Velocity model evaluation through Born modeling and migration: a feasibility study

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ABSTRACT

A way to quickly test many possible migration velocity models would be a valuable interpretation tool. Here, a modified Born modeling scheme is used to simulate a new, smaller dataset from an initial image, allowing for target-oriented migrations in a fraction of the time needed for a full migration of the original dataset. Furthermore, the simulated dataset is migrated with a generalized source function derived from the original prestack image, preserving important velocity information that would be lost if a standard wavelet were used as the source function. While the method is currently limited to analysis of a single reflector, initial tests on a simple 2D synthetic model indicate that this method can accurately and efficiently produce images comparable to full standard migrations.

INTRODUCTION

Building an accurate seismic velocity model is essential for obtaining an acceptable image of the subsurface. When the subsurface is especially complex, for example in geological settings dominated by irregularly-shaped salt bodies, this task becomes particularly challenging. The large contrast between salt and sediment velocities magnifies the effects of inaccurate salt interpretation, resulting in a poor image. Unfortunately, velocity model-building is a time-consuming process that often requires several iterations. A typical salt-interpretation and model-building workflow involves iterative sediment- and salt-flood migrations to identify the top and base of the salt bodies (Mosher et al., 2007). In situations where the top or (especially) base salt interpretation is uncertain or ambiguous, several different salt scenarios may be geologically feasible. Therefore, a means of quickly testing the effects of several different possible velocity models would be extremely useful for judging and refining salt interpretations. Here, we investigate a Born modeling and migration scheme that allows for fast remigrations of data simulated from an initial image, that incorporates prestack velocity information from the initial image's subsurface offset gathers.

An interactive interpretation and imaging environment would be a valuable model-building tool, and several different approaches have been proposed. Wang et al. (2008) introduced a fast migration scheme built on Gaussian beam imaging (Hill, 1990), that can quickly test different salt scenarios. This method relies on seismic demigration and redatuming of wavefields to reduce the computational expense of migrating with several different velocity models. However, this method operates in the poststack image domain, neglecting velocity information that can be obtained from prestack images, and is limited by the approximations inherent to beam imaging. A similar approach has been proposed using reverse time migration (RTM) in a "layer-stripping" manner (Wang et al., 2011), but this remains too computationally intensive to test more than a very small number of possible models. Chauris and Benjemaa (2010) have proposed another method using RTM, which aims to reduce computational expense by summing over time-delays in the subsurface rather than sources. However, at present this method has only been demonstrated in two dimensions, and it remains unclear if an extension to 3D is feasible. Finally, fast migrations may also be achieved through the use of simulated datasets derived from an initial image. Guerra (2010) synthesized wavefields using prestack exploding reflector modeling as a means for performing wave-equation tomography in the image space. However, the significant amount of preprocessing required, especially in 3D, makes this approach less appealing for interactive testing of several velocity models.

Born modeling (Stolt and Benson, 1986) is based on a single-scattering approximation of the wave equation. By taking advantage of this approximation, we can simulate a new dataset (Tang and Biondi, 2010; Tang, 2011) from an initial image, whose size and acquisition geometry can be selected independently from those of the original dataset. Furthermore, the simulated data can be migrated using generalized sources, drastically reducing the number of shots required. In the examples we show, only a single shot is required, allowing for migrations well within an interactive time frame. In order to improve the accuracy of this method, we use a generalized source function derived from subsurface offset gathers of the initial image. This allows for a more accurate and data-driven result than if a simple wavelet were used as the source function; in addition, including non-zero subsurface offset information into this source function incorporates important velocity information available from the initial image.

In the following sections, we review the Born modeling methodology and outline the procedure for obtaining the generalized source function described above. We then demonstrate the method using simple 2D synthetic models. Crosstalk artifacts arising from the modeling procedure limit these examples to isolated image points along a single reflector in the subsurface; however, these tests indicate that this method can effectively provide information about the accuracy of different velocity models on an image. Further enhancements and the inclusion of phase-encoding (Romero et al., 2000) strategies should widen the applicability of the method. Ultimately, we hope to combine this method with elements of an automated image segmentation scheme (Halpert et al., 2011) to create a powerful tool for interactive interpretation and imaging.

METHOD

The goal of the procedure we will describe is to use Born modeling to synthesize a new dataset that is much smaller than the original dataset used to generate an initial migrated image. Since the synthesized data can be "recorded" at any location in x, y, and even z, this procedure is effectively target-oriented. There are three basic steps needed to reach our goal of efficient velocity model evaluation:

1. Generate an areal source function using one or more subsurface offset gathers from the initial prestack image.
2. Using the new source function and a reflectivity model based on the initial image, employ Born modeling to generate a new dataset with acquisition geometry best suited to image the target area.
3. Migrate the simulated data obtained in Step 2, using the source function from Step 1. This step is extremely computationally efficient compared to a full migration of the original data, allowing for testing of several possible velocity models in a fraction of the time it would take to evaluate them using standard migration techniques.

In the following sections we detail the theoretical basis for each of these steps.

Generalized source function

In conventional modeling and migration, a simple wavelet or plane wave is often used as the source function. However, here we can take advantage of the fact that the procedure described above begins with a migrated image. This allows us to perform post-stack "exploding reflector" (Claerbout, 2005) modeling of a reflector or point diffractor in the subsurface; the upward-continued wavefield can be recorded at any location, and then injected as an areal source function during Born modeling. Mathematically, this areal source is described as

$$S(\mathbf{x}_s) = \sum_{\mathbf{x}'} \sum_{\mathbf{h}} G^*(\mathbf{x}' - \mathbf{h}, \mathbf{x}_s, \omega, \xi(\mathbf{x}', \mathbf{h})), \tag{1}$$

where $\mathbf{x}_s = (x_s, y_s, z_s)$ are the arbitrarily defined locations where the wavefield will be recorded; $\mathbf{h}$ is the vector of subsurface half-offsets; ω is angular frequency; ξ is the location of the exploding image point in the subsurface; and G is the Green's function connecting the source to the image point (here, * denotes the adjoint). The Green's function is computed using the same velocity model that was used to image the originally-recorded data, meaning that the recorded wavefield should be independent of the original velocity model choice. However, since this velocity model is unlikely to be correct, the initial image should contain valuable information about the accuracy of this model in the form of subsurface offset gathers. Thus, the inclusion of the subsurface offset term $\mathbf{h}$ in equation 1 is designed to incorporate this information into the modeling. Since post-stack modeling is used to upward continue the wavefields, the non-zero subsurface offset data are mapped to equivalent zero subsurface offset locations:

$$\alpha(\mathbf{x} - \mathbf{h}) = \alpha(\mathbf{x} - \mathbf{h}) + \beta(\mathbf{x}, \mathbf{h}), \tag{2}$$

where α is the zero-offset data that are upward continued, and β is the original subsurface offset gather. To illustrate the advantage gained by incorporating this information, Figures 1(a) and 1(b) show two recorded source wavefields from an image point that is actually located at $z = 1000$ in the subsurface, but was initially imaged with a velocity that was 15% too slow. Both recorded wavefields have been reverse-propagated back to zero time to facilitate comparison. The source function in panel (a) was modeled using only the zero subsurface offset $h = 0$ data from the initial image, while the result in panel (b) uses the non-zero offset information as written in equation 1. When only zero subsurface offset data are used, the source appears to focus at the incorrect depth; when the nonzero offset data are used, the effects of using the wrong velocity are apparent. Using the source function in Figure 1(b) should therefore prove superior for use with the Born modeling and migration scheme described in the next section.

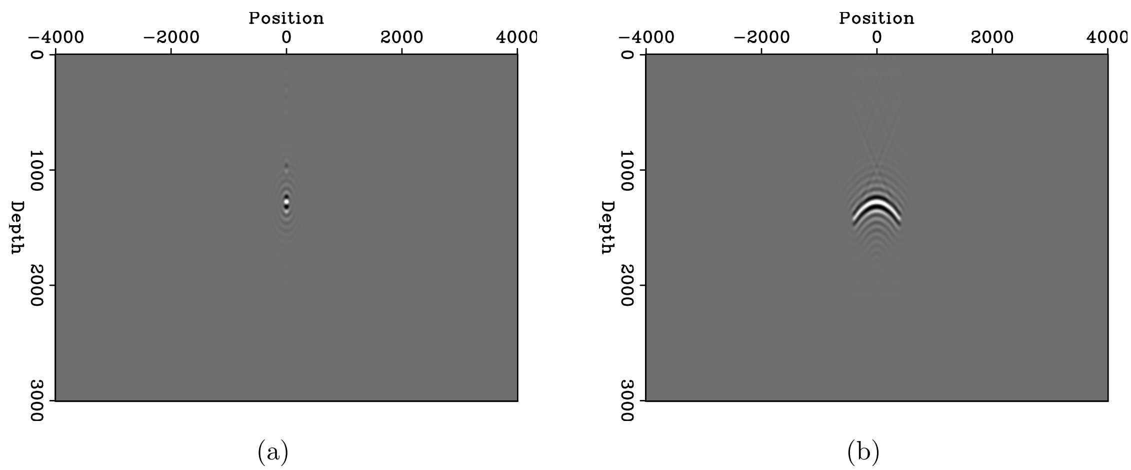


Figure 1: Recorded source wavefields that have been reverse-propagated to zero-time; the result in (a) does not include information from the nonzero subsurface offsets of the initial image, while (b) does include this information. Both the initial migration and the modeling used a velocity model that was 15% too slow.

Born modeling and migration

We now use the modeled areal source to generate a new data set via Born modeling. To do this, we define the simulated dataset d' recorded at arbitrary receiver locations $\mathbf{x}'_r$:

$$d'(\mathbf{x}'_r, \omega) = \sum_{\mathbf{x}'} \sum_{\mathbf{h}} \Gamma(\mathbf{x}_s, \mathbf{h}, \omega) G(\mathbf{x}' + \mathbf{h}, \mathbf{x}'_r, \omega) m(\mathbf{x}', \mathbf{h}). \tag{3}$$

Here, m is the reflectivity model (in our case, the initial image), and the Γ term is defined as

$$\Gamma(\mathbf{x}_s, \mathbf{h}, \omega) = \sum_{\mathbf{x}_s} S(\mathbf{x}_s) G(\mathbf{x}_s, \mathbf{x}' - \mathbf{h}, \omega), \tag{4}$$

where S is as defined in equation 1.

Because the placement of the receiver locations in equation 3 can be arbitrarily determined, they do not necessarily need to be on the surface, like the original recorded data. Placing the receivers at depth can improve the efficiency of this method by providing the capability for target-oriented imaging; if a velocity model is well-determined down to a given depth, the synthesized data can be recorded below that depth, avoiding unnecessary computation. This has a similar effect to re-datuming the wavefields, an approach taken by Wang et al. (2008) in their fast image updating strategy.

Now that we have new source and receiver wavefields, we can produce an image using standard wave-equation migration techniques:

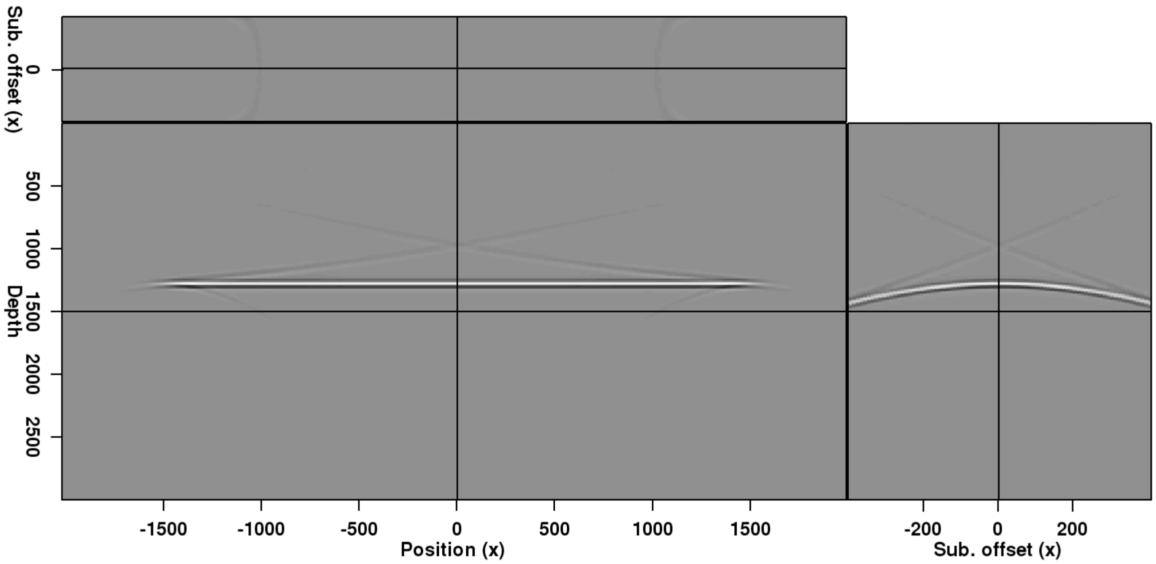
$$m'(\mathbf{x}', \mathbf{h}) = \sum_{\omega} G^*(\mathbf{x}' - \mathbf{h}, \omega) \sum_{\mathbf{x}'_r} G^*(\mathbf{x}' + \mathbf{h}, \mathbf{x}'_r, \omega) d'(\mathbf{x}'_r, \omega). \tag{5}$$

It is important to note that the Green's functions in equation 5 can be computed using any velocity model, and not necessarily the same one used to generate the source and receiver wavefields in previous steps. This can allow for testing of multiple possible velocity models. Furthermore, since subsurface offset gathers are generated during the imaging, we now have a more quantitative means of judging the accuracy of these various models. This represents an advantage over methods such as beam migration that cannot provide this information. Unfortunately, the imaging procedure as written in equation 5 can also generate crosstalk artifacts, since areal source data is used. While various methods are available to help attenuate these artifacts (Romero et al., 2000; Tang, 2008), we restrict our examples in the next section to isolated points in the subsurface, spaced far enough apart to limit the effects of crosstalk.

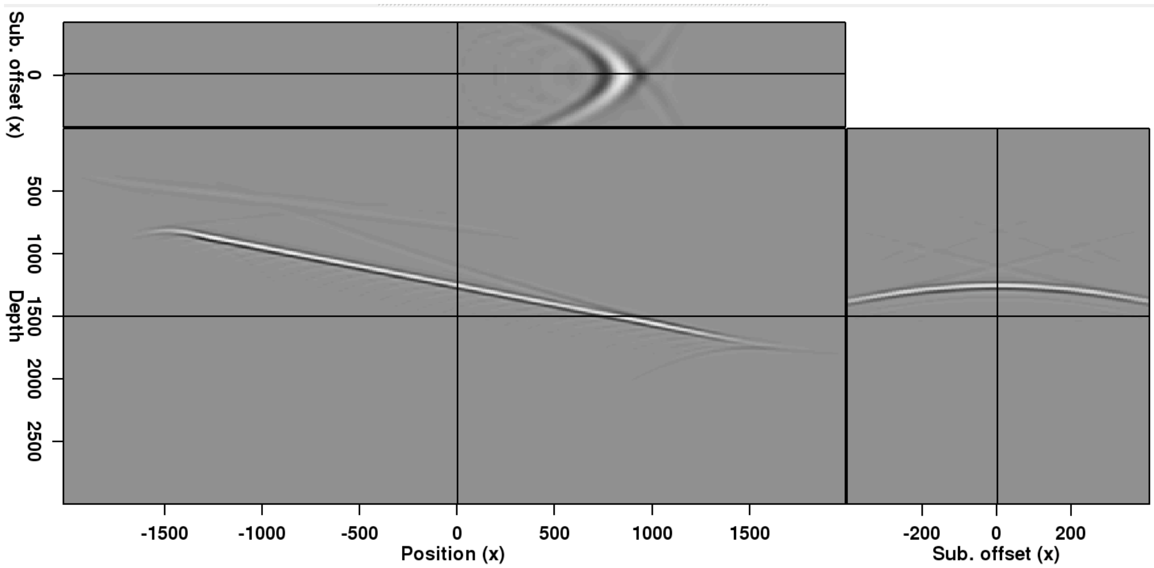
EXAMPLES AND DISCUSSION

To test the feasibility of the method outlined above, we designed two simple synthetic test cases: a single flat reflector in the subsurface (Figure 2(a)), and a single reflector dipping at 20° (Figure 2(b)). We restricted these initial test cases to a single reflector in order to avoid problems related to crosstalk between multiple events or reflectors; while there are methods to attenuate this crosstalk, we hoped to gauge the feasibility of the method using only a single shot to migrate the Born-modeled data, without sophisticated phase-encoding schemes.

Both examples in Figure 2 were generated by migrating with an incorrect velocity model (15% slower than the constant-velocity model used to generate the original dataset). The effects of using an incorrect velocity can be seen clearly on the subsurface offset gather (non-focused event). A key goal of our Born modeling procedure is to replicate this behavior when the same velocity model is used to migrate the Born-modeled data. To test this, we sample isolated points from the reflectors in Figure 2, and use these points to generate the areal source function described in the previous section. In order to avoid unwelcome crosstalk between these points during

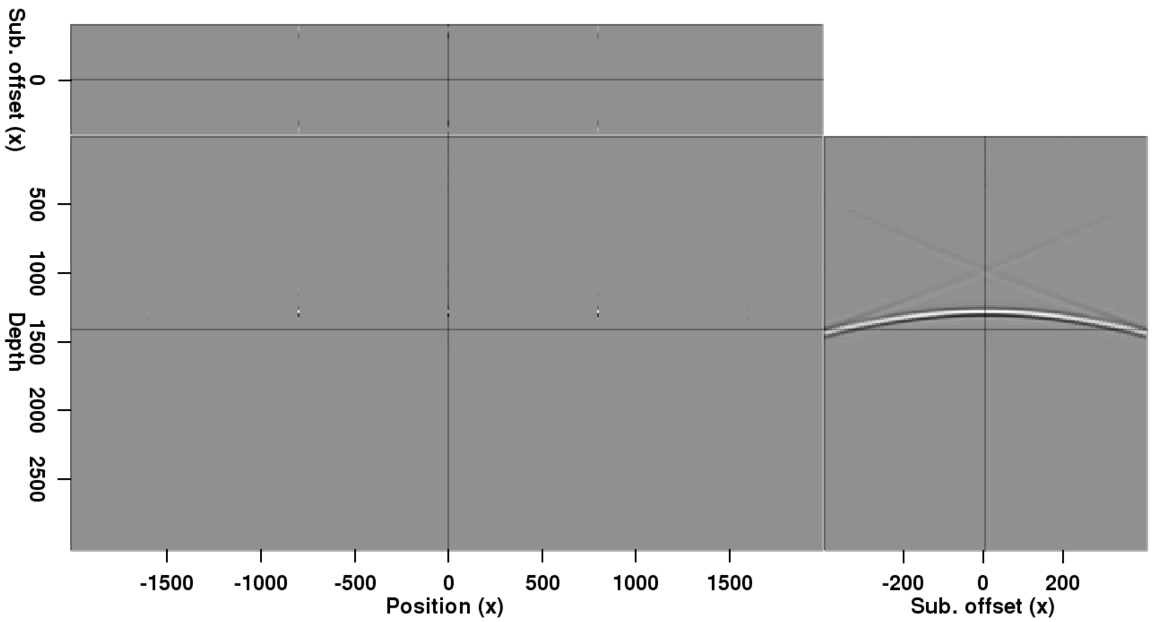


(a)

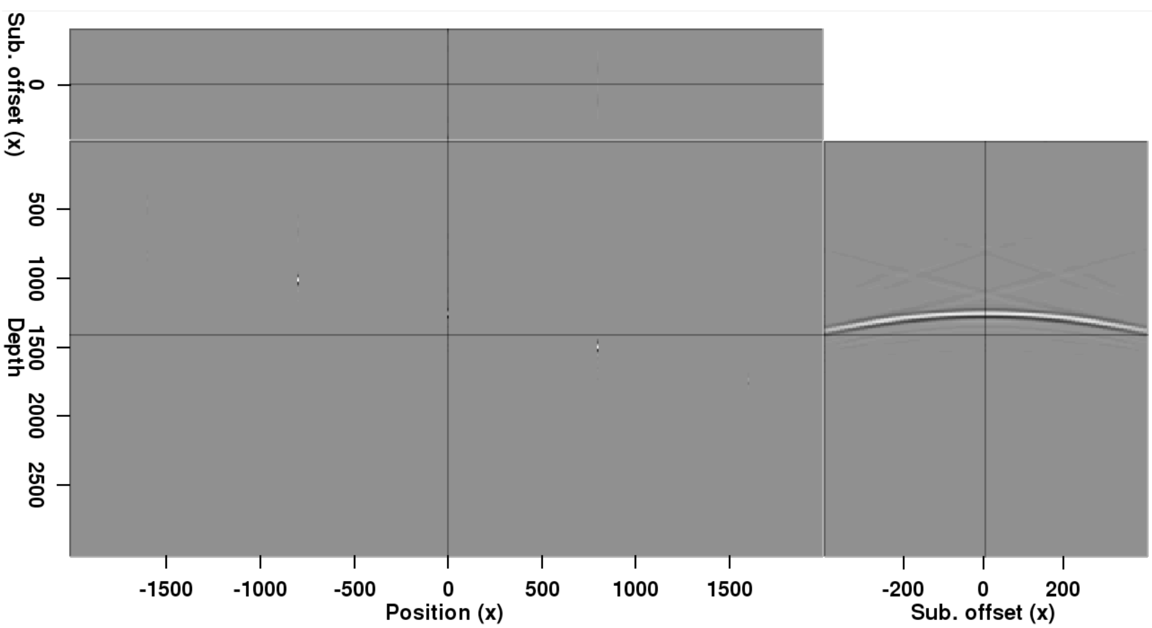


(b)

Figure 2: Prestack depth migration images of (a) a flat reflector and (b) a reflector dipping at a 20° angle. The images were migrated with a constant velocity 15% too slow compared to the true velocity, causing the noticeable artifacts and lack of focusing in the subsurface offset dimension.



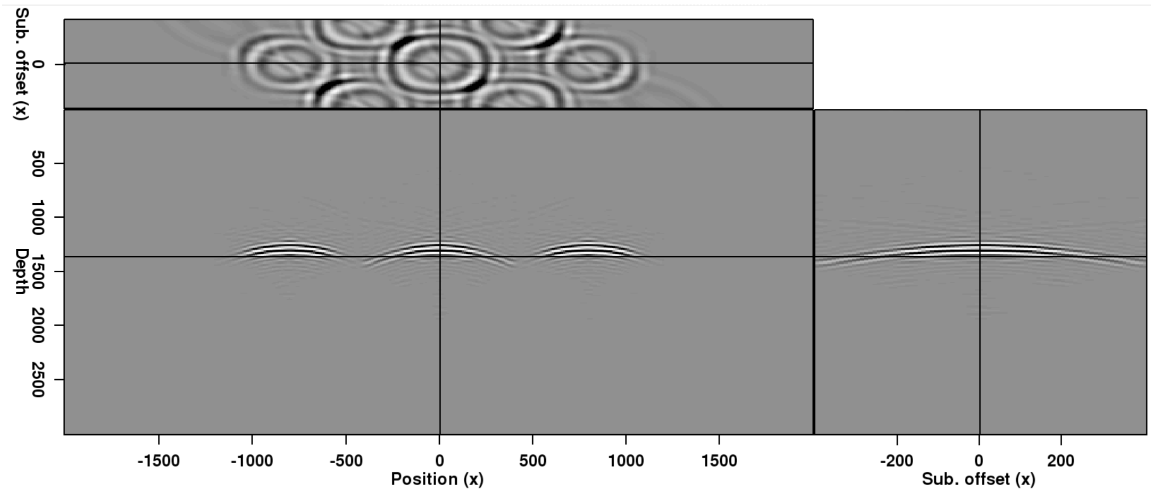
(a)



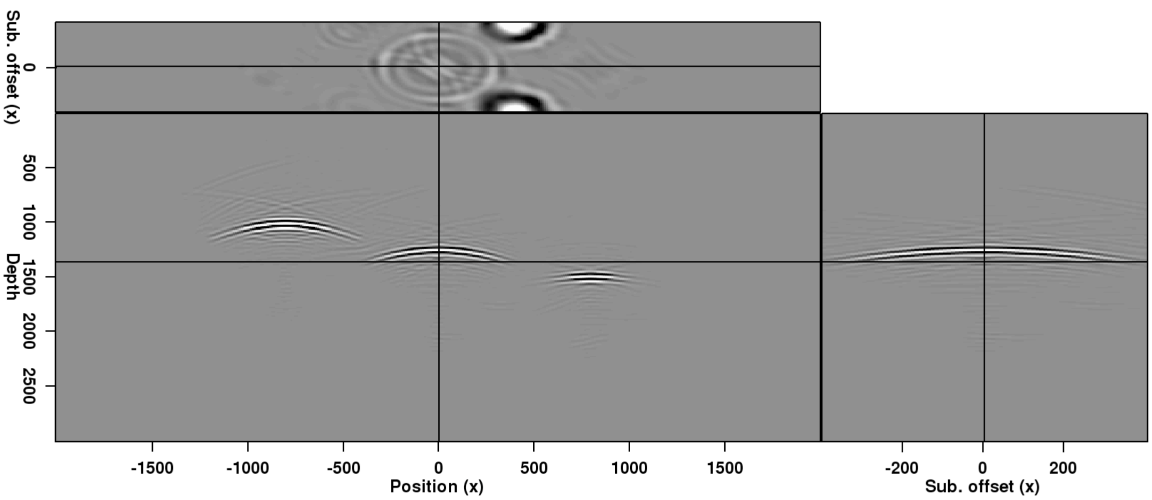
(b)

Figure 3: Isolated image points from Figures 2(a) and 2(b) used for the modeling procedure. The points are separated by twice the maximum subsurface offset value in order to avoid crosstalk artifacts in the modeling.

the modeling process, they are separated by a distance that is twice the maximum subsurface offset, as seen in Figure 3.



(a)



(b)

Figure 4: Migrated images after Born modeling using the images in Figure 3 as the reflectivity model. Although the amplitudes differ, the kinematics of the events in both figures match.

Once the source function is "recorded," Born modeling is performed using the sub-sampled images in Figure 3 as reflectivity models. The results of migrating this Born-modeled data, using the same velocity model used to produce the images in Figure 2, are seen in Figure 4. Because these images were migrated using an areal source function, only a single shot was necessary; this means that the images in Figure 4 were produced in seconds, nearly three orders of magnitude less time than was necessary to compute the images in Figure 2. Comparing the subsurface offset gathers for both of these figures, we see that while amplitudes differ, the kinematics have been accurately preserved in the Born-modeled result. If our goal is to evaluate the velocity model used, the quickly-obtained results in Figure 4 should be sufficient.

The importance of correctly spacing the image points we use for the modeling is illustrated in Figure 5. Here, points from the flat reflector image in Figure 2(a) have been sampled twice as frequently, at a spacing equal the maximum subsurface offset. Figure 5 shows the result of using these points to create the areal source function, and then performing Born modeling and migration as before. Now, crosstalk between the closely-spaced image points results in severe artifacts, including spurious events on the zero-subsurface offset image.

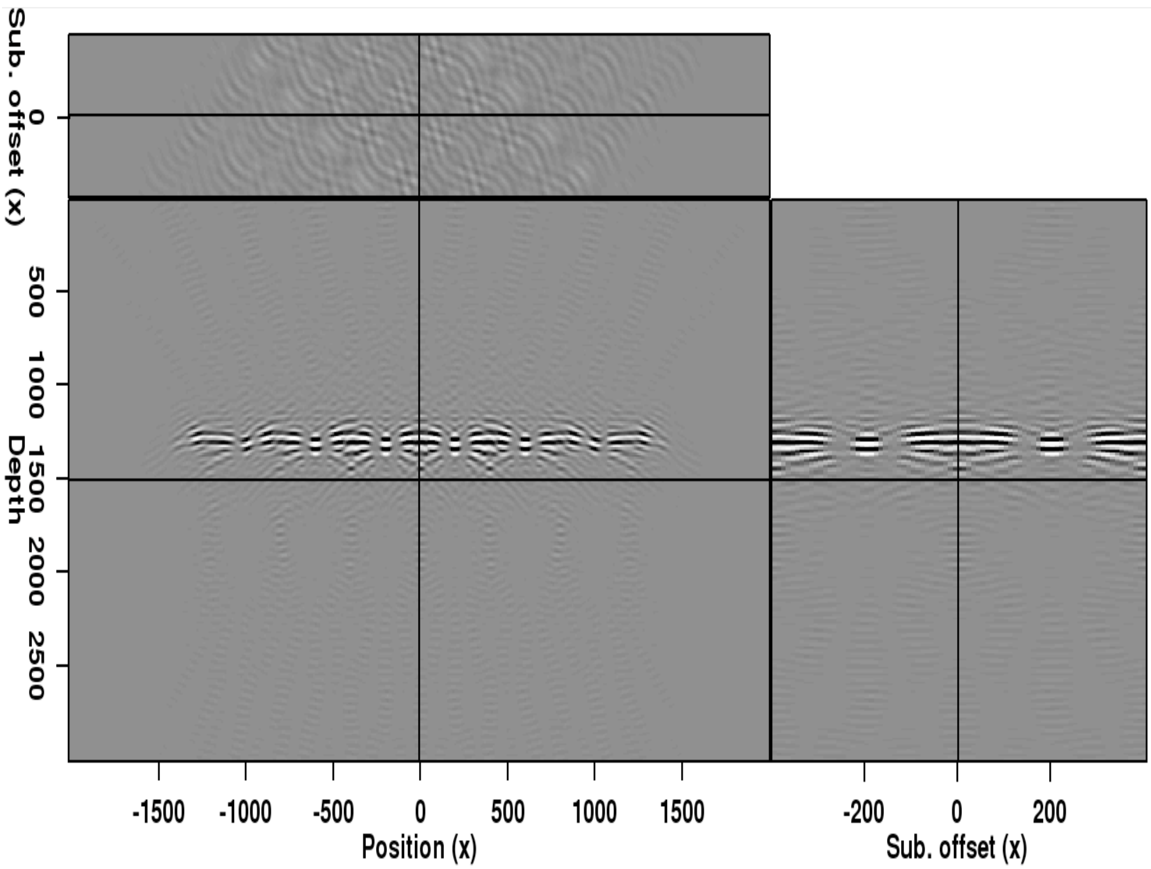


Figure 5: Migration result if the image points sampled from Figure 2(a) are spaced at less than twice the maximum subsurface offset. Crosstalk artifacts dominate the image, making interpretation extremely difficult.

As mentioned in the previous section, an advantage of this Born modeling strategy is that the synthesized data may be recorded at any depth, effectively re-datuming wavefields prior to migration. This can lead to significant computational savings, especially if velocities are well known until a certain depth. To verify that this capability does not effect the accuracy of migration results, we recorded both the areal source wavefield and the Born-modeled data at depth $z = 750$, instead of at the surface. Figure 6 shows the result of migrating this data in the dipping reflector case. Comparison with Figure 4(b) confirms that the two results are virtually identical for the area of interest.

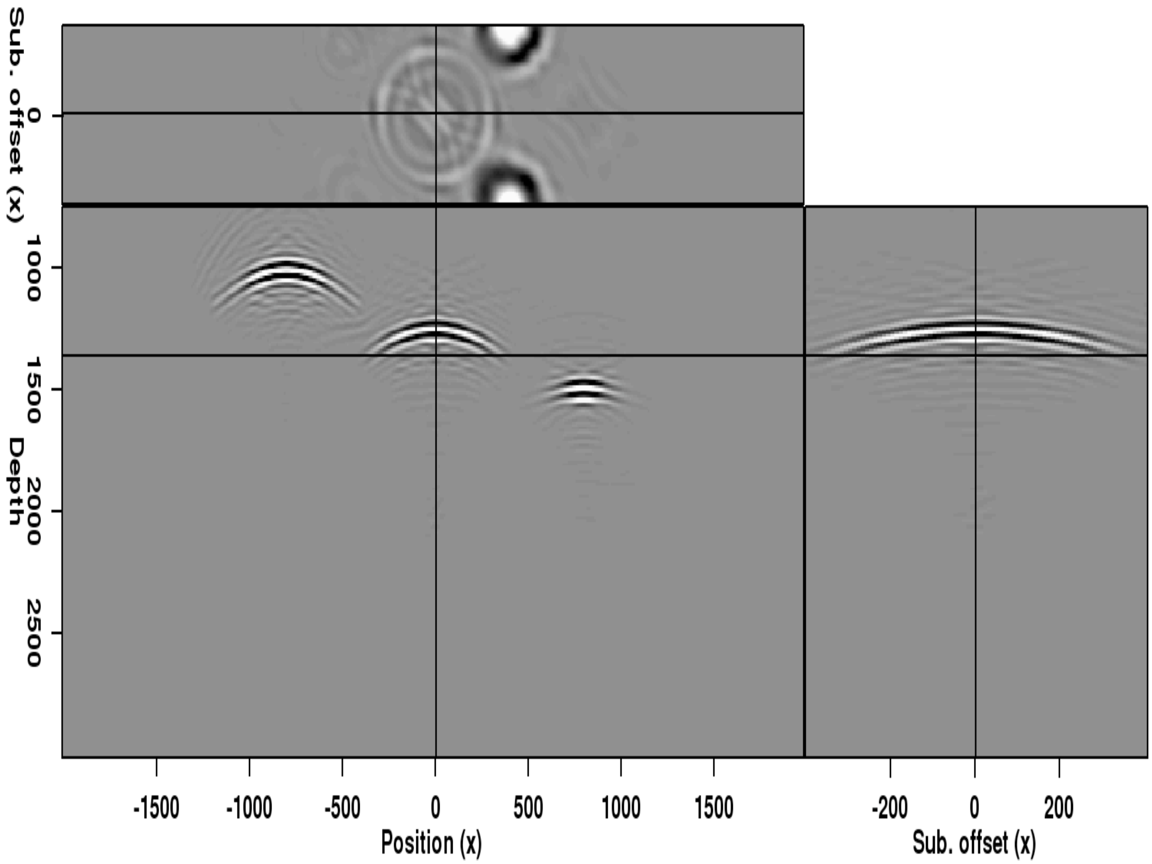
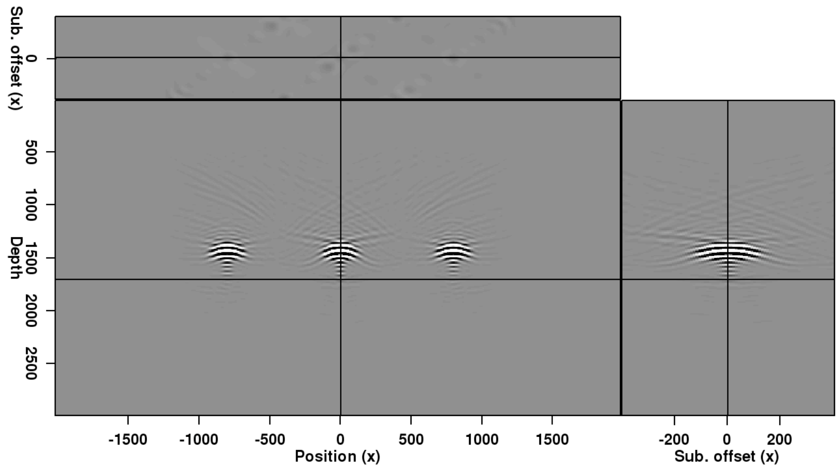
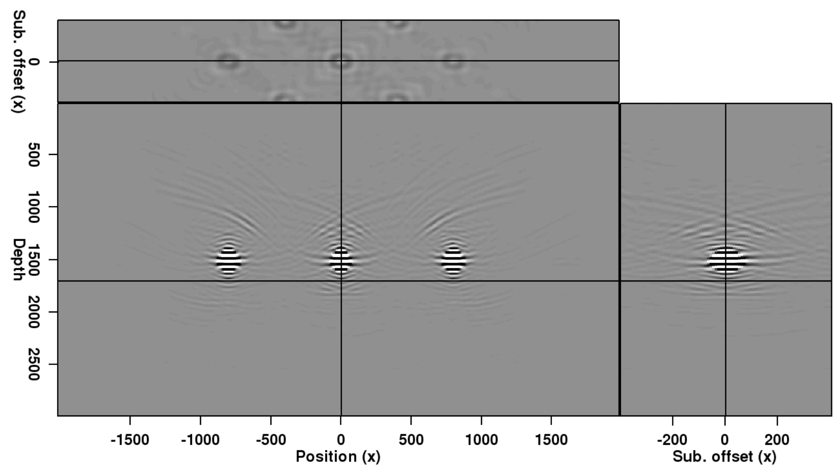


Figure 6: Migration result using Born-modeled data from the model in Figure 3(b). In this case, the synthesized data was recorded in the subsurface instead of on the surface, effectively re-datuming the wavefields.

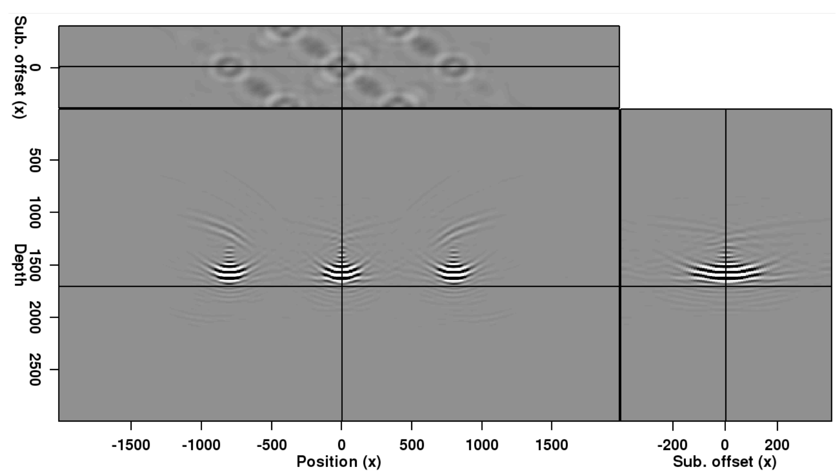
Finally, we wish to test the ultimate purpose of this method: quickly evaluating multiple velocity models. Once the Born-modeled dataset has been synthesized, we can use any velocity model to image the data. Again, we are able to perform these migrations very quickly, on the order of seconds for the examples here. Figure 7 compares the results of using three different velocity models to image the Born-modeled data: one that is 5% slower than the true velocity (Panel a); one that is exactly the true velocity (Panel b); and one that is 5% faster than the true velocity (Panel c). From these results, it is clear that the velocity model used to produce Panel b's result is the most accurate – the subsurface offset gather is flat and relatively focused, and, unlike Panels a and c, there are no signs of over- or under-migration on the zero-subsurface offset image. Because the velocity differences between these three models are relatively small, this is an encouraging sign that this method can ultimately allow us to quickly test more complex models for both synthetic and field data.



(a)



(b)



(c)

Figure 7: Result of migrating the Born-modeled data with (a) 5% too slow velocity; (b) correct velocity; and (c) 5% too fast velocity. Each migration was nearly instantaneous, and the effects of the different velocity models are readily apparent.

CONCLUSIONS

We investigated Born modeling techniques as a means to quickly evaluate multiple possible migration velocity models. By "exploding" subsurface offset gathers from an initial migrated image, we can generate an areal source function with information about the initial velocity model. This source function is used to both generate Born-modeled data from isolated points in the subsurface, and to migrate that data to form an image. While crosstalk issues limit the present implementation of this method to single reflectors, we showed that it can quickly and accurately reproduce the same velocity information (in the form of subsurface offset gathers) obtained from a full migration of the original data. Furthermore, the method allows for re-datuming of wavefields prior to imaging, and can clearly distinguish between velocity models that differ only slightly. With further improvement, this method could form the basis for an efficient and interactive model-building tool.

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