Introduction

In the deep-water Campeche Bay area of the southern Gulf of Mexico, we have complex shallow salt bodies and carbonate rafts. Figure 1 (left) is a map view of the elevation of tops of shallow salt and carbonate geobodies in the study area. Figure 1 (right) is an area map of the study area. The high impedance contrast between these shallow geobodies and the surrounding sediments generate a great deal of high-amplitude, coherent noises that complicate imaging and interpreting base of salt and subsalt events.

Figure 1 On the left is a map view of the elevation of the top of the shallow salts and carbonates; on the right is the area map of the study area, located in the southern side of the Gulf of Mexico.

For noise modeling and attenuation, Dragoset et al. (2010) demonstrated a data-driven method for surface-related multiple attenuation (SRME). An extended internal multiple prediction method (XIMP) was also developed to model interbed/internal multiple (Wu and Dragoset, 2011). The data-driven methods, SRME and XIMP, only model certain types of coherent noises, namely surface-related multiple and certain interbed/interbed multiple between specified horizons. Model-driven methods, such as 3D ray tracing (Lu et al., 2003) and a dual-leg acoustic forward modeling method (Huang et al., 2013; Kobylarski et al., 2015; Hegazy et al., 2017), have been used to model converted-wave-related noises. Other model-driven methods include one-way wavefield downward extrapolation modeling (Stork et al., 2006) and image-domain multiple attenuation (Tang et al., 2014). These methods can predict multiples and converted-wave energies using both primaries and user-prescribed raypath patterns. However, they only model the traveltimes of these coherent noises and require a different velocity model and a separate simulation for each user-specified raypath pattern.

Method

In this case study, we use elastic forward modeling and a geological model to model salt- and carbonate-related coherent noises without a prescription of raypath patterns and remove these noises in the image domain. Elastic forward modeling, although much more expensive than acoustic forward modeling or ray-tracing modeling, represents a more realistic scenario because it can model complicated wave propagation and all types of conversions caused by the shallow noise generators. We migrate the modeled synthetic data to generate a noise model in the image domain. We then apply the techniques in machine learning to pattern-match the noise model with the image volume of the field data (Vercauteren et al., 2008). The outcome of the machine learning approach is a 3D displacement vector volume that measures the difference between the same features that coexist in both image volumes. The displacement vector volume can then be used to translate and twist the noise model volume to reduce kinematic errors between the two image volumes. This is followed by subsequent adaptive subtraction and attenuation.

We also experimented with noise attenuation on the prestack depth-migrated data (offset volumes). We generate reverse time migration (RTM) surface offset gathers (SOGs) for both the noise model and the field data and match them against each other, offset-by-offset. We use an attribute-based method (Neelamani et al., 2010) to remove these noises in each offset plane. Finally, we stack the SOGs to obtain the final enhanced image.

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Data processing and results

The input data for this case study is in the Campeche deep-water area and comprises approximately 320,000 wide-azimuth shots covering an output area of around 7,500 km². The maximum cable length is 9000 m. We used the same geometry as the field input data to generate elastic synthetic data.

The geological model is constructed using the following interpreted horizons: the water bottom, top Miocene, the shallow salt bodies, and carbonate rafts all up to a depth of 5,000 m. We use a legacy velocity model for P velocity because this work is done in parallel with the velocity model building process. The density property is calculated using a fitted function derived from nearby well data. The salt bodies and carbonate rafts were interpreted on the seismic volume migrated with the P-wave velocity model. The S-wave velocity is set to zero inside the water. We insert one layer of sediment with a low S-wave velocity between the water bottom and the top Miocene horizon to mimic the soft mud encountered just below the water bottom. Figure 2 shows a depth section of the elastic model properties (P-wave velocity, S-wave velocity, and density) used for the elastic forward modeling. It is worth noting that the model only contains the following primary reflections including the water bottom, salt interfaces, carbonate interfaces, and top Miocene horizon, and none of the primary events is below the base of salt.

![Figure 2](image)

*Figure 2* Vertical section of the geological model. The top panel is the P-wave velocity property; red are salt bodies, and orange is carbonate rafts. The middle panel is the density property. The bottom panel is the S-wave velocity property.

Using the elastic model and field data geometry, we generate elastic synthetic shot records over the whole area. We also perform ray-tracing modeling using source and receiver positions from a single streamer cable to generate traveltimes for a few prescribed events (Figure 3 (right)). By plotting the traveltimes on top of the field seismic data, we can identify primary reflections and converted-wave-related energies at the salt interfaces in the field data (Figure 3 (left)) and synthetic data shot record (Figure 3 (middle)). One thing to note is that the converted-wave-related noises are not separated from primaries in the shot records, which makes attenuation in the data domain very challenging.

![Figure 3](image)

*Figure 3* The left panel is field shot record with ray-tracing traveltime (key events) overlaid; the middle panel is synthetic shot record and, on the right, are the simulated raypaths for the key events, including
primary reflections from top and base of salt and several conversion modes happening at base of salt PSPP, PPSP, and PSSP.

However, in the image domain, we can easily separate noises and signals because we intentionally put no primary reflections in the subsalt in the model and, as a result, all subsalt energies are noises. To do this, we first migrate both the field data without SRME applied and the elastic synthetic data to output RTM SOGs. We refer to the seismic images from field data as the field data and the seismic images from the elastic synthetic data as the model data. By comparing the field data and the model data (Figures 4A and 4B), we can identify the noises in the field data. The noise energies are the ones that show up in both volumes; however, there is a misalignment between the two due to kinematic errors introduced by inaccuracies in the velocity model. To better align these noises in both data, we first calculate 3D displacement vectors (plotted as red arrows in Figure 4C) between the field data and the model data and apply these vectors to the model data to ensure that it is best aligned with the field data for optimal noise subtraction and/or attenuation. Figure 4D, shows the field data after the elastic noise attenuation. We removed most of the salt-related noises, including surface-related multiples, internal/interbed multiples, and converted-wave related energies, and some other coherent noises of complex raypaths. We observe that there are some high-frequency residuals left in the field data due to the limited frequency band used in the elastic forward modeling. In addition to the first experiment, we also applied the same attenuation process to field data with SRME applied. These examples are shown in Figures 4E and 4F. We obtained even better results with the help of SRME processing (making adaptive subtraction in image domain easier).

**Figure 4** Panel A is the migrated field data without SRME applied for a near-offset plane; Panel B is the migrated noise model. Here, coherent noises are marked with a red M.; Panel C is the 3D displacement vector field, calculated to best align the model data with the field data; Panel D is the filtered seismic data after elastic noise attenuation; Panel E is the migrated field data with SRME applied; Panel F is filtered seismic data using the volume displayed in 4E as input.

Finally, we stack the offset planes after noise attenuation to derive the final field data image (Figure 5). We can remove the coherent noise in the production RTM image (red dash line) and reveal the true subsalt structure (green dash line).

**Conclusions**

In a large area of the Campeche deep water, the complex shallow salt and carbonate bodies generate a great deal of high-amplitude noises that make interpreting base of salt and subsalt events very difficult.
We successfully tested a new method of using a geological model and elastic finite difference to model and attenuate these noises in the final RTM images. We applied pattern matching/machine learning to aid the adaptive subtraction and attenuation of elastic noises, either in the offset domain or in the final stack. Our method works best if applied after SRME or XIMP, but it can also be applied directly to input field data. We see good improvement in field data subsalt. The elastic noise model is also of great utility for interpreters in delineating real reflections from noises subsalt.

**Figure 5** Left is the production RTM image with SRME applied, the middle panel is the noise model in the image domain, on the right is the final image after elastic noise attenuation.

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**References**


