Elastic migration for improving salt and subsalt imaging and inversion
Kun Jiao, Wei Huang, Denes Vigh, Jerry Kapoor, Richard Coates, E. William Starr, Xin Cheng WesternGeco

Summary
In this paper, we investigate the use of elastic migration (reverse-time migration, RTM) to improve the image of highly dipping, subsalt events. We apply acoustic and elastic RTM to two synthetic datasets, where pressure was recorded over elastic models. The elastic migration results clearly show significant improvements including increased continuity and better focusing of highly dipping subsalt events, compared to the acoustic migration results. Furthermore, we explain why and how elastic migration can help subsalt imaging. Finally, we show several real data examples that come from the Gulf of Mexico (GoM).

Introduction
The Gulf of Mexico (GoM) has been a focus for the oil and gas industry since the early 1950s. Seismic imaging is a critical step at the exploration stage to image structure, determine the size of the pay zone and identify drilling targets. One of the biggest challenges of seismic imaging in the GoM is how to identify the geometry of salt bodies and image beneath them (Kapoor et al., 2006; Vigh et al., 2011). During the past decade, the seismic industry has made substantial improvements in both supra-salt and subsalt imaging. Nevertheless, imaging subsalt remains a great challenge.

One obvious limitation of most RTM algorithms is that, despite the fact that Earth is elastic, they treat wave propagation as if it were acoustic. Previously, it was shown that elastic migration can give a more accurate and more promising result than acoustic migration, (Lu et al., 2010). In this paper, we investigate the application of elastic RTM to both synthetic and real data examples.

Elastic wave propagation in a general anisotropic medium is described by the wave equation

$$\rho \frac{\partial^2 u_i}{\partial t^2} - \frac{\partial}{\partial x_j} C_{ijkl} \frac{\partial u_k}{\partial x_l} = f_i$$

where $u_i$ is the displacement component, $\rho$ is the model density, $C_{ijkl}$ is the stiffness tensor and $f_i$ is the source wavelet.

In this study, we use elastic finite-difference modeling (Virieux, 1984; Kelly et al., 1976; Alterman et al., 1968) to calculate the synthetic pressure data sets on two models. These synthetic datasets are then migrated using both acoustic and elastic RTM algorithms. In each case, the exact P-wave (together in the elastic RTM with the exact S-wave) velocity models (without the dipping events) are used for migration. The elastic results show significant improvements in the subsalt image of the highly dipping events.

Model description
We create two 2D elastic models, shown in Figure 1(a) and Figure 4(a). The first is a simple four-layer model, 8 km in depth and 16 km in the inline direction. The first layer is a water layer, acoustic velocity ($v_p$) is 1500 m/s, and shear velocity ($v_s$) is 0. It supports P-wave propagation only. The second and the fourth layers are sediment layers with linear velocity trends ($v_p = 2v_s$), while the third layer represents salt, with $v_p = 4500$ m/s, and $v_s = 2250$ m/s. An acoustic velocity profile is shown in Figure 1(b). In this 1D model, we added a reflecting are below the salt, which provides a gradually changing dipping event from 0° to 75°, as shown in Figure 1(a).

Figure 1: (a) A synthetic velocity model with a subsalt are event. (b) A velocity profile that contains the velocity perturbation are in the subsalt area.
Elastic Migration Improving Subsalt Imaging

The second synthetic model is more realistic of a GoM salt geometry. It is 10 km vertically by 40 km horizontally. Again, we place two arcs vertically below the giant salt body, which represent two very challenging highly dipping subsalt events around the salt keel, shown in Figure 4(a).

The acquisition for the first synthetic model was surface seismic survey; we used fixed-spread-geometry receivers, with 801 sources and 801 receivers, all spaced at 20-m intervals. Recording time was 8-s and 15-s. A 30-Hz Ricker source wavelet was used.

The acquisition for the second synthetic model was also surface seismic survey, but with a towed-streamer geometry. Sources run from 5 km to 35 km with a 50 m interval. The receiver streamer is 8km in length with 25 m sensor spacing. We modeled the acquisition process in both forward and backward directions. Overall, a total of 1282 shots were simulated. We combined modeled data from both directions to achieve a split-spread geometry with 641 shots. The source wavelet was also a 30 Hz Ricker wavelet.

Results and discussion
The first acoustic RTM result was migrated with the 8-s synthetic pressure elastic data and the migration velocity.

The result shows that a partial arc event was imaged only up to 40° dip. The rest of the arc is clearly incomplete, as shown in Figure 2(a).

The 8-s data from the first model were also migrated using the elastic RTM algorithm, with the same (exact) $v_p$ model and the exact $v_s$ model. The elastic RTM result is almost identical to the acoustic RTM result, Figure 2(b). The 15-s data was also migrated by both acoustic and elastic RTM algorithms and the results are shown in Figures 2(c) and 2(d), respectively. While the acoustic result is again almost identical to the previous 8-s data result, the elastic RTM result for the 15-s data, Figure 2(d), differs in one critical respect. The elastic result for the 15-s data shows a much more completed arc than any of the previous images, with dips extending close to 70°.

Understanding this result is important because of the insight of it can provide us into the potential for elastic imaging: when it might improve results, and when it might not. Because the source and receivers in all our models lie in the water layer, we already know that the improvement cannot be due to signals that leave the source or arrive at the receiver as shear waves, as might be the case for land or ocean-bottom cable/node geometries.

The fact that the short recording time (8-s) data migrated with both elastic and acoustic RTM, and the long (15-s) data migrated with acoustic RTM, gave essentially identical results strongly suggests that the extra information is carried in the late-arriving signals that propagate for part of their paths as (slower propagating) shear waves.

In addition to arguments based upon the time of arrival it is also easy to see that unconverted P-P reflections from highly dipping events may never be recorded. It is obvious that the P-wave reflection from the highly dipping event will themselves be traveling at high angles (close to horizontal). To be recorded, these signals must pass back through the salt layer. However, because the P-wave velocity in the salt (4500 m/s) is much greater than that in the sediments (3000 m/s), these high-angle P-waves will be completely reflected by the overlying salt. This argument is equally applicable to P-wave reflections in both acoustic and elastic models and is illustrated in Figure 3.

The same argument also holds for signals propagating as S-waves both in the underlying sediments and salt, because, again there is a large difference in S-wave velocity in the sediment (1500 m/s) and salt (2250 m/s).

However, that argument does not hold for P-wave reflections from the dipping events that are converted to S-waves at the base of salt. In fact, because the S-wave velocity in the salt (2250 m/s) is lower than the P-wave
velocity (3000 m/s) in the sediment, no critical angle exists for these conversions. Thus, P-wave reflections from the highly dipping events, which are converted to shear at the base of salt, may be detected at the surface and are, hence, available for imaging using the elastic RTM algorithm.

This discussion indicates that the information about the highly dipping subsalt events does not exist in the P-wave reflections, but can be present in the converted-wave data provided that we use a sufficiently long recording window. Consequently, elastic migration algorithms are required to image them.

The same tests (acoustic and elastic RTM) are conducted on the second synthetic model. Results are shown in Figures 4(b) and 4(c). The elastic result clearly shows more continuous dipping events toward the salt keel than the acoustic image.

Furthermore, we think all types of elastic migration algorithms, ray-based methods (Chapman, 2004), finite-element-based methods (Hughes, 1987; Marfurt, 1984), should show some improvements in the subsalt and the salt area, not only RTM. However, because RTM is a two-way wave-equation method, it will be one of the most beneficial algorithms. Moreover, because Full Waveform Inversion (FWI) (Crase et al., 1990; Brossier et al., 2010; Vigh et al., 2008) is a similar method to RTM, we should see a similar amount of uplifts in it, also.

Real Data examples
We also run elastic and acoustic RTM on a 16s real GoM dataset, with the shear velocity derived from the Mudrock relation (Castagna et al., 1985). Comparing both elastic (Figures 5(b), 5(d) and 5(f)) and acoustic (Figures 5(a), 5(c) and 5(e)) RTM images, we can see, in the elastic RTM results, some salt flank and base of salt reflectors that are more continuous and more focused. As we expected, some highly dipping subsalt events show up in the elastic migrations, which are missing from the acoustic images, in Figures 5(a), 5(c) and 5(e).
Elastic Migration Improving Subsalt Imaging

Conclusion
We develop two synthetic models to show that elastic migration can improve the subsalt image, especially the highly dipping events where acoustic migration obviously fails. However, to benefit from elastic migration, we need longer acquisition time to record the converted waves, and further migrate it. Finally we show some encouraging results on a real GoM data set. Furthermore this type of uplift should not only exist in elastic RTM, but also other elastic algorithms, for instance, elastic FWI. Essentially, the converted-wave migration also requires a fairly accurate shear velocity model, but how sensitive the migration depends on it is not discussed in this paper.

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EDITED REFERENCES
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REFERENCES


