Applications of interbed multiple attenuation

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Surface-related multiple attenuation schemes have proven useful in attenuating a significant proportion of the high-amplitude multiple content in seismic data. Although generally sufficient for exploration purposes, there is growing recognition that more complicated interbed multiples exist within the data and that they may interfere with the interpretation of reservoirs and other areas of interest. In this paper, we examine a data-driven method and a model-driven method for attenuating internal multiples showing both synthetic and real-world examples of their application.

Introduction

Interbed multiple contamination has been observed previously during reservoir studies from the North Sea, Middle East, and Asia Pacific regions, where shallow carbonates or volcanics generate strong reverberations. Frustrating to all parties, this noise has, for a long time, been categorized as “too difficult” to address because it resists traditional multiple attenuation methods; the multiples and primaries have similar moveout reducing the effectiveness of Radon-based methods, the multiples and primaries have similar frequencies and amplitudes reducing the effectiveness of predictive filtering, and the multiples and primaries have similar dips reducing the effectiveness of f-k filters, tau-p demultiple, and migration methods implementing dipdiscrimination techniques during the imaging (for example, controlled-beam migration).

The discovery of the Tupi/Lula Field, offshore Brazil, in 2006, and later discoveries of Jupiter, Sugarloaf, Iara, Azulao, and Iracema have confirmed the potential for significant, presalt, oil accumulations in the Santos Basin. One of the seismic imaging challenges in the basin, however, is the existence of high-amplitude interbed multiple contamination across the reservoir. An example can be seen in Figure 1 which shows a migrated image.

Figure 2 shows near-offset data from a second line in the Santos Basin. Note that the first surface-related multiple appears well below the presalt target. Strong interbed multiples, however, contaminate the presalt primaries. The interbed multiples are generated by a series of strong reflectors above the target. The water bottom, top of Albian layer, top of salt, and layered evaporites can all contribute toward generating strong interbed multiples. The strongest of these multiples appear below syncline structures in the top of salt and layered evaporites, due to a focusing effect that traps multiple energy in the minibasin (Pica and Delmas, 2008). The migrated results, Figures 1 and 2b, show the interbed multiples cross-cutting the reservoir. These interfere with the interpretation of the base of salt event, the reservoir, and the presalt faulting.

Following the advent of data-driven surface-related multiple attenuation by Berkhout et al. (Berkhout and de Graaff, 1982; Verschuur, 1991; Berkhout and Verschuur, 1998), many authors have extended the data-driven concept to include interbed multiple attenuation. Many methods based on the work of Jakubowicz (1998) have appeared in the literature, for example Ikelle (2004). These all require a two-trace convolution followed by a single-trace correlation or some combination thereof. Equivalent model-driven methods also exist based on the same concept, notably from Pica and Delmas (2008). The concept has also been converted to the inverse data space by Luo et al., (2007). The implicit limitation of this method is that it predicts only internal multiples associated with a single horizon, typically defined inside a single layer, predicting internal multiples from the surrounding reflectors that will cross this horizon along their path.

A second extension to the data-driven internal multiple attenuation methods, again pioneered by Berkhour et al., (Berkhout and Verschuur, 1997 and 1999; Berkhout, 1999), utilizes common focal point transforms (CFP) to partially redatum (receiver side) and fully redatum the input seismic to the level of the multiple-generating horizon. The method is similar to Jakubowicz’s method in that it requires a two-trace convolution followed by a single-trace correlation and predicts only the multiples associated with a single horizon or layer, but it also requires two redatuming steps and the associated CFP operators. Kelamis et al. (2002) and Ala’ai et al. (2006) demonstrated this method on land data highlighting the difficulty associated with the estimation of the CFP operators.

Yet another method of internal multiple attenuation has been pioneered by Weglein et al. (1997) using the inverse-scattering series. This method is again fully data-driven but has the added benefit of being capable of predicting all interbed multiples in a single iteration, (Weglein et al., 2008). Depending upon the implementation complexity, it is possible to predict either an approximation to the internal multiples (leading term), or through an infinite series, the exact internal multiple contribution, (Ramirez, 2008). This method has been previously demonstrated on marine data by Otnes et al. (2004) and on land data by Fu et al. (2010).

With the exception of these inverse-scattering infinite series, all these methods rely upon some form of adaptive subtraction in order to attenuate the internal multiple. This has a plethora of problems associated with it, foremost of which is potential primary damage. None of these issues are covered in this paper—see Abma et al. (2002) for a detailed analysis of adaptive subtraction techniques.

This paper describes the application of two of the above

Figure 1. Migrated image showing strong interbed multiples in data from the Santos Basin. (Courtesy of Petrobras)
methods for attenuating internal multiples: a 3D data-driven method derived from Jakubowicz, and the 3D model-driven method from Pica. The focus is on the interbed multiple contamination at the reservoir level for various exploration interests within the Santos Basin, Brazil. The results, however, are equally applicable to reservoir-level contamination observed in the North Sea, Middle East, and Asia Pacific.

Methodology

Many factors influence the effectiveness of the various internal multiple attenuation algorithms; geological complexity (multiple periodicity) and acquisition design (offset coverage and spatial sampling) are two key factors. It is then not surprising that the application of any algorithm should first consider the input limitations.

The 3D data-driven method, following Jakubowicz, is illustrated in Figure 3. An arbitrary horizon is chosen at a point deeper than the known multiple-generating horizon. The internal multiples predicted are then limited using various muting methods but are always those having the first upward reflection below the user-defined horizon, a downward reflection above the user-defined horizon, and a final upward reflection below the user-defined horizon. The prediction is given mathematically in Equation 1.

\[ P_{212} = P_2 \cdot P_1 \cdot P_3 \] (1)

\( P_1 \) refers to the wavefields from the surface to the multiple-generating horizons, \( P_2 \) refers to the source-side wavefield reflecting from below the multiple-generating horizon, and \( P_3 \)
Multiple attenuation refers to the receiver-side wavefield reflecting from below the multiple-generating horizon. P_1^* refers to the complex conjugate of P_1. Equation 1 neglects both 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. The task of localized wavelet matching falls upon the subtraction.

Without knowledge of the downward reflection point, however, it becomes necessary to sum Equation 1 over a user-defined aperture. The method places a high reliance upon the input acquisition density. For accuracy, it requires shot and receiver stations at all possible surface locations as well as measurements of the wavefield at zero offset. Not surprisingly, these are the same limitations found in the surface multiple implementation and, as such, the method is found to work reasonably well in deeper water where the near offsets can be easily extrapolated and in wide-azimuth acquisitions where the azimuthal sampling is closer to ideal.

The 3D model-driven method also follows the logic of Jakubowicz. In it, the input data are backward-propagated though a predefined model to the user-defined arbitrary horizon (Figure 4). The horizon is defined in the same way as in the data-driven method. Prior to the back-propagation, the input data must first be muted to remove all reflections above the target horizon. Once at the target horizon, the wavefield is upward extrapolated through the model to illuminate the shallow events, thus identifying the downward reflection points in Figure 5.
For each possible reflection point, the wavefield is downward propagated through the model a second time until it reaches the reflecting horizons (Figure 6) where it is finally forward propagated to the surface (Figure 7). The entire procedure mimics the data-driven case but has two distinct advantages; it doesn’t require a dense shot sampling on the surface, and it doesn’t require records at zero offset. It does, however, require a reflectivity and velocity model.

**Application**

3D data-driven interbed multiple prediction was performed on 2D synthetic data and on 3D real data from the Santos Basin. With 3 s of water and shallow multiple generators, these data were well suited to the data-driven interbed algorithm. The syn-

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**Figure 10.** Kirchhoff comparison of Santos Basin 3D data: (left) before and (right) after data-driven interbed multiple attenuation. (From Hembd et al., 2011)

**Figure 11.** Migrated comparison of Santos Basin 3D data: (left) before and (right) after model-driven interbed multiple attenuation. (Courtesy of Petrobras)
thetic data (Figure 8) were generated using an acoustic wave-equation modeling package, a velocity field extracted from the 3D real data processing, and an arbitrary density model. The interbed multiples were predicted using the water bottom (at approximately 3 s) and the top of salt horizon (at approximately 4 s) as the multiple generators. Figure 9 shows the synthetic results after migration highlighting the impressive attenuation of the strongly focused interbed multiples beneath the minibasins.

The real data results (Figure 10) were generated using a single iteration of interbed multiple prediction targeting the water-bottom multiples. Analysis of the postmigration interbed attenuation results shows a considerable reduction in the subsalt migration noise (attributed to interbed multiples). However, some residual multiple-related events are visible on the real data cross-cutting the base of salt. Although the subtraction is by no means perfect, these residuals are most likely related to an imperfect or incomplete prediction. Interbed multiples generated from the top of salt horizon and from the layered evaporate horizons remain unaccounted for.

3D model-driven prediction was also performed on the real data to target the intrasalt multiples (Figure 11). The reflectivity model was obtained through prestack time migration of a few near offsets and the arbitrary reference horizon was chosen 100 ms below the top salt (hence, considered the principal downward reflector). All reflectors down to 1 km below top salt were considered as potential upward generators. A minimum gap separating upward and downward reflectors was also used. This corresponds to the shortest leg of the modeled multiple and is needed to avoid modeling primary signal. After modeling, a conservative 3D adaptation and subtraction was performed in the offset domain. The results (Figure 11) show a promising attenuation of some events cross-cutting the base of salt and slightly improved continuity on some targeted presalt events.

Conclusion
In this paper, we have demonstrated the impact of interbed multiple attenuation on synthetic and real data from the Santos Basin. It has been shown that clearer images of the reservoir zone can be obtained by attenuating the influence of shallower, internal multiple-generating horizons in an informed and deliberate fashion. The choice between data-driven and model-driven prediction is shown to be one of convenience with both methods performing admirably.

References
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