Application of interbed multiple attenuation in the Santos Basin, Brazil
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Summary
Imaging of pre-salt reservoirs in the Santos Basin can be significantly affected by the presence of strong interbed multiples in the data. These multiples can be predicted using a data-driven, true azimuth convolution method similar to surface-related multiple elimination (SRME), and removed using a suitably constrained subtraction technique. We discuss the application of this method to Santos Basin data, and present initial results on both synthetic and real data from the Tupi oilfield.

Introduction
The Santos Basin, offshore Brazil, has emerged as one of the most exciting exploration prospects in recent years. The discovery of Tupi in 2006 confirmed the potential of the pre-salt play. Since then, new pre-salt discoveries have followed in quick succession: Sugarloaf in 2007, Jupiter and Iara in 2008, and Azulao and Iracema in 2009. Further test drilling after the initial discoveries at Tupi, Jupiter, and Iara have indicated billions of barrels of light sweet oil in each field. With reserves of this size, there is considerable interest in overcoming the unique challenges of imaging in this region.

One of the unique challenges to seismic imaging in the Santos Basin is the presence of strong interbed multiples. An example of these multiples can be seen in Figure 1(a), which shows near offset data from a line near the Tupi discovery. Note that the first surface-related multiple appears well below the pre-salt target. Strong interbed multiples, however, contaminate the pre-salt primaries.

interbed multiples are generated by a series of impedance contrasts above the target. First, the water bottom is strongly reflective. Between water bottom and top of salt, another impedance contrast appears at the unconformity with the older, faster sediments in the Albian layer. Finally, the layered evaporite salt structure introduces a series of impedance contrasts within the salt. All these reflectors above the target can contribute towards generating strong interbed multiples.

The interbed multiples can have an apparent velocity that is very similar to the primaries. Migration of the multiple-contaminated data therefore produces migration artifacts that cut across real events. A sample Kirchhoff migration result from this area is shown in Figure 1(b). Migration artifacts extend from beneath the layered evaporite sequences and across base of salt. In some areas, the artifacts can interfere with fault interpretation in the target.

Several methods have been proposed for attenuating interbed multiples. We review some of these methods, and discuss our own data-driven, true azimuth method. We then present initial results from the application of our method to synthetic and real data from the Santos Basin.

Methodology
Interbed multiple attenuation methods include model-based and data-driven approaches. The simplest of the model-based methods is move-out discrimination. This method attenuates events whose move-out on CMP gathers is not consistent with the local velocity model. This fails in areas

![Figure 1](https://example.com/figure1.png)

(a) Near offset data.  
(b) Kirchhoff migration

Figure 1: Interbed multiples in data from the Santos Basin. Note the strong interbed multiples obscuring the pre-salt target in the near-offset data. The first surface-related multiple appears at the bottom of the figure, below the target. The migrated image shows migration artifacts crossing the base of salt and interfering with fault interpretation in the target.
Interbed multiple attenuation in the Santos Basin

with complex structure, as well as when multiples and primaries have similar move-out (El-Emam et al., 2005). More sophisticated model-based methods include wave extrapolation and illumination inside a migrated volume to generate a multiple model (Pica and Delmas, 2008). The success of any model-based method, however, depends on accurate information about the subsurface. This is the motivation behind the search for a data-driven interbed multiple prediction procedure.

SRME works well because a dense sampling of the surface wavefield can be easily obtained from the recorded data. For interbed multiple prediction, however, the wavefield at the downward reflector is not directly recorded. Berkhourt and Verschuur (1997) approached this problem by using common-focus-point (CFP) operators to downward-continue the data to the multiple generating horizon. Multiple prediction in the downward-continued data is then a simple SRME-like convolution. The drawback to this method is the dependence on exact CFP operators. Jakubowicz (1998) removed this dependence by introducing an intermediate cross-correlation with the downward reflecting primary. With Jakubowicz’ method, interbed multiples can be modeled directly from the data recorded at the surface.

The method we used is similar to the one described by Jakubowicz, as illustrated in Figure 2. A horizon is interpreted to separate the multiple generating events. The interbed multiple prediction is then given by equation 1, following Jakubowicz (1998).

\[ P_{ikm} = P_i^* P^* P_{km} \]  

(1)

Where \( P \) refers to the wavefields from horizons \( l, k, \) and \( m \), and \( P^* \) refers to the complex conjugate of \( P \). Equation 1 neglects the source term and the surface reflectivity which can both be compensated for using a least squares matching filter during the subtraction stage. It also includes both primary and higher order multiple contributions to the interbed multiple prediction with the latter having more complicated source and reflectivity terms. The task of source-term compensation falls upon the subtraction.

Some of the challenges of this method include computational cost and aperture definition. The required aperture must capture the secondary source location, \( S' \) from figure 2, and the secondary receiver location, \( R' \). It also needs to be carefully constrained as aperture definition is critical for accurate, alias free prediction.

Application

Interbed multiple prediction was performed on 2D synthetic data and on real data from a line near the Tupi discovery. The synthetic data was generated by acoustic modeling using a velocity taken from the real data model-building result. The initial density model was derived from this velocity via Gardner’s equation. The density was then iteratively updated until the synthetic data closely resembled real data. The final density model is displayed in Figure 3. The synthetic data is compared to the real data in Figure 4(a) and (d). The close resemblance between the synthetic and real datasets allowed for a direct confirmation of the results seen in the noisier real data.

Interbed multiple prediction in both datasets was performed using the water bottom as the downward reflecting horizon. Subtraction results on two channels from the synthetic dataset are presented in Figure 4(a)-(c). Multiples below base of salt are well attenuated, with little damage to deep primaries. Real data results are shown in Figure 4(d)-(f). The difference shows good removal of the stronger multiples, especially under minibasins.

Some residual multiples under minibasins remain in both datasets after subtraction. The shorter period of the residual multiples suggests that these could be generated by downward reflections from the closely-spaced evaporite layers. This indicates that further iterations of interbed multiple prediction are required to model multiples from deeper horizons.

To test the effect of interbed multiple attenuation on the final image, migration comparisons were run. Figures 5(a) and (c) compare reverse time migrated (RTM) stacks on the synthetic data. Kirchhoff migration of a few near offsets from the real data is compared in (b) and (d). Migration of the input data in both cases leaves several strong migration artifacts in deep data, along with a series of weaker migration artifacts that cross base of salt. After attenuation of the multiples reflecting downward from water bottom, most of the widely-spaced stronger artifacts disappear. The weaker remaining artifacts are more closely spaced, and appear to be related to reflections from the evaporite layers.

Conclusion

In this paper, we demonstrated the impact of interbed multiples on the imaging of pre-salt reservoirs in the Santos Basin. We then reviewed some of the available attenuation methods, and discussed the application of a data-driven, true azimuth method to Santos Basin data. Initial results were presented, showing attenuation of multiples reflecting downward from water bottom. Additional iterations are required to predict multiples generated at deeper horizons. However, the migrated image is already improved with the first iteration, showing the potential value of interbed multiple attenuation for data from this region.
Interbed multiple attenuation in the Santos Basin

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Figure 2. Modeling multiples on trace \( SR \) reflecting downward from horizon \( k \).

Figure 3. Density model used to create the synthetic dataset.

Figure 4: Interbed multiple subtraction in channel domain.
Figure 5: Migration results before and after interbed multiple attenuation. Each image displays 15 km horizontally.