Subsalt Marchenko imaging: A Gulf of Mexico example
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SUMMARY
We apply Marchenko imaging to field data for subsalt structures in the Gulf of Mexico, with emphasis on its effectiveness in eliminating the artifacts caused by internal multiples. We demonstrate a theoretical and practical framework of the Marchenko method for producing a target-oriented subsalt image using marine towed-streamer data, along with a workflow for data preparation and processing. The subsalt image we produced using Marchenko imaging is consistent and comparable, for the most part, with the image produced using Reverse Time Migration (RTM). Significantly, compared to the RTM image, the Marchenko image: 1) shows better continuity and coherence of the subsalt reflectors; 2) improves the clarity and comprehensibility of the sedimentary layers near the salt body; and 3) reveals more structural features below the edge of the salt body.

INTRODUCTION
Marchenko imaging is a technique which aims to produce an image that is free of artifacts caused by multiple reflections. This imaging technique is based on the redatumed reflection response created by a method referred to as Marchenko redatuming, which virtually moves surface seismic sources and receivers to an arbitrary depth in the subsurface, using only surface seismic data and a background velocity model. The redatumed data contains only the reflection response below the redatumed depth, and the medium above is reflection-free. Marchenko redatuming (core of the Marchenko framework) work contains two steps: receiver redatuming and source redatuming (Figure 1). Receiver redatuming, also referred to as autofocusing, aims to retrieve wavefields from sources at the surface to a virtual receiver in the medium using Marchenko-type equations. In the process of receiver redatuming, both the primary waves and the multiple reflections can be accurately estimated and retrieved (Rose, 2002; Broggiini et al., 2012; Wapenaar et al., 2014), moreover, the retrieved wavefields are separated into up- and downgoing components. In source redatuming, these up- and downgoing wavefields are utilized to virtually move the sources to the redatumed level by approaches such as multidimensional deconvolution (van der Neut et al., 2011).

A number of synthetic studies demonstrate and validate the effectiveness of Marchenko imaging in the removal of the artifacts caused by multiple waves (Broggiini et al., 2014; Behura et al., 2014; Singh et al., 2015; Wapenaar et al., 2014; da Costa Filho et al., 2015). Recently, Ravasi et al. (2016) applied Marchenko imaging to field data for producing a subsalt Marchenko image and compare it to a standard RTM image created using the same data and the same background velocity model, and discuss the improvements accomplished in the Marchenko image.

METHODOLOGY
We outline the methodology for the Marchenko framework, including receiver redatuming, source redatuming, and imaging. Readers who do not need the details of the mathematical derivations for receiver redatuming, can treat the Marchenko redatuming process as a black box. Given a background velocity model and the surface seismic reflection response, the black box accurately produces the seismic wavefield recorded at a pre-defined subsurface point (responding to the surface sources) with both primary and multiple reflections. In other words, we can retrieve a virtual reverse Vertical Seismic Profile (rVSP) with surface seismic data and a background velocity model using Marchenko redatuming.

Receiver redatuming (autofocusing)
In this study, we use an iterative scheme for receiver redatuming which is adapted from the work of Broggiini et al. (2014) on the basis of the earlier theoretical Marchenko framework (Rose, 2002; Broggiini et al., 2012; Wapenaar et al., 2014). The heart of the Marchenko redatuming is the convolution- and correlation-type reciprocity theorems, which relate two wave states with dif-
According to the one-way reciprocity theorem, the Green’s functions as the wavefields of state $B$ represent the actual wavefields in the subsurface (upgoing components). The focusing functions (upgoing component $G^-$) are represented by the focusing functions (upgoing component $G^+$). With the up- and downgoing Green’s functions shown are convolved with the responses to impulsive point sources. In our examples, the “Green’s functions” shown are convolved with a Ricker wavelet for display purposes.

According to the one-way reciprocity theorem, the Green’s functions and the focusing functions are related by (Wapenaar et al., 2014; Neut et al., 2014)

\[
G^-(x_i, x_0, \omega) = - f_1^+(x_0, x_i, \omega)
\]

\[
+ \int_{\partial D_0} R(x_0, x_0', \omega) f_1^+(x_0', x_i, \omega) dx_0'.
\]

\[
G^+(x_i, x_0, \omega) = [f_1^+(x_0, x_i, \omega)]^* - \int_{\partial D_0} R(x_0, x_0', \omega) [f_1^+(x_0', x_i, \omega)]^* dx_0'.
\]

Here $G^-(x_i, x_0, \omega)$ and $G^+(x_i, x_0, \omega)$ are the up- and downgoing Green’s functions, with a point source at $x_0$ at the acquisition surface and a receiver at $x_i$ at a desired subsurface location. The focusing functions $f_1^+(x_0, x_i, \omega)$ and $f_1^+(x_0, x_i, \omega)$ are the up- and downgoing parts of the solution for a specified wave equation whose wavefield focuses at the subsurface location $x_i$. $R(x_0, x_0', \omega)$ is the earth’s reflection response. We solve for $G^-(x_i, x_0, \omega)$ and $G^+(x_i, x_0, \omega)$ following the iterative scheme proposed by Broginni et al. (2014); Wapenaar et al. (2014).

Source redatuming

Once the up- and down-going Green’s functions are correctly retrieved, we obtain the redatumed reflection response $\tilde{R}(x_i, x_i', t) = 0$ from the redatumed reflection response $\tilde{R}(x_i, x_i', t)$, and construct an image of the zero-offset reflectivity using

\[
I(x_i) = \tilde{R}(x_i, x_i, t = 0).
\]

SYNTHETIC EXAMPLE

As a preparation for our field data application, we demonstrate and interpret the up- and downgoing Green’s functions retrieved by Marchenko receiver redatuming with a synthetic example. The background velocity model (Figure 3a) is estimated from a GOM field dataset (the dataset that is used in our field data application). In the corresponding density model (Figures 3a and 3b), we add four flat horizontal reflectors with the thickness of 100 m at the depth levels of 3 km, 4 km, 5 km, and 6 km. The density of these four reflectors is 100 $g/cm^3$ smaller than the surrounding areas. We generate 1000 shot records with 361 receivers in each shot record using acoustic finite-difference modeling. The spacing between sources and receivers is set as 26.67 m. This synthetic dataset is simulated to match the field dataset for source and receiver locations.

Using Marchenko receiver redatuming, we retrieve the up- and downgoing Green’s functions for a subsalt point at $x = 12,225$ m and $z = 3,500$ m, which is referred to as the virtual receiver. The retrieved downgoing Green’s function (Figure 4a) can be interpreted as the seismic wavefields that are excited by the surface sources and are propagating downward when they reach the virtual receiver. The first event (labeled with a) in the downgo-
Figure 4: (a) Retrieved down-going Green’s function $G^+$. (b) Retrieved up-going Green’s function $G^-$. (c) Physical interpretation of $G^+$ and $G^-$. 

Figure 5: (a) Marchenko image and (b) RTM image for the area in the green box in Figure 3b.

Figure 6: Work flow for Marchenko imaging

Figure 7: (a) Raw field data. (b) Field data after SRME and source-designature.

FIELD DATA EXAMPLE: GULF OF MEXICO

The 2D marine field dataset we use was acquired over the Mississippi Canyon in the Gulf of Mexico. This area contains a shallow salt body in a deep water environment. A total of 1000 shots were fired along a 26 km source line with a shot spacing of 26.67 m.

Data Processing

We show our work flow to apply Marchenko imaging to this marine streamer dataset in Figure 6. With a background velocity model, we estimate the direct arrivals from each subsurface point in the target zone to the surface by computing the travel time using an eikonal solver based on the fast marching method (Fomel, 1997) and placing a Ricker wavelet at the direct arrival time. For the data processing, we: 1) apply Surface Related Multiple Elimination (SRME) to the surface seismic data; 2) deconvolve the source signature with its bubbles using the sparse log-domain deconvolution approach of Guitton and Claerbout (2015); 3) generate a two-sided dataset based on the source-receiver reciprocity theorem; and 4) calibrate the amplitudes of the field dataset using a scaling factor which is estimated from an amplitude comparison between the field dataset and the numerically modeled dataset. Figures 7a and 7b show a near-offset section of the raw field data and the data after SRME and source-designature.

Field data images

For imaging, we retrieve the up- and downgoing Green’s functions for all the subsurface imaging points inside the target zone (red box in Figure 3a, 4.0 km - 16.0 km horizontally and 2.4 km - 4.0 km vertically). This
target area contains the bottom and the left edge of the salt body, some sediment layers to the left of the salt body, and structures below the salt body. Following equation 3, we create the redatumed reflection response $\tilde{R}(x_i, x'_i, \omega)$ at each depth level. We then produce the Marchenko image by extracting the zero-time zero-offset value $\tilde{R}(x_i, x_i, t = 0)$, as instructed in equation 4.

A comparison between the Marchenko image (Figure 8b) and the image produced using standard RTM (Figure 8a) shows that they are comparable for the most part: both present similar structures for the bottom of the salt body, the structures of the sediment layers to the left of the salt body, and the detailed structures of the subsalt area. Furthermore, we find significant improvements in the Marchenko image: 1) the reflectors are more continuous and smoother (green arrows in Figures 8a and 8b); 2) the structures of the sediment layers to the left of the salt body are more clearly revealed (red arrows in Figures 8a and 8b); 3) additional structural features are revealed (blue arrows in Figures 8a and Figures 8b).

To better understand these improvements accomplished in the Marchenko image, we produce an RTM image for the same target area using the synthetic dataset generated using the models in Figure 3. In this RTM image (Figure 8c), we observe some artificial reflectors who have a shape similar to the bottom of the salt (dashed green arrow in Figure 8c), which indicates the artifacts result from internal multiple reflections at the salt bottom. When these artificial structures interfere with the horizontal reflector at 3 km, the phases of the horizontal reflector are either added or subtracted, creating amplitude discontinuities (solid green arrows in Figure 8c). Hence, the discontinuities in the field-data RTM image (Figure 8a) could also result from the interference between the multiple artifacts and real sedimentary layers. As the Marchenko imaging method correctly handles internal multiples, it is able to produce an image (Figure 8b) that is more continuous and free from the multiple artifacts. The layered structures to the left of the salt body (red arrows in Figures 8a and 8b), revealed both in the RTM image and the Marchenko image, are sedimentary layers beneath the seabed. Note that the amplitudes of these sedimentary layers in the RTM image are suppressed, while the layers are more clearly revealed and more comprehensible in the Marchenko image (red arrows in Figure 8a and 8b). Moreover, Marchenko imaging reveals some structural features (blue arrows in Figure 8b) that are not presented in the RTM image.

CONCLUSION

We successfully apply Marchenko redatuming and imaging to a marine dataset from the Gulf of Mexico. We show that the image produced by Marchenko imaging is more continuous than the RTM image produced using the same dataset and velocity model. Furthermore, the Marchenko method seems able to reveal some structures that cannot be found in the RTM image. We use an RTM image produced with a synthetic dataset to demonstrate that the discontinuities in the RTM image are very likely caused by internal multiples. The improvements in the Marchenko image over the RTM image demonstrate that for field data, the Marchenko framework is applicable and effective in suppressing the artifacts caused by internal multiples.

ACKNOWLEDGMENTS

This work was funded by the sponsor companies of Center for Wave Phenomena. We acknowledge F. Broggini, C. and A. da Costa Filho for helpful discussions.
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