



A new approach in reverse time migration for properly imaging complex geological media

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Abstract

Reverse time migration (RTM) artifacts usually start to appear in large reflection angles which include a wide-angle range. On the other hand, the only proposed starting reflection angle for RTM artifacts is 60 degrees which is not based on a proven investigation and it seems to be just a suggestion based on trial and error. As an important issue, we determine a predominant starting reflection angle (PSRA) for RTM artifacts which enables us to suppress artifacts properly. Therefore, first we try to open and discuss some issues from a new fundamentally perspective about the number of cross-correlations (NOCC) and its relationship with RTM amplitude and artifacts at reflection and nonreflection points. Second, the cross-correlation and its related NOCC at each subsurface position form a new approach to determine PSRA for RTM artifacts. Using NOCC values, the reflection angle of 55 degrees was determined as PSRA at which the RTM artifacts often start to appear. Finally, a new imaging condition based on the down- and upgoing wave fields and a new weighting function were proposed to suppress RTM artifacts. The new imaging condition can maintain the desired information and suppress artifacts properly for the angle domain of 55° to 90°. A key point in the suppressing process is the direct relationship between reflection angle and artifact production where each reflection angle in the domain of 55° to 90° can produce a different amount of artifacts. Therefore, the proposed imaging condition is able to designate a suitable weight for each reflection angle to properly maintain the desired amplitude and suppress artifacts.

Keywords RTM artifacts · Cross-correlation · Reflecting and nonreflecting points · NOCC · PSRA · Imaging condition

Introduction

Reverse time migration (RTM) was introduced in the late 1970s (Baysal et al. 1983; McMechan 1983; Whitmore 1983), but it has been widely used in recent years due to the affordable computational resources and increasing imaging challenges posed by the complex geological media with steeply dipping structures. Solving the acoustic wave equation RTM is very faithful in reproducing all kinds of P-wave propagation phenomena (reflections, refractions, diffractions, multiples, and evanescent waves) without dip limitations (Etgen et al. 2009; Moradpouri et al. 2017a, b).

RTM implementation includes two steps: first is the wave-field extrapolation where the wave fields are extrapolated forward from the source and backward from the receiver by solving the following acoustic wave equation.

$$\frac{\partial^2 P}{\partial t^2} = c^2 \nabla^2 P = -L^2 P \text{ or } \frac{\partial Q}{\partial t} = c^2 \nabla^2 P \quad (1)$$

where P is the wave-field pressure, ∇^2 denotes the Laplacian operator, c is the velocity of propagation and Q Also is the first derivative of P . Also $L^2 = -c^2 \nabla^2$.

The second step is to apply an imaging condition to the extrapolated wave fields to obtain the migrated image. The straightforward way to produce a stacked migrated image in RTM is via the conventional zero-lag cross-correlation imaging condition of Eq. (2) (Claerbout 1985; Liu et al. 2011; Yan 2013):

$$I(\mathbf{x}) = \int_{t=0}^{t_{\max}} S(\mathbf{x}, t) R(\mathbf{x}, t) dt \quad (2)$$

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where the image $I(\mathbf{x})$ is the stack over all shots, receivers, and times of the cross-correlation for the forward-source-propagated wave field $S(\mathbf{x}, t)$ and the back-propagated receiver wave field $R(\mathbf{x}, t)$; $t_{\max}$ is the maximum extrapolation time.

In spite of the RTM superiorities, the low-frequency artifacts are the major concern in the RTM method which mainly occur in shallow depths in the presence of strong velocity contrast (Moradpouri et al. 2017a, b; Zheng et al. 2018; Liu et al. 2019). RTM artifacts usually start to appear in large reflection angles of almost 40° degree to 90° which overwhelm a wide-angle domain. The domain could be restricted to a smaller one, or we can determine a predominant starting reflection angle (PSRA) for these artifacts. However, more accurate information on PSRA would be of great importance to suppress artifacts for a high-quality image. As far as we know, any research-based study has not been conducted to determine the starting angle for RTM artifacts and the limited attempts just were based on trial and error or simple assumptions. Yoon and Marfurt (2004) assumed $\theta = 60$ degrees in which the low-frequency artifacts start to appear, and they employed the weight zero to the energy for a wide-angle range of 60°–90°. Costa et al. (2009), Zhang et al. (2010), Araujo et al. (2014), Moradpouri et al. (2017a, b) also used 60 degrees as PSRA and developed their works to suppress artifacts. Araujo et al. (2014) used a high-pass filter to suppress artifacts for $\theta > 60$. Costa et al. (2009) and Moradpouri et al. (2017a, b) proposed their imaging condition based on Poynting vector to suppress RTM artifacts. As the result, the reflection angle of 60 degrees at which RTM artifacts start to appear is not a demonstrated and an accurate angle to be used.

In this paper, we first present the concept of the number of cross-correlations (NOCC) and its physical meaning through a two-layered model. Also, the relationship between NOCC, cross-correlation (at reflecting and nonreflecting points), and RTM artifacts is discussed. Second, a new approach is proposed to determine a predominant starting reflection angle (PSRA) at which RTM artifact starts to appear using NOCC. Then, a new imaging condition based on the down- and upgoing wave fields and a new weighting function are proposed to suppress RTM artifacts. The proposed imaging condition can suppress artifacts for each reflection angle independently. Finally, the proposed RTM procedure is tested using BP and Sigsbee velocity models.

RTM artifacts

The conventional imaging condition of Eq. (2) is not able to distinguish between cross-correlation from real reflecting points and nonreflecting points at the imaging points. Thus, it suffers from the creation of artifacts when there is complicated wave propagation, especially in complex media (Yoon and Marfurt 2004; Moradpouri et al. 2017a, b; Zhang et al. 2018).

Figure 1 shows the velocity variation of two typical BP 2004 and Sigsbee2A complex media. The velocity model of BP 2004 in Fig. 1a was built after facing the complex subsalt structures in the Gulf of Mexico and west of Africa (Angola). Overturned and prismatic waves play a key role in imaging these two flanks. The second velocity model of Sigsbee2A in Fig. 1b presents a constant density acoustic velocity and includes a complex subsalt media, whose base

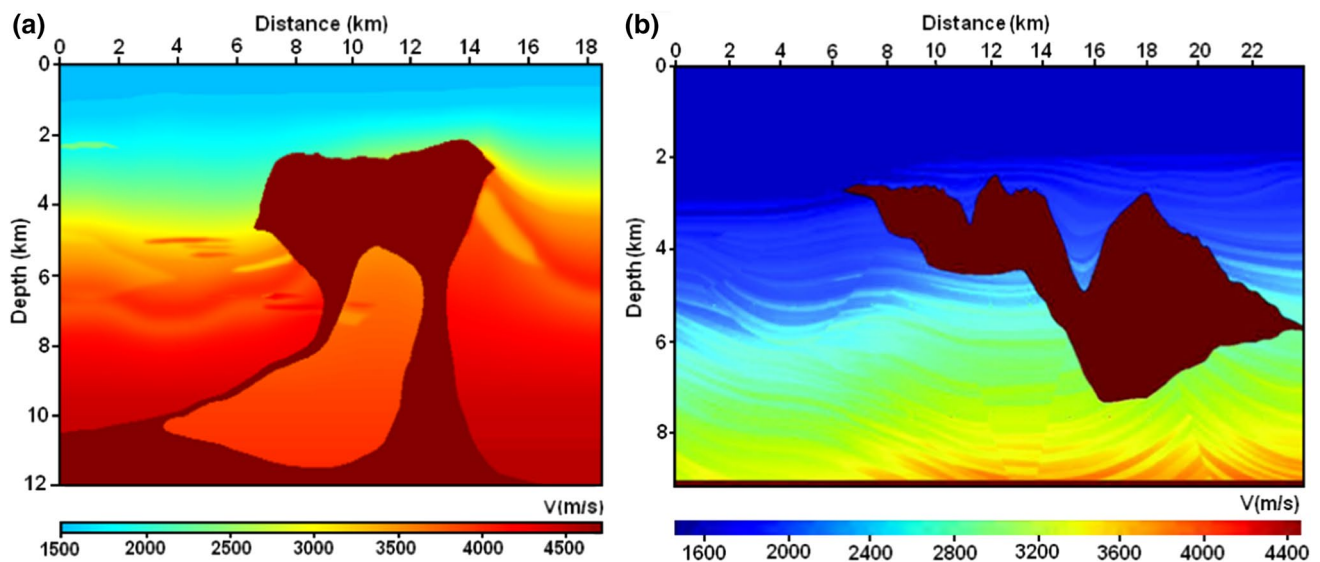


Fig. 1 Velocity variation. **a** BP 2004 model (Billette and Brandsberg-Dahl 2005); **b** Sigsbee2A model (released by the SMAART JV Consortium, 2001)

exhibits flat and steep dip structures. It also exhibits diffraction points, faults, and subsalt structures (Fernandez 2010).

RTM results using the conventional imaging condition of Eq. (2) cause a large number of low-frequency artifacts on migrated images and can be seen in Fig. 2. This was expected considering the two-way wave-field extrapolation of RTM. More clearly, the imaging condition of Eq. (2) is based on the zero-lag cross-correlation which occurs not only at the reflection points but also at all nonreflecting points along the entire wave path (Moradpouri 2017). Therefore, this type of cross-correlation and the number of its occurrences at any subsurface point could play a key role in our research.

Cross-correlation, artifacts, and the NOCC

As we mentioned above, in RTM the wave equation is solved through a two-way procedure in both sources and receiver sides. Therefore, the cross-correlation at reflection and

nonreflecting points is inevitable and the number of its occurrences could be too many times in each specific subsurface point. Hereafter, we are going to open the concept and the physical meaning of cross-correlation at reflection and nonreflecting points and NOCC in each subsurface imaging point.

The concept and the physical meaning of NOCC

Figure 3 illustrates a simple two-layered model with one and two pairs of sources and the receiver at the surface. In the presence of the real interface, Fig. 3a shows the cross-correlation at a real reflection point (real reflector), whereas Fig. 3b, c shows the same event at nonreflecting points; thus, the NOCC for all three situations is one. It means that the occurred cross-correlation between the extrapolated wave fields from the source and the receiver is only once. Although the NOCC is one for all three cases, the cross-correlation at Fig. 3a produces amplitude at the reflecting point, whereas it produces artifacts at Fig. 3b, c as nonreflecting points. A little more complicated situation in Fig. 3d, e shows the cross-correlation at real reflecting and nonreflecting points with difference in NOCC which is twice here. Thus, the NOCC in Figs. 3a–c is computed 1, whereas it is computed 2 for Figs. 3d, e. As a result, increasing the NOCC could affect the produced amplitude/artifacts intensity of real reflecting/nonreflecting subsurface points. The aforementioned information is briefly presented in Table 1.

To compute the NOCC for the complex media of Fig. 1, we set up a code in our RTM implementation procedure to monitor and count all occurred cross-correlations for all subsurface points (x, z). On the other hand, based on the velocity model, we were able to recognize which cross-correlation is for real reflector (amplitude from reflecting points) and which is not (artifacts from nonreflecting points).

As a result, one can say there is a direct relationship between the NOCC and the amplitude or artifacts at reflecting and nonreflecting points. In fact, the NOCC is an important factor and could be increased too many times for each subsurface point based on the media complexity. During any RTM implementation, the NOCC is calculated using a code as a part of our complete RTM procedure. It counts all occurred cross-correlation at each subsurface point (e.g., for results shown in Fig. 2). The NOCC information forms a theory to determine PSRA in RTM which is discussed in the next sections.

Relationship between NOCC and PSRA

In this section, the relationship between NOCC and PSRA is discussed, which clearly describes how to determine PSRA using NOCC. If we look at both velocity models of Figs. 1a,

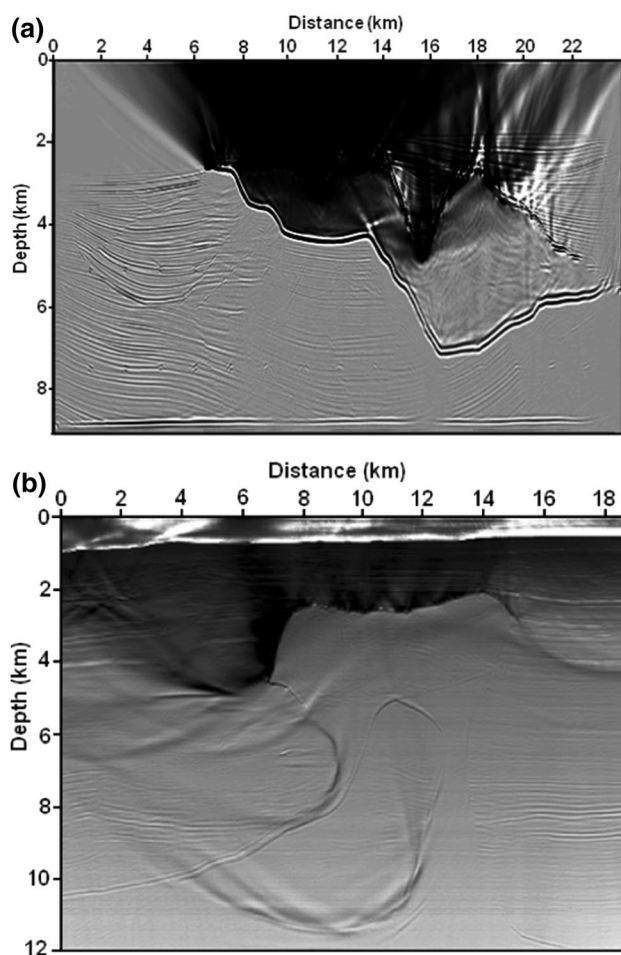


Fig. 2 RTM result using the zero-lag cross-correlation imaging condition of Eq. 2. **a** for Sigsbee model; **b** for BP model

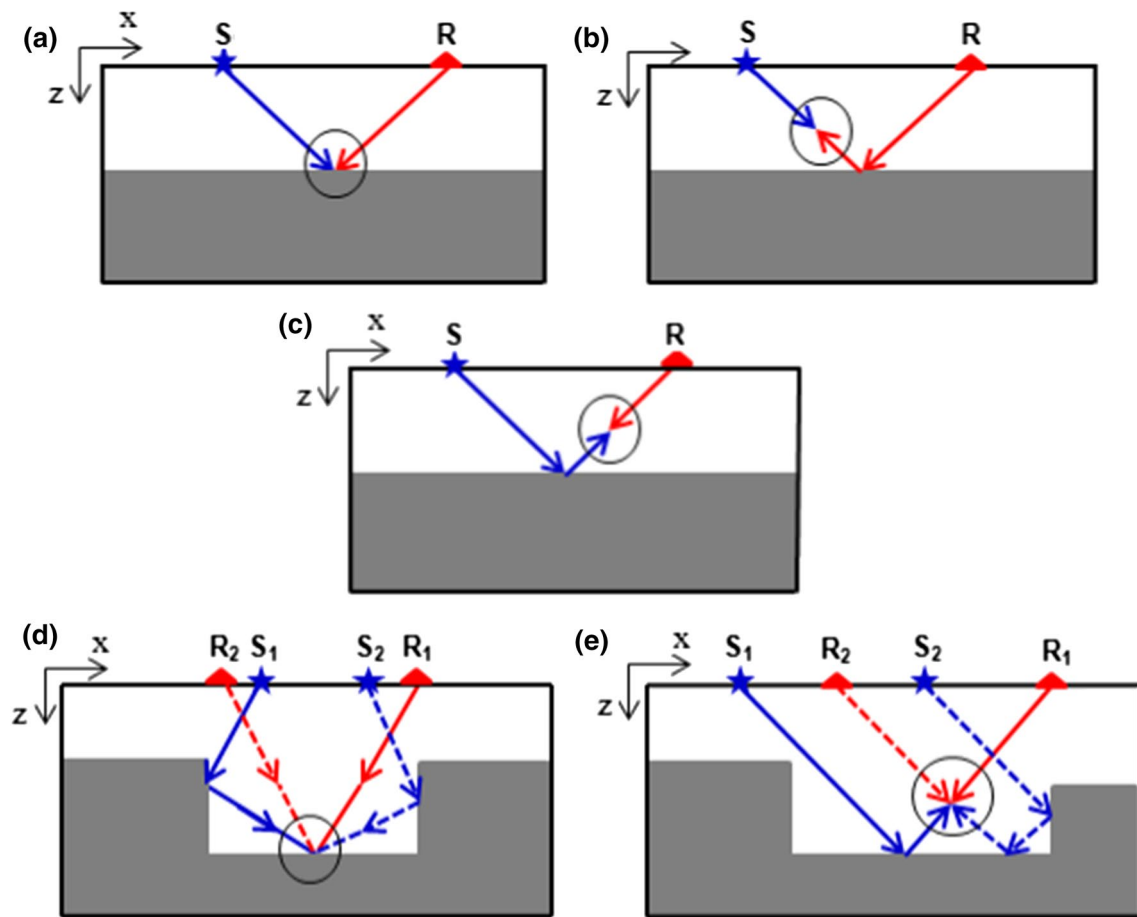


Fig. 3 A simple two-layered model. **a** Cross-correlation at a real reflecting point which produces amplitude with the NOCC of one; **b** and **c** cross-correlation at a nonreflecting point which produces artifacts with the NOCC of one; **d** cross-correlation at a real reflecting

point which produces amplitude, when the NOCC is twice; **e** cross-correlation at a nonreflecting point which produces artifacts when the NOCC is twice

Table 1 Brief explanation of whatever shown in the simple model of Fig. 3

	Subsurface position	NOCC	Type	Amplitude/artifact intensity (*)	Desired RTM result
(a)	Reflecting point	1	Amplitude		Yes
(b)	Nonreflecting point	1	Artifact		No
(c)	Nonreflecting point	1	Artifact		No
(d)	Reflecting point	2	Amplitude		Yes
(e)	Nonreflecting point	2	Artifact		No

(*)It is just a simple schematic example to show that the produced amplitude or artifacts intensity in cases (a), (b) and (c) is less than cases (d) and (e)

b, we can see two complex bodies with steep deep structures in the middle. On the other hand, we know that the low-frequency artifacts in RTM covered the image and reduce its quality, but these artifacts are much more challenging in shallow depth facing the strong velocity contrasts. With this perspective, the relationship between the NOCC, artifact, and PSRA could be described easier.

As can be seen in images of Figs. 2a, b, in deep depths, although the media include both the horizontal simple reflector and media with steep deep structures, migrated images have better quality with less challenging artifacts. It was expected and could be discussed from two points of view, in the area with a simple setting, and the possibility of cross-correlation between two wave fields on the real reflectors (reflecting points) is much more and the NOCC belongs often to this type of cross-correlation which leads to the amplitude. In areas with more complexity, cross-correlation and NOCC of both types existed on (at reflecting and nonreflecting points) which means that both amplitude and

artifacts could be produced. However, as the characteristics of RTM, artifacts, and their relating NOCC at deep depths in comparison with shallow depths are not serious and challenging. As can be seen in Fig. 2, in the shallow depth area of images in Figs. 2a, b, both types of aforementioned cross-correlation occurred and the NOCC of both is high. It means that a large amount of artifacts is produced and covers the desired amplitude. These will be well explained in the next paragraphs based on its NOCC.

Hereafter, the determination of PSRA is presented based on the NOCC. First, we defined the reflection angle (θ) as the half-angle between the incident wave and the reflected wave. As we mentioned before, many researchers used a reflection angle of 60° which the artifacts start to appear, but it has not been proved based on any investigation so far. On the other hand, most of the researchers employed the weight zero to the reflection angles domain of 60° – 90° which kill a piece of desired information. Here, to determine the PSRA, we first broke the reflection angles domain of 0° – 90° to the three subdomains including 0° – 30° , 0° – 60° , and 0° – 90° . Then, an image was produced for each subdomain to have a clear perspective on the NOCC occurring in each subsurface

imaging point. Figure 4a–c shows the NOCC images for 0° – 30° , 0° – 60° , and 0° – 90° subdomains for the Sigsbee model. As can be seen in Fig. 4a, the variation of the NOCC for 0° – 30° has a mild increasing trend that changes gradually from deep to shallow depths. Although the value of NOCC is naturally a bit high near to the complex body, it shows that artifacts have not appeared yet. Furthermore, Fig. 4b shows more increase in NOCC for the 0° – 60° domain. At first glance, the increase might be interpreted as a result of wider reflection angles domain, (0° – 60° instead of 0° – 30°); actually, this is true but fast variation in NOCC in comparison with the Fig. 4a indicates that artifacts start to appear and this is exactly cross-correlation at nonreflecting points. This is more obvious near to the complex body. Figure 4c shows the NOCC in the whole reflection angles domain. As can be seen in this figure, the NOCC increase is almost triple and twice compared to the NOCC values in Fig. 4a and b, respectively. This was expected, because the main cross-correlation at nonreflecting points that cause artifacts occurred when the reflection angle became larger in shallow depths with strong velocity contrasts. Considering the events taking place in the three above subdomains, increasing the NOCC

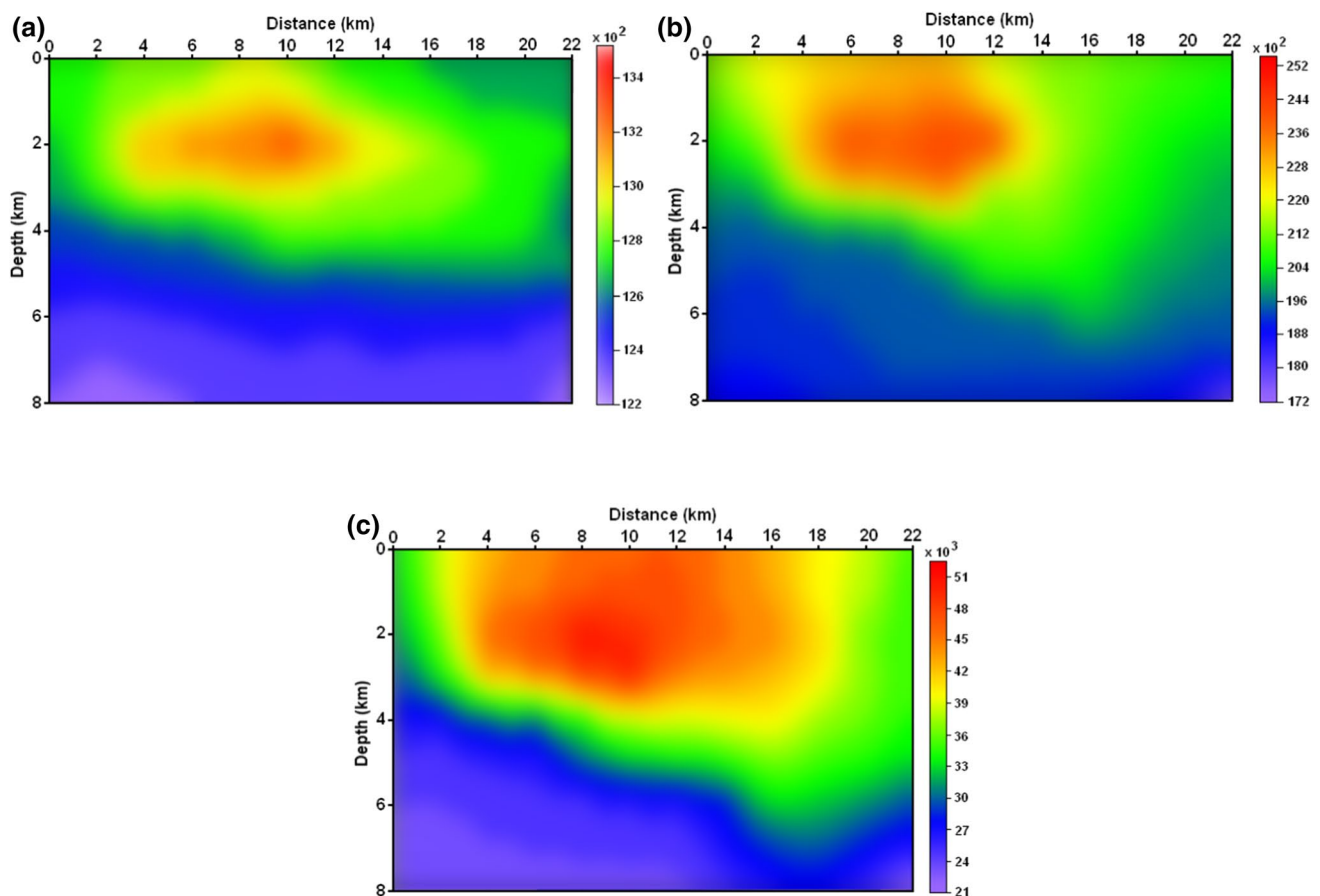


Fig. 4 Results of the NOCC monitoring for the Sigsbee model. **a** for the reflection angle domain of 0° – 30° ; **b** for the reflection angle domain of 0° – 60° ; **c** for the reflection angle domain of 0° – 90°

can be strongly interpreted as the main factor for artifact production. However, the evidence was not only confined by the Sigsbee model, so that the procedure also was tested on the BP model and the results demonstrated our previous idea. The results of NOCC monitoring for the BP model are shown in Fig. 5a, b.

The predominant starting reflection angle for RTM artifacts

The PSRA for RTM artifacts could be determined using the information of reflection angles and NOCC. Figure 6a, b shows the relationship between reflection angle and NOCC of two groups of ten imaging points for Sigsbee2A and BP models. The first group is located at shallow depths from 4 to 12 km in length and 0 to 4 km in depth, and the second one at deep depths is located from 4 to 12 km in length and 4 to 8 km in depth. The criterion for choosing these two areas was the amount of produced artifacts. The above areas have the possibility to show the maximum difference in artifacts and so NOCC in shallow and deep depths of the images in Fig. 2.

In both models, for the group of imaging points at deep depths, one can see an increasing mild trend between reflection angle and NOCC which shows the lack of cross-correlation at nonreflecting points which causes artifacts. For the second group at shallow depth, at small reflection angles up to 40 degrees the NOCC has almost close values compared to the shallow depths. It indicates a relatively similar condition at shallow and deep depths for the two groups, and we called it as the lack of cross-correlation at nonreflecting points. The behavior but at larger reflection angles ($> 40^\circ$) is more different. The graphs in both models show a steep trend that growth fast with reflection angle. In addition to the rapid growth in NOCC after 40 degrees, it should be added

that a gap can be seen in both graphs which occurred at 55 degree. Thus, the reflection angle of 55 degrees is realized as the angle that artifacts grow rapidly and we called it as predominant starting reflection angle (PSRA) for RTM artifacts. The new PSRA is proposed to be used instead of 60 degrees for suppressing artifacts or any related research. In the next section, a new imaging condition is proposed to suppress the RTM artifacts for the angle domain of 55 to 90 degrees.

A New imaging condition to suppress RTM artifacts

As it was mentioned before, artifacts start to appear at large reflection angles and the starting reflection angle for the artifact was determined as PSRA with values of 55 degrees. Thus, the angle domain of 55° – 90° includes both a piece of desired information and a large amount of artifacts. Filtering and designating weight zero to the mentioned domain have been used as the two main methods to remove these artifacts. But employing a filter might cause removing a part of the signal because of its overlapping frequency with artifacts, and using Laplacian filter causes a phase inversion and changes in amplitude. Also designating weight zero to the disputed domain leads to losing a piece of desired information that can enhance image quality. Therefore, the best solution could be the use of a proper imaging condition that maintains the desired information and suppresses the artifacts. As the first step, the imaging condition of Eq. (3) is used to suppress the artifacts:

$$I(x) = \frac{\int_0^{t_{\max}} [S_d(x, t)R_u(x, t) + S_u(x, t)R_d(x, t)] dt}{\int_0^{t_{\max}} S^2(x, t)} \quad (3)$$

where $S_d(x, t)$, $S_u(x, t)$ and $R_d(x, t)$, $R_u(x, t)$ are the downgoing and upgoing separated wave-field components for the

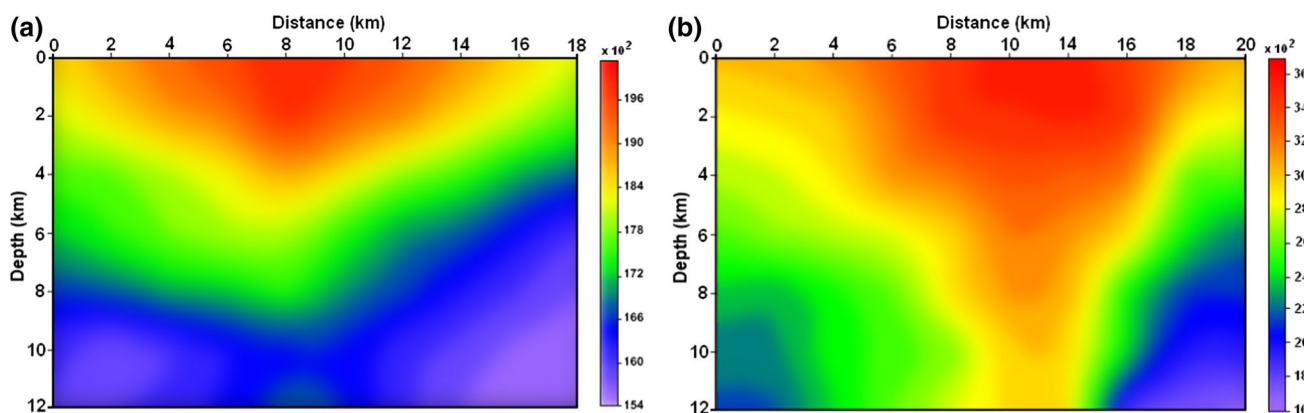
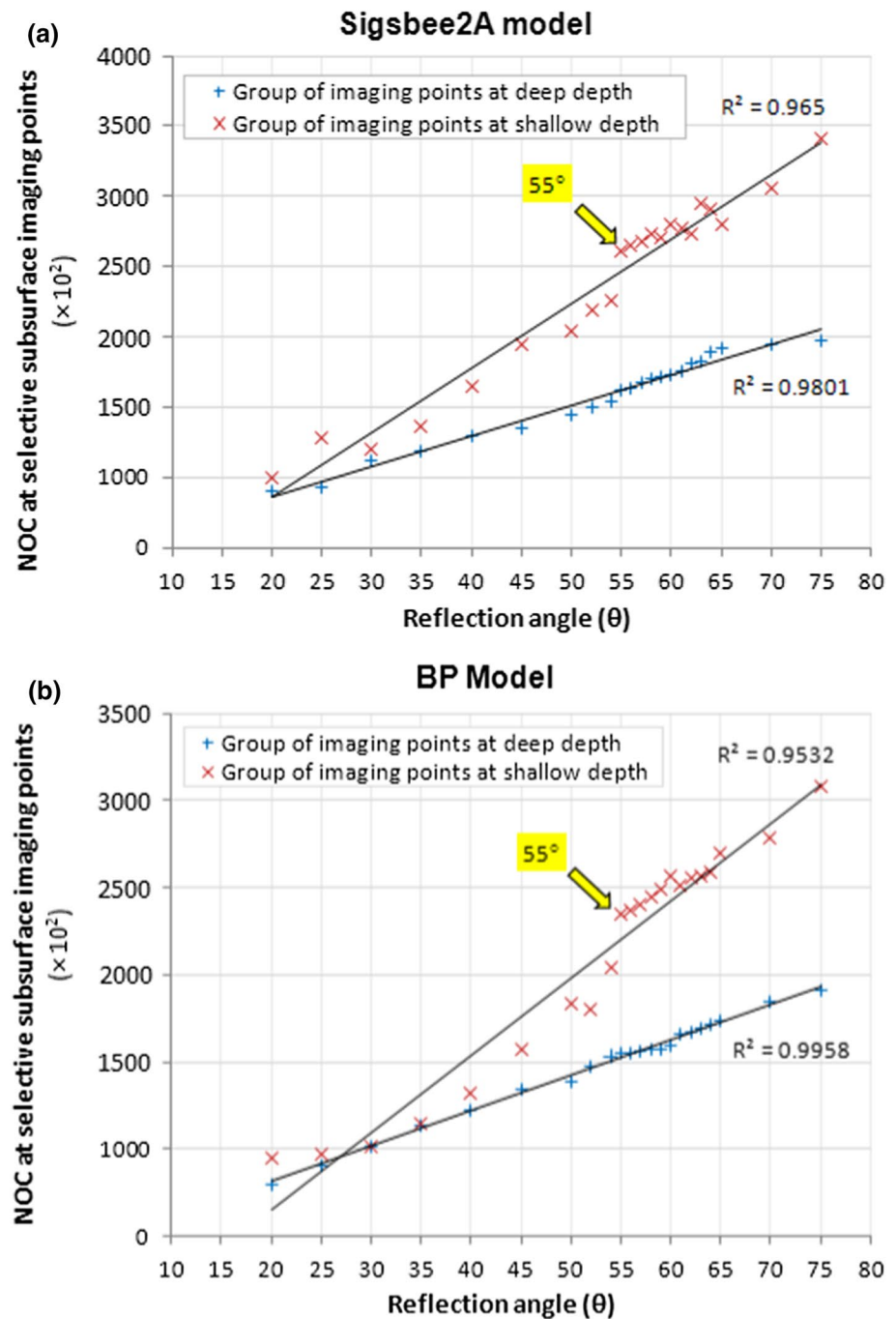


Fig. 5 Results of the NOCC monitoring for the BP model. **a** for the reflection angle domain of 0° – 60° ; **b** for the reflection angle domain of 0° – 90°

Fig. 6 Relationship between NOCC and reflection angle for the two groups of ten imaging points at shallow and deep depths. **a** For Sigsbee model; **b** for BP model



source and receiver, respectively, and $S^2(x, t)$ is the source-normalizing term. The wave-field separation was implemented using the Poynting vector that describes the energy flux density and can be calculated as a product of the time derivative and the gradient of the wave field in Eq. (4) (Yoon and Marfurt 2004):

$$J(x, t) = -\frac{\partial P(x, t)}{\partial t} \nabla P(x, t) \quad (4)$$

where $J(x, t)$ is the Poynting vector and $P(x, t)$ is the wave-field pressure. Separation is implemented using Eq. (5):

$$\beta = \arctan \left(\frac{J_z}{J_x} \right) \quad (5)$$

where β is the direction angle of wave-field propagation, J_x and J_z are the horizontal and vertical Poynting vectors, respectively. The downgoing part of the wave field is

considered when $\beta \in [0, -\pi]$, and the upgoing part of the wave field is considered when $\beta \in [0, \pi]$.

Figure 7a, b shows RTM results using the imaging condition of Eq. 3 for the reflection angles of 0° to 90° . As the result of wave-field separation, an improvement can be seen in the image quality in comparison with images in Fig. 3, but some artifacts still exist. These artifacts refer to the cross-correlation at nonreflection points. On the other hand, the results using the same imaging condition for the reflection angles of 0° to 55° (PSRA) are shown in Fig. 7c, d. One can see that the artifacts suppress fairly well, but some desired information above the structure is lost (top middle of both figures). The missing information more likely is related to the lack of information for the removed part of reflection angles (55° to 90°).

At the second step, a function of $\psi(\theta_i)$ in Eq. (6) was proposed to be added to the imaging condition of Eq. (3), where $\psi(\theta_i)$ is defined as a function based on the reflection angle of θ_i and θ_i is the reflection angle as the half-angle

between the incident wave and the reflected wave that was calculated through Eq. (6):

where J_S and J_R are the source and receiver wave-field Poynting vectors. Also m is a regularization parameter based on the θ to set up the artifact-suppressing process for each reflection angle in the 55 to 90 angle domains.

$$\gamma = 2\theta = \arccos \frac{J_S \cdot J_R}{|J_S| |J_R|} \quad (6)$$

$$\psi(\theta_i) = \cos^m(\theta_i) \text{ where } m = 1 + \frac{1}{90 - \theta_{i-1}}, \quad (7)$$

$$\theta_i = \theta_{i-1} + 1 \forall \theta_0 = 54^\circ \text{ and } i = 1, 2, \dots, 36$$

Adding $\psi(\theta_i)$ to Eq. (3) completes our proposed imaging condition in the form of Eq. (8):

$$I(x) = \frac{\int_0^{t_{\max}} [S_d(x, t)R_u(x, t) + S_u(x, t)R_d(x, t)] \psi(\theta_i) dt}{\int_0^{t_{\max}} S^2(x, t)} \quad (8)$$

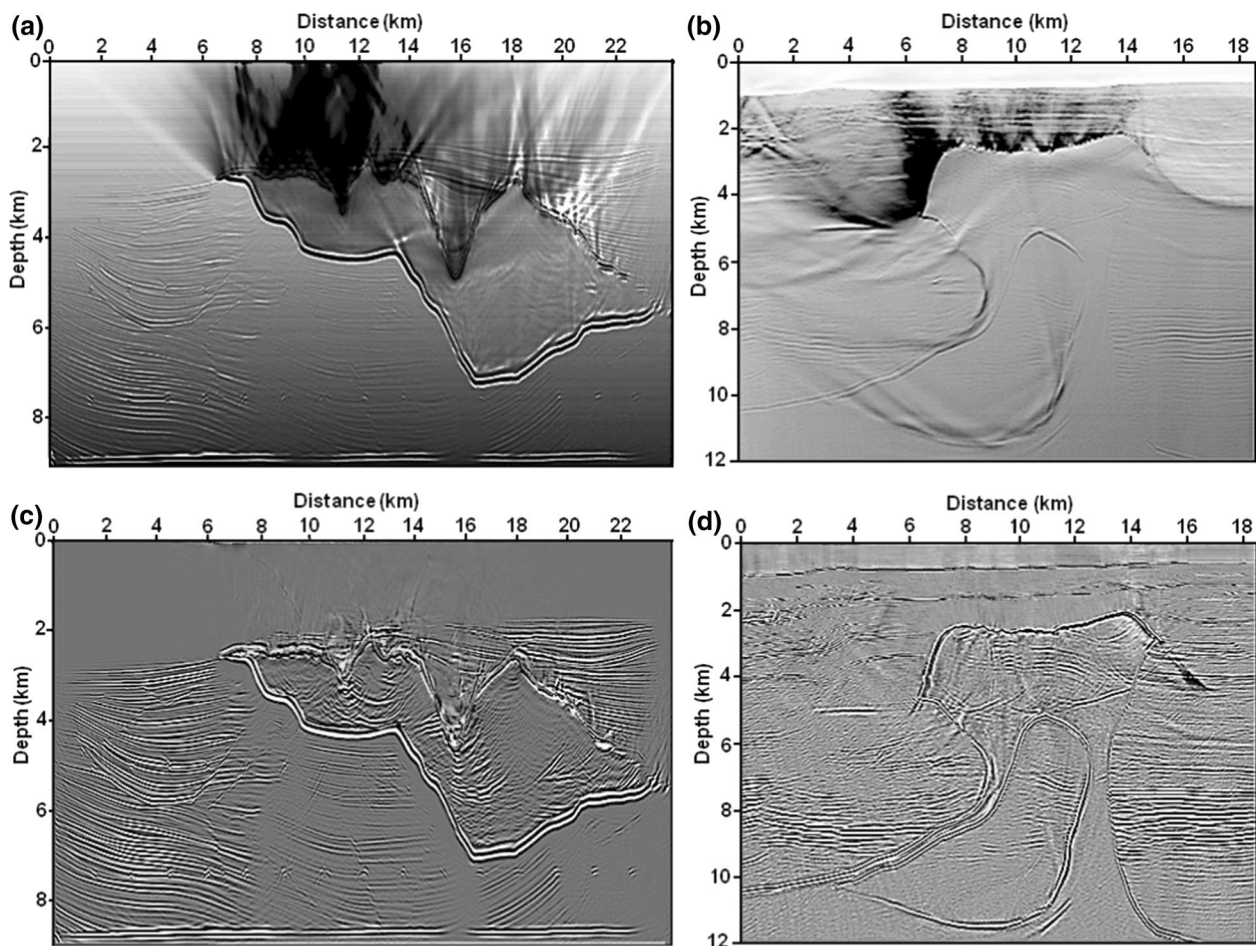


Fig. 7 RTM results using the imaging condition of Eq. (3) for the Sigsbee2A (left side) and BP (right side) models. **a** & **b** for the reflection angle domain of 0° – 90° . **c** & **d** for the reflection angle domain of 0° – 55°

It is interesting to note that the imaging condition in Eq. (8) can maintain the desired information to suppress artifacts properly for the angle domain of 55° to 90° . A key point in the suppressing process is the direct relationship between reflection angle and artifact production where each reflection angle in the domain of 55° to 90° includes a different amount of artifacts. Therefore, the imaging condition must be able to designate a suitable weight for each reflection angle to properly maintain the desired amplitude and suppress artifacts. This is achieved well by imaging condition of Eq. (8).

The final RTM results using the complete imaging condition in Eq. (8) for the whole reflection angle domain of 0° to 90° are shown in Fig. 8a, b. As can be seen, the final migrated images are considerably free of artifacts with a rather high quality including all structures in the models. The superiority of images in Fig. 8 versus images in Figs. 2 and 7a, b is obvious. To compare the RTM results in Fig. 8 with Fig. 7c, d, the best area is above the Sigsbee model (depths of 10–12 km in length and 2–4 km in-depth) and BP model (depths of 4–16 km in length and 0–3 km in-depth).

Conclusion

Reverse time migration as a full-wave equation method can image steeply dipping structures without dip limitations. In spite of its advantages, low-frequency artifacts are the major concern in the RTM method which especially occurs in strong velocity contrast in shallow depths. RTM artifacts usually start to appear in large reflection angles, but this angle domain could overwhelm a wide-angle range and it needs to be restricted to a smaller domain. Furthermore, we can determine a predominant starting reflection angle

(PSRA) for these artifacts. More accurate information on PSRA would be of great importance to suppress artifacts to improve the quality of the migrated image. As far as we know, any research-based study has not been conducted to determine an angle that artifacts start and the limited attempts just were based on trial and error or simple assumptions. The only reflection angle that has been proposed is 60 degrees which is not based on any proven investigation, and it seems to be just a suggestion based on trial and error. As the artifacts are the major challenging concern in RTM, the angle they start to appear is an important issue as well. Therefore, we might be able to determine a predominant starting reflection angle (PSRA) for RTM artifacts which enables us to suppress artifacts properly.

In the current paper first, we try to open and discuss some issues from a new fundamental perspective. The issues will be on the cross-correlation at real reflection and nonreflecting points, their number of occurrences which we named it the number of cross-correlations (NOCC), and its relationship with artifacts. These issues form the body of our research to determine PSRA. Then, a new approach is proposed to determine PSRA using NOCC. The proposed value for PSRA at which the RTM artifacts often start to appear is 55 degrees for the two models of Sigsbee and BP.

Finally, a new imaging condition based on the down- and upgoing wave fields and a new weighting function are proposed to suppress RTM artifacts. The new imaging condition has the capability to maintain the desired information and to suppress artifacts properly for the angle domain of 55° to 90° . A key point in the suppressing process is the direct relationship between reflection angle and artifacts production where each reflection angle in the domain of 55° to 90° includes a different amount of artifact. Therefore, our new imaging condition is able to designate a suitable weight for

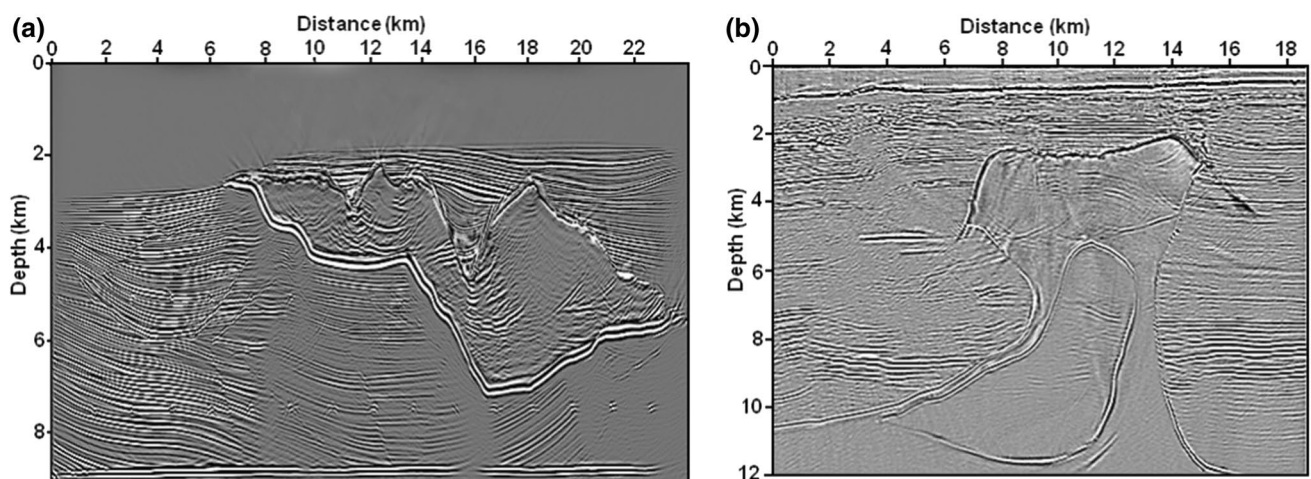


Fig. 8 RTM final migrated images using the imaging condition in Eq. (8) for the reflection angle domain of 0° to 90° . **a** for Sigsbee2A **b** for BP (Right side) models

each reflection angle to properly maintain the desired amplitude and suppress artifacts.

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