Complex salt model building using a combination of interactive imaging and layer-stripping RTM

Bin Wang,[1*] Chuck Mason,[1] Kwangjin Yoon,[1] Jean Ji,[1] Jun Cai,[1] Sang Suh[1] and Zhiming Li[1]

Abstract

A new methodology for building salt velocity models is proposed that allows effective testing of different salt interpretation scenarios. In this methodology, we combine the strength of efficient interactive imaging with the accuracy of layer-stripping RTM to derive a more accurate salt geometry. A set of interactive imaging tools enables a large number of salt interpretation scenarios to be quickly tested and narrowed down to a small number of likely salt interpretation cases. This is followed by a reduced number of layer-stripping RTM runs to single out the final salt velocity model. Redatuming the wavefield from the surface to a user-defined subsurface datum plays a pivotal role in this methodology; it enables the improvement of the quality of beam migration and the efficiency of RTM.

Introduction

Pre-stack depth migration has been used routinely for subsalt imaging. To produce a good subsalt image, an accurate velocity model is needed. The generation and refinement of the velocity model in a routine production project is often a complex process involving several iterations (Singer, P., 2005, Subsalt imaging: is the salt winning? CSM Summer Workshop). The final model typically has multiple embedded salt bodies with complex geometries.

Due to marked contrast between the high velocity salt and its surrounding low velocity sediments, the accuracy of the salt geometry has a first-order impact on the quality of subsalt imaging. The need for accurate salt interpretation and salt model building has been emphasized by many authors (e.g., Mosher et al., 2007; Sayers and Herron, 2007). The identification and definition of the salt geometry is a critical step for a successful subsalt imaging project. Time dedicated to accurate interpretation of the salt is always time well spent, and can account for approximately 70% of the time spent on a typical depth imaging project (Reasnor, 2007).

The existing methodology for building salt velocity models may not be effective in the complex areas where the salt geometry cannot be clearly identified in the seismic migration image. The industry-standard method of salt model building follows a series of sediment flood and salt flood iterations. At each step of this standard flow, only a single top of salt (TOS) or base of salt (BOS) interpretation is allowed. The fundamental assumption for this methodology is that the salt boundary is well imaged by the seismic migration, and therefore the salt boundary is interpreted and picked with relative certainty. This may not hold true for areas with complex salt geometry, where the salt boundary is often not well defined in seismic migration images. In cases where the salt geometry is not well imaged due to complex salt or other causes, and the standard methodology breaks down, a new more effective salt model building methodology is required.

Generally, salt model building is an iterative process that requires integration of salt interpretation and pre-stack depth migration processing. Salt interpretation is often not clear-cut for complex salt geometries, and in these cases testing different interpretation scenarios is required, especially for the BOS where imaging can be poor. Since depth imaging is an iterative process of velocity model building and depth migration, it is desirable to develop fast depth migration algorithms for velocity model building (Hill, 1990; Wang et al., 2008a).

Reverse time migration (RTM) has shown great potential not only as a final imaging tool, but also as a velocity model building tool. RTM accurately models complex wave propagation including turning waves and multiple bounce waves such as prism waves (Jones, 2007). RTM not only defines steep-dip boundaries better, but also has potential for imaging shadow zones and so improves event termination at salt boundaries. RTM has demonstrated its great strength to enable interpreters to define a more accurate salt model, especially for complex salt geometries (Ortigosa et al., 2008; Yoon et al., 2008). To enable quick testing of different salt

[1] *TGS, 2500 CityWest Blvd Suite 2000 , Houston, Texas 77042, USA.*
**Corresponding author, E-mail: bin.wang@tgsnopec.com*

interpretation scenarios, we have developed an efficient variation of RTM called layer-stripping RTM, which can be up to an order of magnitude faster than standard RTM. The key ingredient of this layer-stripping RTM is wavefield redatuming (Berryhill, 1984; Wang et al., 2006; Guan et al., 2009).

New methodology of complex salt model building

Why do we need a new methodology for complex salt model building? The basic assumption of the current standard methodology of salt model building is that TOS is clearly defined in sediment flood migration images, and BOS is well defined in salt flood migration images. This standard methodology for salt model building is effective for most cases, especially for simple or mildly complex salt models. However, in many complex areas, the salt boundary is not clearly identifiable by seismic imaging, especially when there are multiple salt bodies in close proximity. Figure 1a shows an example where the BOS is not well defined, though there is significant subsalt energy. Clearly, with the current estimation of the BOS, optimal subsalt imaging could not be obtained. Furthermore, in cases where there is a deeper second salt body, it is seldom that we can interpret the second deeper body with any certainty. Additionally, many interpretation scenarios need to be tested before the salt interpretation is finalized. Clearly, the existing standard salt model building methodology is not effective or efficient for building such complex salt models.

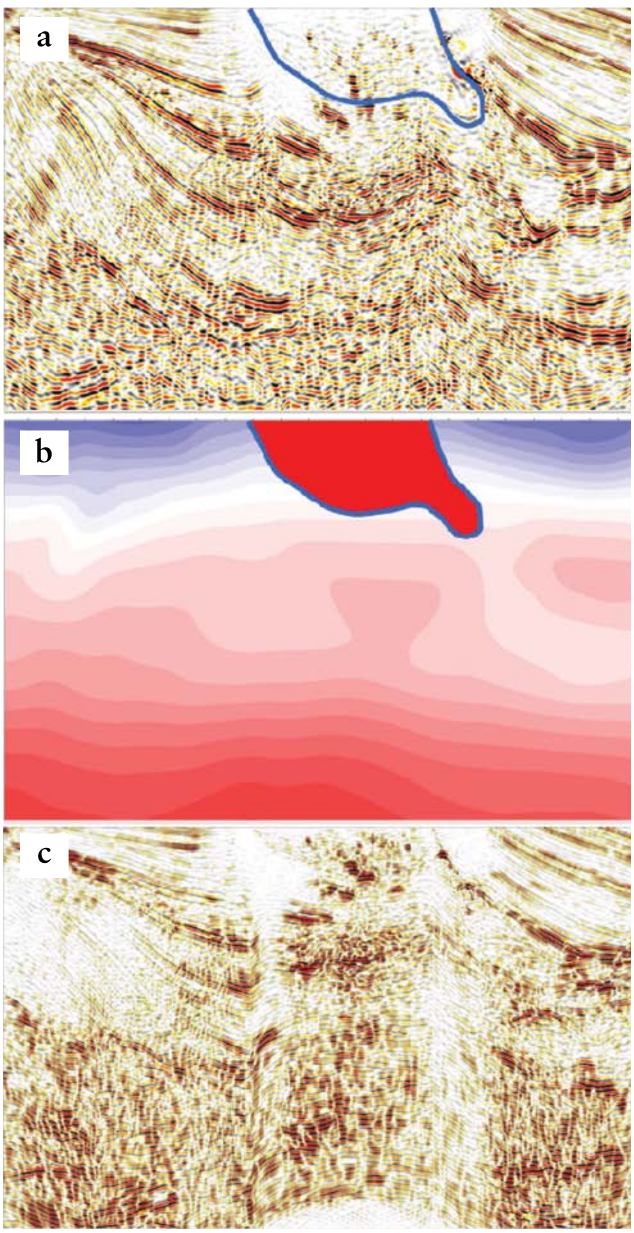

Figure 1 (a) Example of a pre-stack wave-equation-migration image of a salt body. (b) Migration velocity model. (c) Demigration to datum depth 3200m.

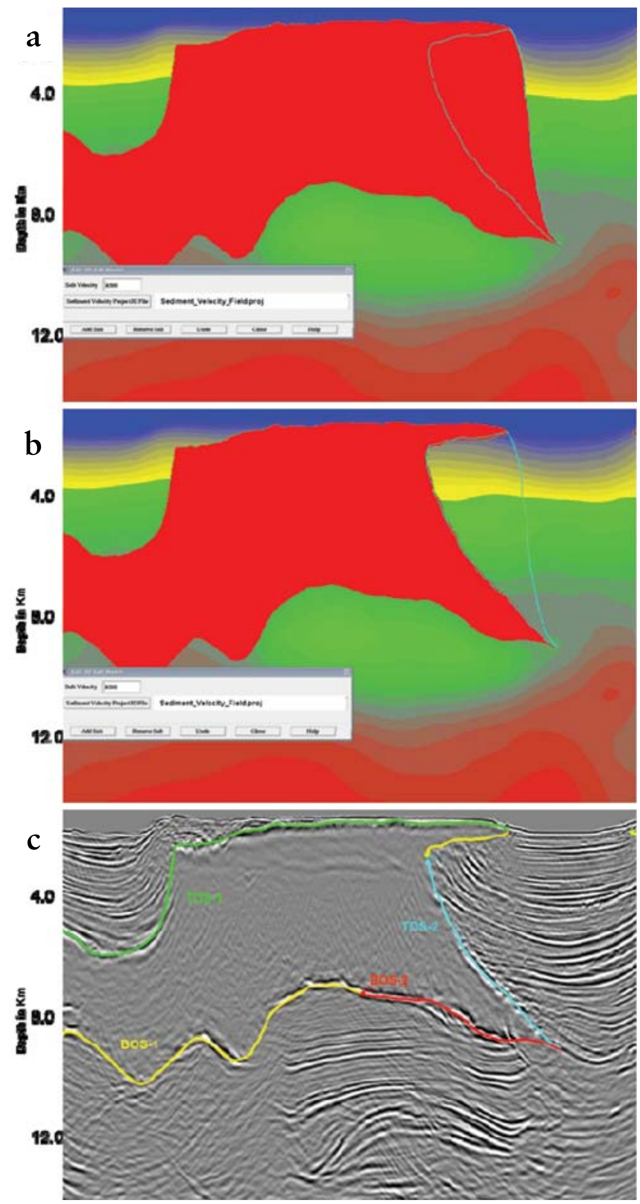

Figure 2 Example of a salt velocity model (a) before removing a piece of salt; and (b) after removing a piece of salt. (c) RTM image with overlay of salt body defined by standard multiple horizons.

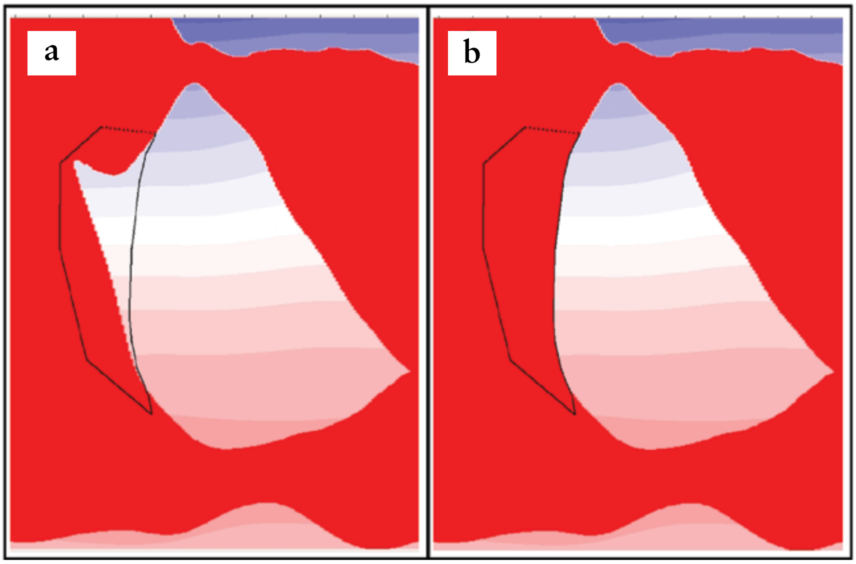

Figure 3 *Example of a salt velocity model (a) before adding a piece of salt; and (b) after adding a piece of salt.*

The proposed methodology takes advantage of the sensitivity of seismic depth migration on salt geometry. In some areas, due to the high velocity contrast across the salt boundary, the accuracy of the salt geometry has a first order impact on the depth migration image quality in the areas around or beneath salt bodies. The new methodology enables different salt interpretation scenarios to be tested before finalizing a salt model.

There are two key components in the proposed methodology for salt model building: interactive imaging and layer-stripping RTM. Efficient interactive imaging tools (Wang et al., 2008a) are used to quickly test a very broad range of salt interpretation scenarios. Typically, about 20 to 30 salt models are tested by using interactive imaging, and subsequently these are narrowed down to a smaller number of more likely salt interpretation scenarios (typically, three to five models). A more accurate and high quality layer-stripping RTM (Yoon et al., 2008) is then used to determine one final model from the remaining models.

Interactive imaging for salt model building

Production time-lines often put tremendous pressure on the interpreter to make prompt decisions regarding salt geometry, which may result in a sub-optimal salt model being used. In order to test many different salt geometries interactively within production time frames, we need not only fast migration algorithms, but also fast salt editing tools.

A set of interactive imaging tools has been developed to quickly test a large number of salt interpretation scenarios. These near real-time interactive imaging tools include a quick salt-editing tool and efficient migration tools. These consist primarily of a polygon-based salt editing tool, a wave-equation based post-stack demigration and remigration tool, and an interactive beam migration tool.

Instead of using TOS and BOS surfaces to insert a salt body into a sediment velocity model, we use a polygon to define a salt body. Figure 2 shows an example in which a piece of salt is removed to create a salt overhang. A polygon is first defined, and then, inside the polygon, salt velocity is replaced by the underlying sediment velocity field. Using a standard flow, creation of a salt overhang is a complicated process that requires the definition of two TOS surfaces and two BOS surfaces. Similarly, to add a piece of salt, we simply

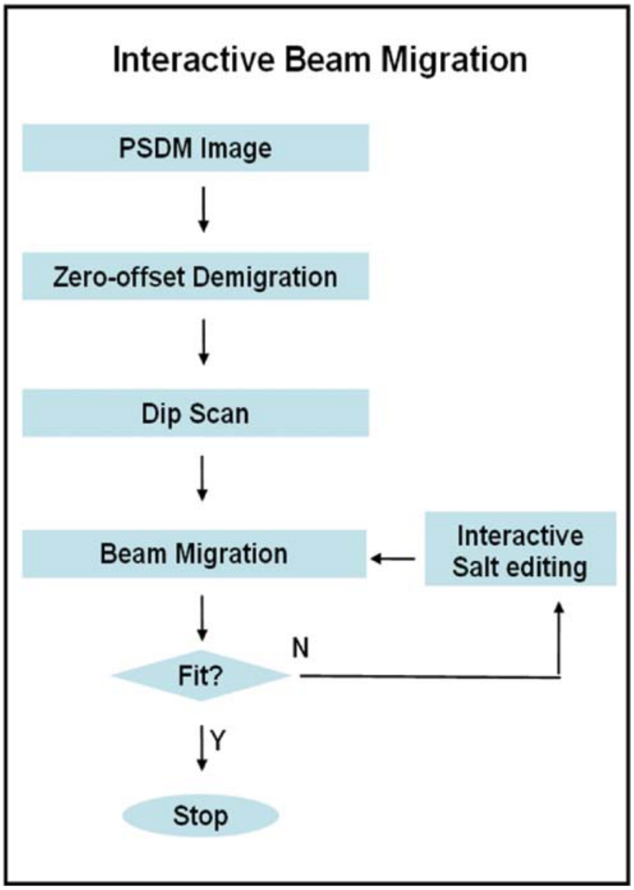

Figure 4 *Flow chart of interactive beam migration for testing different salt interpretation scenarios.*

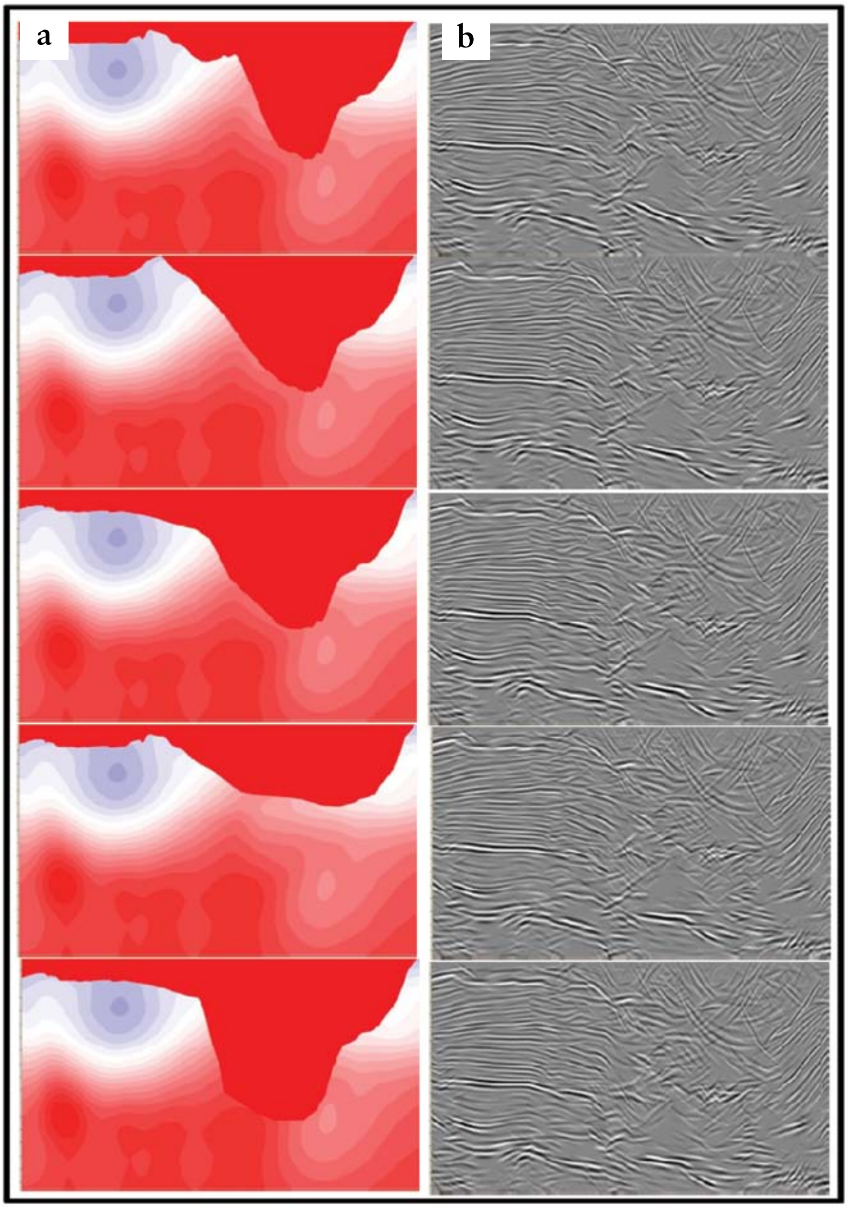

***Figure 5** (a) Salt interpretation velocity models with (b) corresponding beam migration images.*

define a polygon and replace the velocity inside the polygon with a salt velocity (Figure 3). To define a 3D salt body, we pick a set of polygons in the inline direction and interpolate polygons in the crossline direction.

To allow quick testing of a large number of salt models, we have two migration tools. Both tools are in the post-stack mode and are, therefore, extremely fast allowing interactive feedback concerning the impact of salt changes on the subsalt image. In a complex area such as a salt body region, the conventional way of performing post-stack migration by directly using input stacked data is not suitable and will not be able to achieve acceptable subsalt imaging quality.

To use the efficient, and yet high quality, post-migration algorithm for complex subsalt imaging, we start with a migrated image. On this migrated image we perform an upgoing wave-equation-based post-stack demigration to a subsurface datum to generate a demigrated wavefield at this subsurface datum. The demigrated wavefield is used for a later post-stack migration (called remigration). The subsurface datum is typically chosen to be right below the TOS; above this datum the velocity model is fixed and finalized.

The input volumes for wave equation based demigration include the 3D migration image cube and the corresponding migration velocity model. The image cube used for this step is not dependent upon using any particular algorithm but must have sufficient subsalt reflections, even though they may be incorrectly positioned. Wave equation, Kirchhoff and RTM cubes have all been successfully used for this process. TOS should be defined with as much accuracy as possible as this will be fixed for the testing process. Using the migration image as the reflectivity model together with the migration velocity model, we perform a post-stack wave-

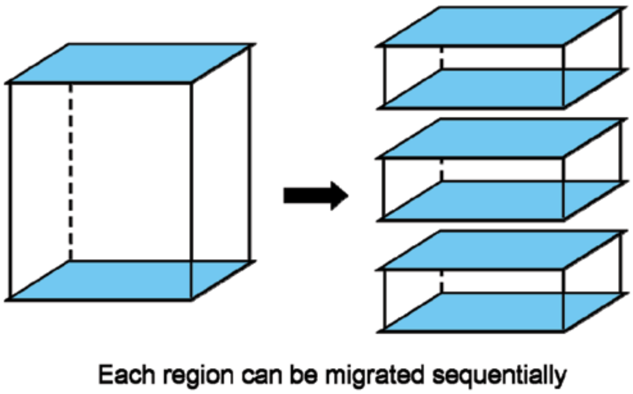

***Figure 6** Schematic diagram of layer-stripping RTM.*

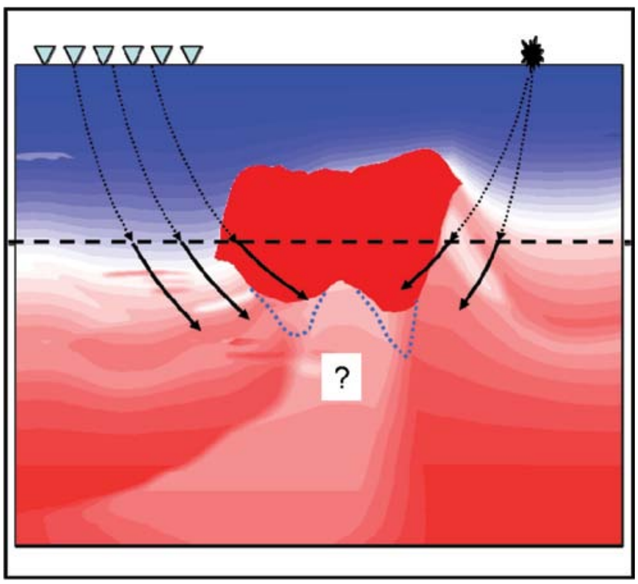

***Figure 7** Schematic diagram showing redatuming of both receiver side and source side wavefields from surface to a subsurface datum.*

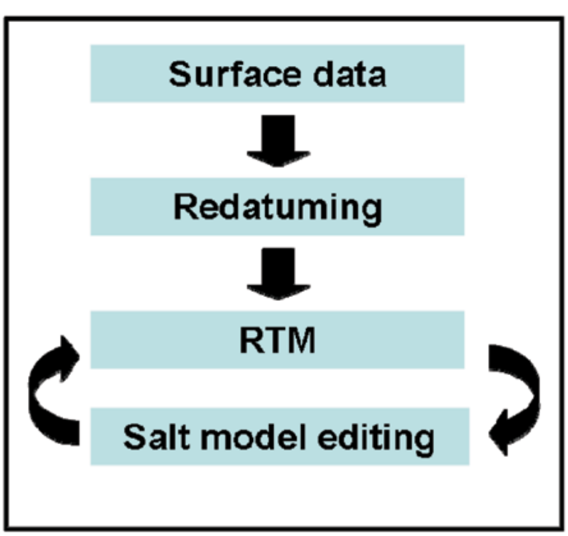

***Figure 8** Flow chart with initial imaging from surface and subsequent RTMs using redatumed wavefield.*

equation based demigration to get the zero-offset (post-stack) wavefield (Wang et al., 2005). The whole process of downgoing pre-stack migration followed by upgoing demigration effectively achieved a wavefield redatuming from the surface to the subsurface datum. Figure 1a shows an example migration image, and Figure 1b shows its corresponding migration velocity model. Figure 1c illustrates the demigrated zero-offset wavefield at a subsurface datum of 3200 m; the redatumed wavefield is greatly simplified when compared to the surface post-stack wavefield. The demigrated wavefield can be used as input to the two subsequent migration algorithms: wave-equation-based post-stack remigration from the subsurface datum; and interactive beam migrations (Wang et al., 2008b).

In order to interactively test many different salt boundaries, we need a very fast and near real-time migration algorithm such as beam migration. The importance of making this process interactive must be emphasized. It is critical to maintain continuity of the interpretive thought process while exploring various geometry scenarios. Batch processing is only sufficient when testing a number of discrete, predefined models. By introducing interactivity, the interpreter can immediately compare the image quality difference between the proposed modification and the current model. Figure 4 shows a flow chart of how we perform salt interpretation scenario testing using the interactive beam migration tools.

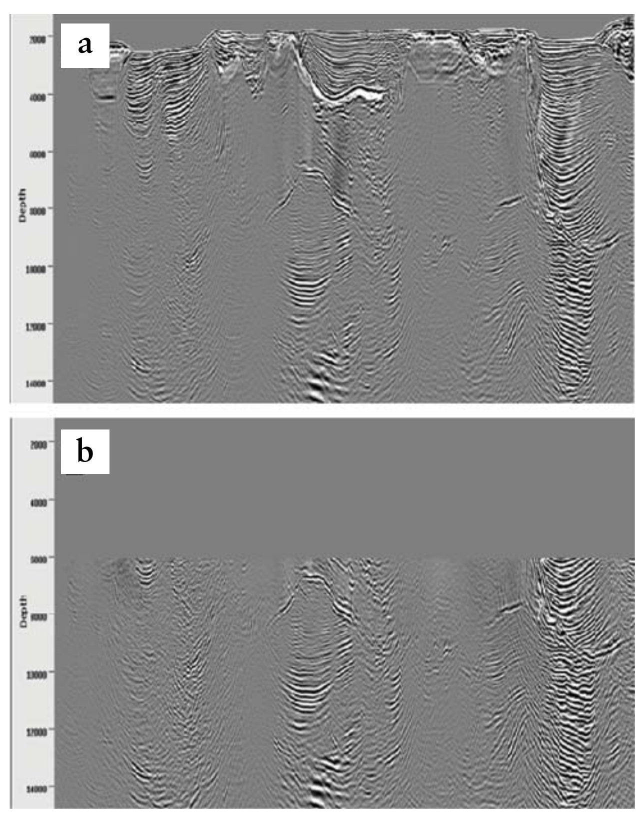

***Figure 9** (a) RTM image using surface input data. (b) RTM image using redatumed wavefield.*

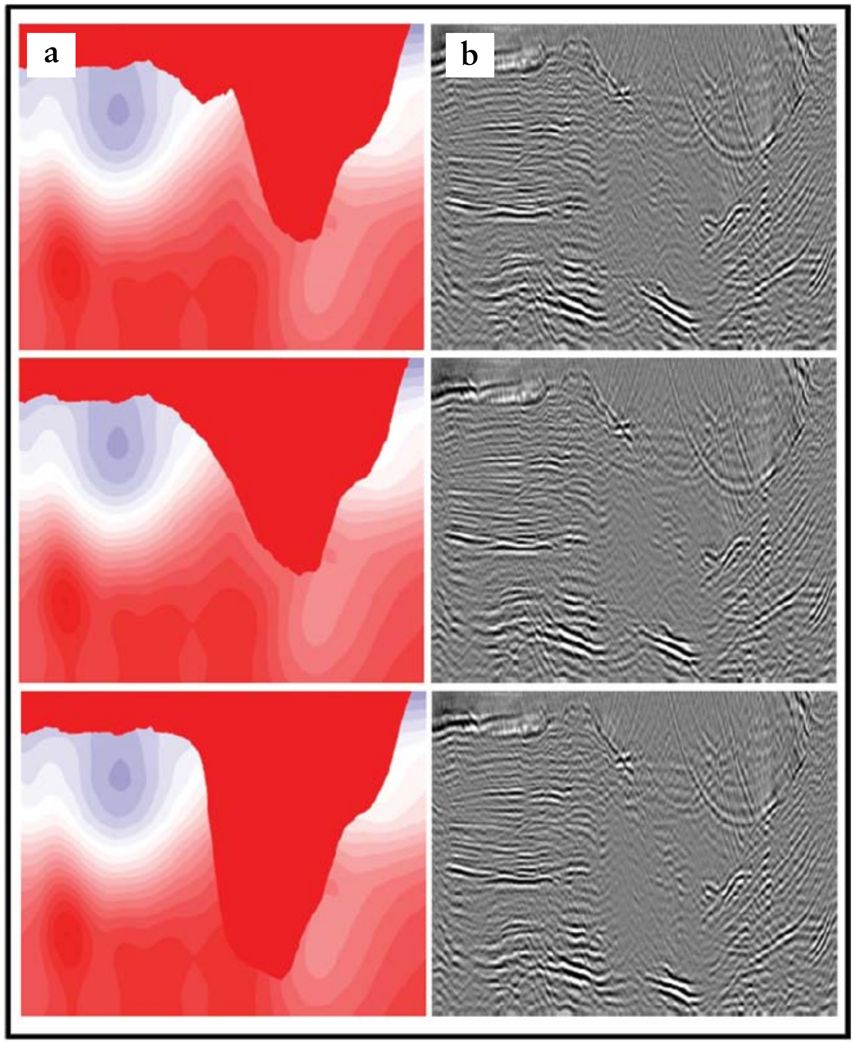

Figure 10 (a) Different salt interpretations and velocity models. (b) The corresponding layer-stripping RTM images using the velocity models on the left.

We first perform a wave-equation-based post-stack demigration to a subsurface datum, above which the velocity model is finalized. The demigrated wavefield is used as the input for post-stack beam migration to test different salt interpretation scenarios. By effectively redatuming the wavefield from the surface to a subsurface datum, the resulting wavefield is greatly simplified (Figure 1c). If data recorded on the surface were to be used, the wavefield would become very complex with many crossing events as it propagates across high-velocity contrasts such as the TOS (Wang et al., 2005). With a simplified wavefield, some critical steps of beam migration (Wang et al., 2008b) such as dip scanning and picking are more accurate, resulting in better quality subsalt beam migration images.

Figure 5 shows a few examples of salt velocity models and their corresponding beam migration images for a 3D data set from the Gulf of Mexico. In the first iteration, we suspect there is a problem with the salt model due to the discontinuity in the deep reflector known from regional geology. The BOS interpretation is questionable since there is not a distinct image of the BOS in this area. From the seismic image it is not clear whether there is a salt keel or not, and how deeply it may reach if it exists. Numerous BOS interpretations were tested attempting to heal this discontinuity by adding or removing salt from the velocity model. For this example, more than 20 salt models were tested using the interactive beam migration tools we have described. These were narrowed down to three models which were further tested by using a more accurate layer-stripping RTM.

Layer-stripping RTM for salt model building

To make RTM more affordable for salt scenario testing, such as how deep the salt keels go (Figure 5), we need to dramatically improve the RTM efficiency. We have developed an efficient variation of RTM called layer-stripping RTM. Simply speaking, for layer-stripping RTM, we divide the model into two or three horizontal regions and run RTM sequentially from top to bottom, as illustrated in Figure 6. For the top region, we run a regular RTM. The key ingredient for layer-stripping RTM is wavefield redatuming. When we run RTM for a shallow region, we save the wavefield for the datum at the bottom of the region with an overlap zone. These saved redatumed wavefields become the input for the subsequent RTM run. Figure 7 is a schematic diagram for wavefield redatuming. RTM is typically implemented in the shot domain. Wavefield redatuming is required on both the source side and the receiver side.

RTM-based wavefield redatuming possesses a number of important benefits. For example, the computation cost can be dramatically reduced by performing RTM using only a redatumed wavefield below the subsurface datum. This reduction is due to two main factors. Firstly, the computation grid size can be greatly increased without introducing dispersion noise, because the minimum velocity in a region typically increases with depth. For example, assuming the minimum velocity is increased from 1.5 km s^{-1} at the surface to 2.5 km s^{-1} at the redatuming surface of 6 km depth, the computation grid size can be increased by a factor of 1.67, considering three dimensions in space and one dimension in time, which translates to an increase in speed by a factor of seven. Secondly, the migration aperture can be greatly reduced. The required migration aperture is linearly proportional to the target depth. The computation savings due to the smaller required aperture apply for both the RTM-redatuming step as well as the subsequent multiple RTM runs using the redatumed wavefield. Additional cost savings can also be achieved by identifying and pre-selecting only those input shots which contribute to, or illuminate, the target areas. Other benefits of using redatuming for RTM, such as saving on computer memory, are discussed by Guan et al. (2009).

Figure 8 shows the flow chart for our layer-stripping RTM. First, input shot gathers (or selected shot gathers) are redatumed from the surface to a user-defined subsurface datum. On the source side, the forward-modelled wavefields are saved to the local disk on the redatuming surface at a given time interval. One alternative view of source-side redatuming is that it converts a point source at the surface into an area of sources in the subsurface datum. On the receiver side, the receiver wavefields (input shot records) are reverse-time propagated and the wavefields on the redatuming surface are saved to the local disk. The saved redatumed wavefield is used to test different salt velocity models by performing multiple RTM runs.

We have developed a 3D RTM-based tool to redatum the wavefield from the surface to a subsurface datum. Figure 9 shows an example of the effectiveness of the 3D RTM-based redatuming. Figure 9a is a 3D RTM image produced by a one-step RTM run using the surface input data, and Figure 9b is the corresponding RTM image produced by using the redatumed wavefield at 6 km depth. Except for some visible amplitude differences, the two images are very comparable.

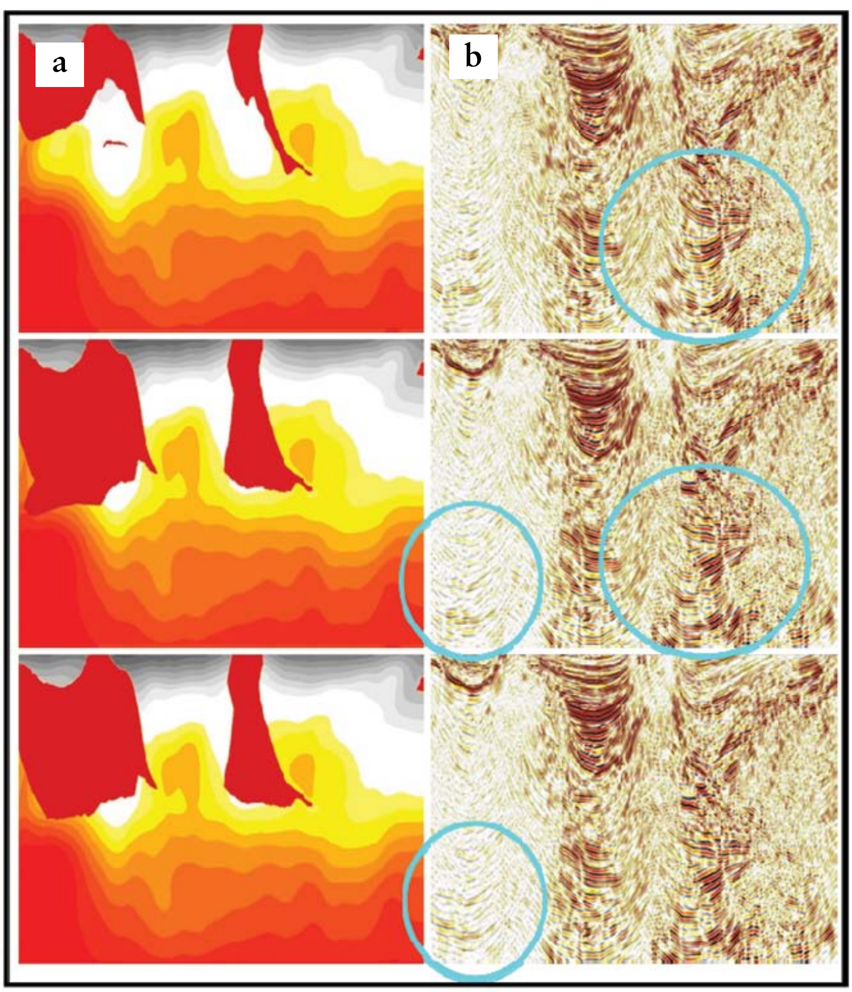

Figure 11 *(a) Different salt interpretations and velocity models. (b) The corresponding layer-stripping RTM images using the velocity models on the left.*

One technical challenge we have resolved is the 'data explosion' problem. A typical 3D narrow-azimuth survey only has six to eight cables, and even a development wide-azimuth survey has only 80 cables or so in a super shot gather. However, after redatuming, in the crossline direction, hundreds of lines need to be saved, so the data volume could be increased by as much as one to two orders of magnitude. To solve the data explosion problem, we have used robust data compression technology.

Figure 10 shows an example of how layer-stripping RTM is used to test different salt velocity models. This is the same 3D data set shown in Figure 5. Interactive beam migrations were used to test more than 20 different salt geometries. The three most promising salt models (Figure 10, left column) were selected, then layer-stripping RTM was used to produce the RTM images shown in the right-hand column of Figure 10. Based on the RTM image, the bottom salt geometry was chosen to be the final model, because it makes the most geological sense. Figure 11 shows another example of using layer-stripping RTM for salt model building. The bottom left salt model results in an RTM image which is more focused and has deeper events that follow the regional dip trend.

Conclusions

We have developed a methodology for salt model building which allows effective testing of many different salt interpretation scenarios. The new methodology takes advantage of the sensitivity of migration images to salt geometry changes. We are able to use increasingly more precise algorithms as our certainty of the salt geometry increases. The interactive imaging tools, which consist of efficient migration (post-stack demigration and remigration plus interactive beam migration) and practical interactive salt editing tools, allow us to rapidly test a large number of salt interpretation scenarios. The accuracy of RTM, especially in areas around and beneath salt bodies, makes it an effective tool for building good salt models.

Wavefield redatuming plays an important role in this methodology. Wavefield redatuming enables us to use a layer-stripping approach to salt model building. For the interactive beam migration step, the redatuming is achieved by the wave-equation-based downgoing migration and upgoing demigration; and for the layer-stripping RTM step, the redatuming is directly achieved in the shot domain. Data compression is a practical way to address the data explosion problem of 3D redatuming.

Acknowledgements

We would like to thank Pete Bennion for his interest in this work and his encouragement to submit this paper. We also thank Laurie Geiger, Wilfred Whiteside and Simon Baldock for their reviews.

References

Berryhill, J.R. [1984] Wave equation datuming before stack. *Geophysics*, **49**, 2064–2067.

Guan, H., Kim, Y., Ji, J., Yoon, K., Wang, B., Xu, W. and Li, Z. [2009] Multistep reverse time migration. *The Leading Edge*, **28**, 442–447.

Hill, N.R. [1990] Gaussian beam migration. *Geophysics*, **55**, 1416–1428.

Jones, I., Goodwin, M.C., Berranger, I.D., Zhou, H. and Farme, P.A. [2007] Application of anisotropic 3D reverse time migration to complex North Sea imaging. *77^{th} SEG Annual Meeting*, Expanded Abstracts, **26**, 2140–2143.

Mosher, C., Keskula E., Malloy, J., Keys, R., Zhang, H. and Jin, S. [2007] Iterative imaging for subsalt interpretation and model building. *The Leading Edge*, **26**, 1424–1428.

Ortigosa, F., Liao, Q., Guitton, A. and Cai, W. [2008] Speeding up RTM velocity model building beyond algorithmics. *78^{th} SEG Annual Meeting*, Expanded Abstracts, **27**, 3219–3223.

Reasnor, M.D. [2007] Salt interpretation practices for depth imaging in the Gulf of Mexico. *The Leading Edge*, **26**, 1438–1441.

Sayers, C. and Herron, D. [2007] Introduction to this special section: subsalt exploration. *The Leading Edge*, **26**, 1404–1405.

Wang, B., Qin, F., Audebert, F. and Dirks, V. [2005] A fast and low cost alternative to subsalt wave equation migration perturbation scans. *75^{th} SEG Annual Meeting*, Expanded Abstracts, **24**, 2257–2260.

Wang, B., Audebert, F., Wheaton, D. and Dirks, V. [2006] Subsalt velocity analysis by combining wave equation based redatuming and Kirchhoff based migration velocity analysis. *76^{th} SEG Annual Meeting*, Expanded Abstracts, **25**, 2440–2443.

Wang, B., Ji, J., Mason, C., Gajawada, S. and Kim, Y. [2008a] Interactive imaging: an effective way to build a better salt model. *70^{th} EAGE Conference & Exhibition*, Extended Abstracts, F040.

Wang, B., Kim, Y., Mason, C. and Zeng, X. [2008b] Advances in velocity model-building technology for subsalt imaging. *Geophysics*, **73**, VE 173–181.

Yoon, K., Wang, B., Kim, Y. and Guan, H. [2008] Localized reverse time migration for salt model building. *78^{th} SEG Annual Meeting*, Expanded Abstracts, **27**, 2331–2335.

Received 28 January 2011; accepted 1 May 2011.

doi: 10.3997/1365-2397.2011019