basin, Myanmar

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The Rakhine Basin in the northeastern Bay of Bengal is an active field in hydrocarbon exploration and development. It contains fault structures and steeply sloping stratigraphic reservoirs, both primary features of interest for hydrocarbon exploration that needs to be accurately imaged to improve the interpretation of seismic data and facilitate the accurate identification of features of interest. Although faults are an indicator of possible hydrocarbon traps, they are difficult to identify in seismic images using traditional stack or prestack time migration due to the rather complex behaviors of wave propagation. On the other hand, prestack depth migration (PSDM) can significantly improve the accuracy of seismic images, especially of complex subsurface structures such as faults, folds, overthrusts, and salt domes. Among the various PSDM approaches, reverse time migration (RTM) has been shown to be the most powerful. Here, we show how PSDM-RTM can significantly improve the representation of fault structures and steeply dipping structures in seismic images from field data collected in Rakhine Basin, which is characterized by complex geology including stratigraphic and stratigraphic traps as well as complex channel systems. Typically, these structures appear heavily blurred and are difficult to identify using normal stack and prestack time migration. We demonstrate that they become clearer and easier to detect with the PSDM-RTM approach, making this approach particularly suitable for seismic interpretations of geologically complex areas within the context of hydrocarbon prospecting.

1. Introduction

The Rakhine Basin in Myanmar is an active area for offshore hydrocarbon exploration offshore with most hydrocarbon reservoirs being stratigraphic or strati-structural traps. It consists of steeply dipping layers and small-scale fault structures along a submarine canyon [1, 2]. Fault structures are well-known hydrocarbon traps in sedimentary basins which is why fault detection plays such an important role in petroleum exploration and development. Fault structures analyses require enhanced seismic images that are capable of resolving fault structures. In general, faults produce a wide scatter of seismic waves and reduce their velocity within the fault zone compared the surrounding layers. In addition, the various structures present in the fault zone lead to highly complex wave propagation patterns due to multiple reflections, backscattering, and partial absorption of the wave energy, which makes it challenging to image subsurface faults using seismic data.

Standard seismic migration images the subsurface only by assuming horizontal reflectors, a small offset-to-depth ratio, and minor velocity variations in the lateral and vertical directions. However, in a steeply dipping layer, the source-receiver common midpoint (CMP) does not coincide with the common reflection point (CRP), and as a result, post-stack migration does not yield images suitable for seismic interpretation. Prestack depth migration (PSDM) is unaffected by any CMP issues that might affect normal moveout (NMO) processing, making it a suitable approach for imaging complex subsurface structures such as salt domes or
Figure 1: Continued.
Figure 1: Maps showing the location of (a) the Rakhine Basin (adapted from Racey and Ridd [34]). (b) The offshore blocks in Myanmar (adapted from Cliff and Carter [2]).
overthrust folded and faulted layers [3]. PSDM also enhances the accuracy of seismic images and suppresses artifacts that can occur in poststack migration. From among the different PSDM approaches, reverse time migration (RTM) tends to yield the best subsurface images, although it requires substantial computational resources [4–6]. Being based on the two-way wave equation, the PSDM–RTM approach is an unencumbered multipath arrival problem that is typically superior to ray-based PSDM [7, 8]. The algorithm correctly images steep dips (even when angles exceed 90°) and complex stratigraphic structures [3, 9–12]. RTM generally works well not only for seismic imaging of steeply dipping faults but also at crustal scales [13–16]. Since RTM employs an adjoint operator instead of a Hessian matrix, it has an intrinsic amplitude fidelity but suffers from resolution problems. Complex subsurface structures with strong lateral velocity variations are particularly challenging for obtaining high-resolution images with correct amplitudes. Several authors have tried different approaches such as least-squares RTM (LS-RTM) which uses iterative least-squares inversion to correct migration errors [17–19] or combinations of the least-squares inverse problem and RTM [20–24]. While LS-RTM produces sidelobes around reflectors and high-wavenumber migration artifacts, its results in the image resolution, reducing artifacts, and compensating amplitudes are auspicious. Seismic diffraction is another approach that has been used for imaging faults and steep dips, yielding improved subsurface imaging with better representations of structural topographies at high spatial resolutions [25–28]. Also, Bashir et al. [29, 30] have shown that this approach is particularly useful to improve the results in 0 to 10 Hz and 50 to 60 Hz frequency bands. Since diffraction stack migration can improve the representation of faults, fractures, and salt bodies, LS-RTM employs the generalized diffraction stack image condition to improve the identification of steep dips and the pinch-out through numerical modeling data [31].

In this study, we used PSDM-RTM on offshore field data collected in Rakhine Basin to enhance otherwise blurry and ambiguous seismic images of faults and stratigraphic structures, including of steeply dipping layers in the local submarine canyon. We limit our discussion to image resolution enhancements and will not touch on other issues like the actual analysis of fault structures or seismic interpretation.

2. Geological Setting

The Rakhine Basin lies to the west of Myanmar in the eastern part of the Bay of Bengal (Figure 1). The Rakhine coastal lowlands form the southward extension of the hydrocarbon bearing regions of Assam and eastern Bangladesh. This basin formed over converging plate boundaries, namely, the Indian plate subducting under the Eurasian plate in a right-lateral slip motion [32, 33]. The basin contains thick Tertiary foredeep sediments deposited over upper Cretaceous deep marine sediments. As a result, the formations of thrust components are predominantly oriented in the East–West direction. Concerning the petroleum system, most of the hydrocarbon reservoirs lie within stratigraphic or strati-structural traps [1, 34]. The area comprises the offshore blocks A1–A7 and deepwater blocks AD1–AD16 (Figure 1(b)). Based on an analysis of seismic facies and attributes, previous studies found that the architectural elements mainly consist of a confined slope channel complex system and an aggradational channel levee complex [35, 36]. Some studies hypothesized results that the basin underwent a rapid progradation during the Oligocene-Middle/Upper Miocene, a gradual retrogradation during the Middle/Upper Miocene–Early Pliocene, and a gradual progradation during the Early Pliocene–Pleistocene [36]. Basu et al. [37] described the stratigraphic chart and structural trends in the Rakhine Basin. Since submarine canyons are possible targets for hydrocarbon exploration [38, 39], high-quality images are required to be able to identify the relevant structures with a high degree of accuracy. Verifying the existence of complex stratigraphic structures is a crucial first step that precedes further hydrocarbon exploration.

3. Methodology

To briefly summarize prestack reverse time migration, we follow the approach by Tarantola [17], according to whom the basic concept for imaging reflectors is based on the inner product of the partial derivative wavefield and the observed wavefield:

$$\text{Map}(x, z = 0, t) = \sum_{i=1}^{n_{\text{shots}}} \frac{\partial u_i(x, z = 0, t)}{\partial P} \cdot d_i(x, z = 0, t),$$

(1)

where $d$ is the observed wavefield, $u$ is the calculated wavefield, and $P$ is the geological element vector (velocity, density, and position). As the calculation of the partial derivatives of wavefields requires a highly computing intensive wavefields, RTM instead uses the inner product of the forward and backward source and receiver wavefields. The
Figure 2: Schematic representation of the field survey geometry with estimated and guessed velocity model geometry.

Figure 3: Flowchart of the PSDM-RTM processing applied to the field data. The upper part corresponds to conventional NMO processing to obtain a model of velocity over time. The lower part is two steps: applying RTM to create a final stack of individual PSDM image gathers after amplitude correction.
underlying rationale uses the acoustic wave equation in the frequency domain as a starting point [40]:

$$K(P)u(P, \omega) - \omega^2 M(P, \omega)u(P, \omega) = F(\omega),$$  

where $M$ is the $n \times n$ mass matrix, $K$ is the stiffness matrix, $F$ is a source term, and $\omega$ is the angular frequency. Rearranging as a complex impedance matrix gives

$$S(P, \omega)u(P, \omega) = F(\omega),$$

where $S(P, \omega)$ is given by

$$S(P, \omega) = K(P, \omega) - \omega^2 M(P, \omega).$$  

Taking the partial derivative of Equation (4) with respect to the geological parameters $p$ gives

$$\frac{\partial u(P, \omega)}{\partial P} = S(P, \omega)^{-1} f_i^*,$$

where $f_i^*$ is

$$f_i^* = -\frac{\partial S(P, \omega)}{\partial P} u(P, \omega).$$

Substituting Equation (5) into Equation (1) gives

$$\text{Map}(x, z = 0, t) = \sum_{i=1}^{\text{nshots}} <S(P, \omega)^{-1} f_i^*, d_i(x, z = 0, t) > .$$

In accordance with the adjoint operator of the wave equation,

$$\text{Map}(x, z = 0, t) = \sum_{i=1}^{\text{nshots}} <S(P, \omega)^{-1} d_i^*(x, z = 0, t), f_i > .$$

Table 2: Preprocessing modules and parameter values used during the basic processing.

<table>
<thead>
<tr>
<th>Processing modules</th>
<th>Parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling interval</td>
<td>4 ms</td>
</tr>
<tr>
<td>Amplitude correction</td>
<td>8 dB</td>
</tr>
<tr>
<td>Deconvolution: Operator length: Lag</td>
<td>80 ms 12 ms</td>
</tr>
<tr>
<td>Time-variant bandpass filtering</td>
<td>8-12-80-120 Hz</td>
</tr>
<tr>
<td>1000 ms</td>
<td>8-12-60-80 Hz</td>
</tr>
<tr>
<td>3000 ms</td>
<td>5-10-50-60 Hz</td>
</tr>
<tr>
<td>5000 ms</td>
<td>5-10-40-50 Hz</td>
</tr>
</tbody>
</table>

Figures 4: (a) A representative field shot gather from the 1001 shot point number. (b) The same shot gather after preprocessed using trace muting, amplitude correction, deconvolution, and bandpass filtering (see Table 2 for processing parameters).
In Equation (8), the multiplication of the complex impedance and observed wavefields refers to back-propagated wavefields in the receiver domain. Hence, RTM does not depend on the partial derivative of wavefields but can be derived using the inner product of the forward wavefields in shot domain and the back-propagated wavefields from observed wavefields rather than the partial derivative wavefields. Due to the RTM, the geometrical spreading of wavefields the RTM method yields an unscaled image in which the amplitudes need to be adjusted. This can be

![Figure 5](image-url)
achieved using a pseudo-Hessian matrix to enhance amplitude correction [41]. In RTM, both the back and forward propagating wavefields are calculated using a velocity model after conventional processing and velocity analysis. The inner product of these wavefields is performed to obtain a single image gather. Then, the migrated image is the sum of all the single images. In short, RTM is a process that (i) calculates back-propagated wavefields in the receiver domain and forward wavefields in the shot domain, (ii) uses the inner product for single image gathers, (iii) stacks single image gathers, and (iv) requires amplitude correction.

4. Data Processing

To accurately image the faults zones and steep dips from the field dataset, we first conducted some basic data processing before applying a PSDM-RTM. The acquisition parameters of the field data set are summarized in Table 1, and a schematic survey diagram is shown in Figure 2. The field data consists of 2-D seismic data acquired in the 1970s that was originally intended for imaging sedimentary stratigraphic structures through reprocessing. Therefore, we employed the following data processing strategy: (i) enhance the signal-to-noise ratio (SNR), (ii) generate a model of velocity as a function of depth, and (iii) apply PSDM and stacking (Figure 3). The flowchart for the data processing steps applied to the raw shot gather until obtaining the final PSDM-RTM image is shown in Figure 3. The flowchart consists of two parts. The first is a conventional NMO processing for making a velocity model in time, and the other is two steps, applying RTM and stack of all single image gathers. We employed basic conventional processing modules, such as bandpass filtering, deconvolution, and amplitude corrections to enhance signal-to-noise ratios. The NMO velocity model is converted from the time to the depth domain based on the field survey geometry in Figure 2. In the RTM part of the analysis, we calculated the inner product of forward wavefields from the shot domain and the backward wavefields from the receiver domain to generate a single image gather. Eventually, the subsurface image was obtained from stacking all individual image gathers and correcting the amplitudes.
Figure 7: Forward-propagated wavefields in the shot domain (left column) and backward-propagated wavefields in the receiver domain (right column) for a source located at the 7.6 km shot point.
4.1. Conventional Data Processing. We performed some conventional data processing to enhance the SNR and generate a velocity model with the PSDM-RTM approach. The field data were collected in the 1970s and consist of a total of 1669 shot gathers, acquired using a recording length of 6 s, a 4 ms sampling interval, and a 25 m shot point interval, on 48 receivers placed 50 m apart (see Table 1 for all acquisition parameters). Figure 4(a) shows a typical shot gather. General basic processing and iterative velocity analysis were performed to construct a reasonable velocity model. The main processing modules for the prestack shot gathers were amplitude correction, deconvolution, and time-variant bandpass filtering (Table 2, Figure 4(b)). The input data for the prestack depth migration consist of the shot gather and a velocity model. To obtain an appropriate velocity model from the conventional velocity analysis, it is necessary to calculate the correct semblance spectrum. This is achieved by iteratively calculating velocity spectrum after muting the normal moveout (NMO) stretched parts, thereby, improving the accuracy of the stacking.

Figure 8: Result of applying PSDM-RTM. (a) The result of the inner product of the wavefields shown in Figure 7. (b) Resulting image after summing all 1669 single image gathers. The right-hand side shows steep dips, folds, and complex stratigraphic sediments in the submarine canyon at distances between about 30–40 km, both at the surface and at a depth of around 2.1 km. Note that the depth scale is vertically exaggerate.

Figure 9: Zoomed image of the prestack RTM around the submarine canyon showing faults and steep dips with angles of about 60°.
velocities (Figure 5(a)). After applying a velocity analysis to the supergathers (Figure 5(a), left panel), stacking the NMO corrected gathers with the chosen velocities yielded a subsurface image (Figure 5(a), right panel). In order to obtain reliable high-resolution images of the steeply dipping reflectors and faults in the migration, it is essential to have a good velocity model. We generated our velocity model by smoothing the NMO velocities onto a 25 m × 10 m grid (Figure 5(b)), covering an area of 42 km horizontally × 5.1 km vertically with a 25 m × 10 m resolution, thus yielding 1805 × 511 cells to map the survey geometry. Note that the depth axis is vertically exaggerated. The conventional stack image shows discontinuous reflectors and diffracted events with dipping layers and faults, as well as sedimentary layering structures such as bedding faults and steep dips apparent in the submarine canyon on the right-hand side of the image (Figure 6(a)). After prestack time migration using the Kirchhoff method [42], the resulting prestack time image (Figure 6(b)) exhibits more clearly resolved subsurface than the stack image, although it still requires further enhancement to resolve some of the fault structures.

4.2. PSDM–RTM. High-quality subsurface images are necessary for fault structure analyses and sedimentary stratigraphic interpretation. In turn, the imaging of complex depositional stratigraphic structures requires special processing modules such as reverse time migration (RTM) in the prestack depth domain. We applied PSDM-RTM to our offshore field data to facilitate a better identification of fault structures and steep dips in the submarine canyon. The PSDM–RTM approach calculates the inner product of the forward wavefields in the shot domain and the backward wavefields in the receiver domain [3]. We used the generated velocity model (see previous section) to calculate the forward extrapolated wavefields in the shot domain (Figure 7, left column). The backward extrapolated wavefields in the receiver domain were obtained through modeling and back-propagation using the shot gather as input (Figure 7, right column). The result of the inner product of the two wavefields is imaged with the maximum true energy at the strata boundaries (Figure 8(a)). However, the high amplitudes present at low frequencies in the general RTM results lead to a relative weakening of the reflectors. Of the various alternative imaging approaches that have been developed to remove these low-frequency artifacts [3], RTM seems best suited for imaging steep dips and faults. However, since RTM uses an adjoint instead of an inverse operator, the low-frequency amplitudes remain mainly due to geometrical spreading, making it necessary to employ amplitude correction. In this study, we address the low-frequency problem by normalizing the amplitudes with the square root of the amplitudes and applying them to the inner product of two wavefields at each shot gather [41]. All 1669 single image gathers were stacked to obtain the subsurface image in the depth domain (Figure 8(b)). After applying PSDM–RTM, the image has improved and clearly shows the presence of faults near steep dips at distances of about 30–40 km and depths of around 2.1 km.

From the geometry, we estimated the dip angle to be about 60°. The image also reveals the presence of several other fault structures. By enlarging the relevant image area, the steeply dipping layers, horizons, and fault structures in the submarine canyon become easier to identify (Figure 9). Compared to the image obtained from the stack and prestack time migration (Figure 6), the improvement is significant.

5. Results and Discussion

This work demonstrated how subsurface images obtained using the PSDM-RTM approach reveal sedimentary stratigraphic structures that were difficult to detect in images created with stack and prestack time migration. The PSDM-RTM images clearly show the presence of stratigraphic structures with steep slopes of about 60° (located at a horizontal distance of 30–40 km and a depth of about 2.1 km) as well as small- and medium-sized fault zones at greater depths, e.g., at distances of 27–30 km and depths of 2.45–4.5 km (Figure 9). Fault zones are major reservoir traps, making their correct detection and identification pivotal for interpreting hydrocarbon exploration data. In this study, by applying PSDM-RTM to offshore data, we were able to obtain a usable subsurface image that revealed the presence of several faults and sedimentary stratigraphic structures (see Figure 10 for possible locations). While the relatively large steep dips seem to be concentrated in the submarine (right-hand side of Figure 10), the faults appear at a wide range of distance from 25 to 38 km.

6. Conclusions

While faults and sedimentary stratigraphic structures are possible indicators for hydrocarbon reservoirs, they are notoriously difficult to identify in the seismic images of a stack or prestack migration. Prestack depth migration (PSDM) is commonly used to improve the representation of these structures in seismic images, especially when imaging complex geological structures. From among the various PSDM techniques, RTM yields the highest resolution depth
images. Here the objective of our study was to improve the imaging of faults and steeply dipping reflectors that are often difficult to identify in the stack and prestack time migration. To improve the visibility of complex subsurface structures in the submarine canyon, we applied a PSDM-RTM approach to field data collected in offshore areas of the Rakhine Basin, Myanmar, in an attempt to improve the imaging of faults and steeply dipping reflectors. We employed basic processing modules such as amplitude correction, deconvolution, and bandpass filtering before stacking and constructed a velocity model from the smoothed velocities and the survey geometry from the stack image. The PSDM-RTM approach improved the representation of steeply dipping strata present at depths of about 2 km and extending about 30–40 km laterally, making it easier to identify faults. Based on our evaluation, the PSDM-RTM method is superior to existing post- and prestack time migration methods when it comes to processing prestacked seismic data. We expect that high-quality subsurface images obtained with the PSDM-RTM approach will lead to improve the processing and will facilitate more accurate interpretations of seismic data. Since the quality of migration images strongly depends on the accuracy of the velocity model, the quality of subsurface images can be further improved by choosing a more appropriate velocity model.

**Data Availability**

The seismic raw data used to support the findings of this study were supplied by KIGAM under license and so cannot be made freely available. Requests for access to these data should be made to Seonghyung, shjang@kigam.re.kr.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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