The multiple attenuation toolbox: Progress, challenges and open issues

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SUMMARY

This paper describes recent progress in attenuating free surface and internal multiples for marine and on-shore plays. While there is much to celebrate within the multiple attenuation toolbox, with recent progress and improved capability, there are also significant fundamental open issues and practical challenges that remain to be addressed.

INTRODUCTION

Multiple removal is a longstanding problem in exploration seismology. Although methods for removing multiples have advanced and have become more effective, the concomitant industry trend toward more complex exploration areas and difficult plays has at times outpaced advances in multiple-attenuation capability. The topic of multiples, and the need for developing ever more effective methods for their removal, remains high in terms of industry interest, priority and research investment.

We advocate a tool-box approach and orientation for understanding: (1) overall multiple attenuation capability, and (2) the place and role that each method within the toolbox plays within the spectrum of different capabilities and responses, and (3) how to choose the method that's a best match for the user's application and objective. In this paper, we present a status report on the multiple attenuation toolbox and the open and prioritized issues yet to be addressed.

THE MULTIPLE ATTENUATION TOOLBOX

Among the current methods within the multiple attenuation toolbox, we will focus on: (1) Radon transform, (2) DELPHI feedback methods, and (3) the inverse scattering series approach. These methods were chosen because they each represent different assumptions and knowledge of subsurface properties, and the reflectors that have generated the multiples.

As we move from Radon, to feedback, to inverse scattering series (for free surface and internal multiples), the need for subsurface information and user intervention decreases and the commensurate cost increases. The cost-effective and appropriate choice depends on the complexity of the geology, the data, and your processing objective. If one can well estimate the velocity of primaries and there is sufficient moveout between primaries and multiples then Radon methods are often the indicated choice (Foster and Mosher, 1992; Trad et al., 2002, 2003; Nowak and Imhof, 2006; Abbad et al., 2011). If the free surface multiples are isolated (and temporally distinct from primaries) the SRME (from DELPHI) plus Radon followed by adaptive subtraction is an effective strategy. The DELPHI approach to internal multiple attenuation (Berkhout and Palthe, 1980; Berkhout and Verschuur, 1997; Berkhout, 1999; Berkhout and Verschuur, 2005b,a; Kelamis and Verschuur, 2000; Kelamis et al., 2002, 2006b, 2008; Luo et al., 2007; Verschuur et al., 1992) requires some information about the generators of internal multiples and will be a cost-effective choice when that criteria can be satisfied. The inverse scattering series (ISS) for free surface multiples predicts the amplitude and phase of free surface multiples at all offsets, doesn't require a Radon transform or adaptive subtraction and can eliminate the multiple in the presence of proximal or interfering events (Carvalho et al., 1992; Weglein et al., 2003). The latter is more costly than: (1) Radon, and (2) SRME (DELPHI) combined with Radon followed by adaptive subtraction, but can be the cost effective choice when the surgical removal of free surface multiples that are proximal to primaries or other multiples of different orders is the goal. Inverse scattering series methods for removing internal multiples (see, e.g., Araújo et al. (1994); Weglein et al. (2003)) require no subsurface information or interpretive intervention, cost more than Radon or feedback loop methods, but are the appropriate and indicated choice under the most complex and daunting geologic and data conditions, and when one is interested in predicting the amplitude and phase of multiples at all offsets. The latter elimination provides the surgical removal of multiples without injuring primaries. Choosing the appropriate tool for the specific exploration play and application is how we advocate using the current capability within the multiple attenuation toolbox. In fact, if your data set and prospect objectives can be accommodated by Radon, then it would be contraindicated to use a method that is more than necessary and will not provide a return on the added investment. Progress and future advances in capability will add to (and facilitate) the choices within the toolbox and broaden the circumstances under which multiples can be effectively removed without damaging primaries. The expanded and enhanced toolbox empowers those interested in paying more to access more capability to have that opportunity. Advances in computer capability always mitigate the cost factor. The use of different methods within the toolbox has varied over time, as industry trends and portfolio move from the readily accessible to the more complex and challenging plays.

OFFSHORE AND ONSHORE MULTIPLE REMOVAL: PROGRESS AND OPEN ISSUES

In offshore exploration, the industry trend to explore in deep water, with even a flat horizontal water bottom and a 1D subsurface, immediately caused many traditional and useful signal processing/statistical-based multiple-removal methods to bump up against their assumptions, break down, and to fail. The confluence of (1) high drilling costs in deepwater plays, (2) specific deepwater challenges (e.g., shallow subsea hazards), (3) the need to develop fields with fewer wells, (4) the complex and rapidly laterally varying overburden and boundaries/target and (5) the record of drilling dry holes, drives the need for greater capability for removing marine free-surface and internal multiples, as well as improving methods of imag-

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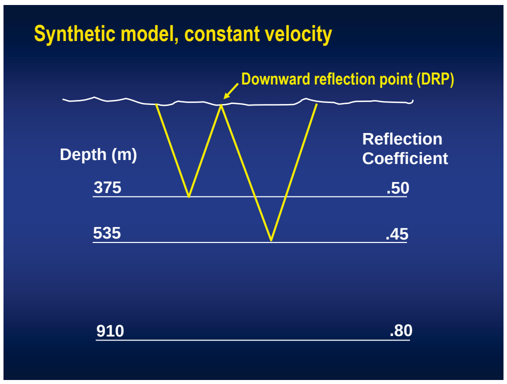
ing.

Marine field data tests have demonstrated that under complex data and subsurface conditions that the ISS methods demonstrate their mettle and delivery. The ISS algorithms were recently employed on offshore Brazil data in Ferreira (2011) (see Figure 2). One of the conclusions of the latter study with Petrobras was "no other method was able to show similar effectiveness in attenuating the internal multiples generated by the salt layers".



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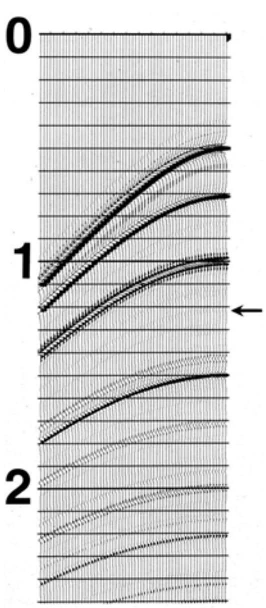

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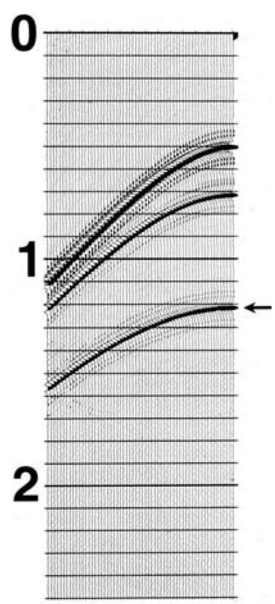
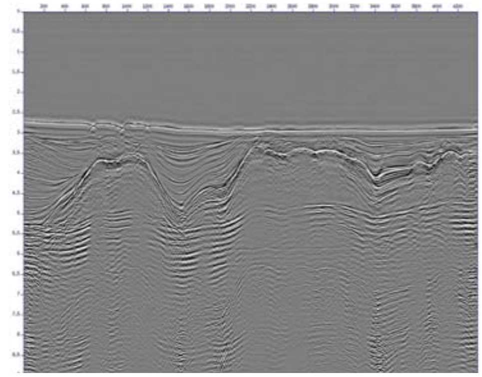


(c)

Figure 1: Hidden reflector example: (a) Synthetic Model; (b) Shot record; (c) Shot record after an accurate amplitude and phase prediction of free surface multiple elimination. This example shows that the ISS free surface algorithm doesn't require a residual Radon or adaptive step. Note that the energy minimization criteria fails in this example. (Example provided courtesy of Bill Dragoset.)

Moving onshore, the estimation and removal of land internal multiples can make the toughest marine-multiple problem pale in comparison. The presence of proximal and interfering pri-



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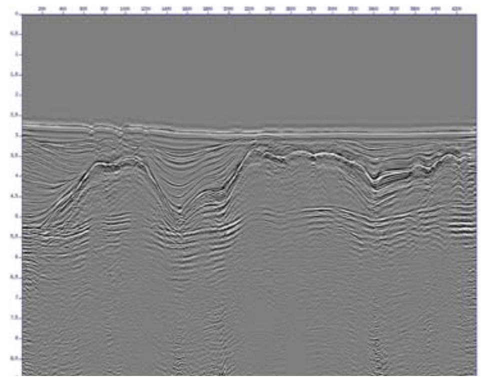

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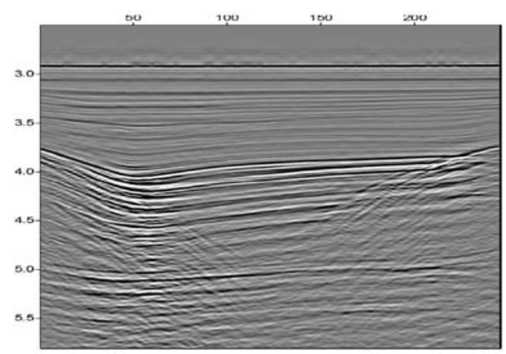

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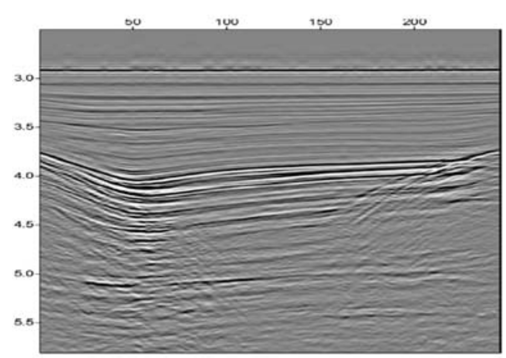

(d)

Figure 2: Stack before (a) and after (b) free surface multiple removal; common offset sections before (c) and after (d) internal multiple attenuation (Ferreira, 2011).

maries and internal multiples of different orders can occur in marine situations, but their frequent occurrence for land internal multiples raises the priority and interest in both the amplitude and phase fidelity of prediction. Developing an alternative to energy-minimizing-based adaptive subtraction techniques is also a priority and pressing need. For example, in Kelamis et al. (2006a), Fu et al. (2010), Luo et al. (2011), Weglein et al. (2011), and Kelamis et al. (2013), the basic cause of the land multiple-removal challenge in Saudi Arabia is identified as a series of complex, thin layers encountered in the near surface.

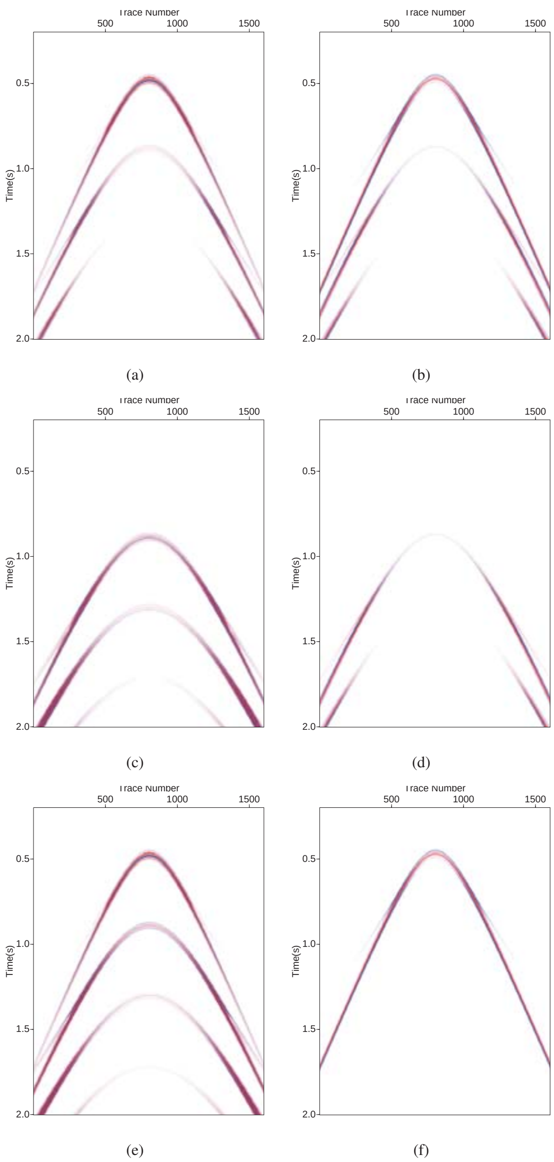

Figure 3: The left column is data and processing with ghosts in the data , and the right column is data and processing with ghosts removed. (a) and (b) are input data, (c) and (d) are free surface multiple predictions, and (e) and (f) after free surface multiple removal through a simple subtraction. Comparing (e) and (f) shows the residual if we do not remove ghosts.

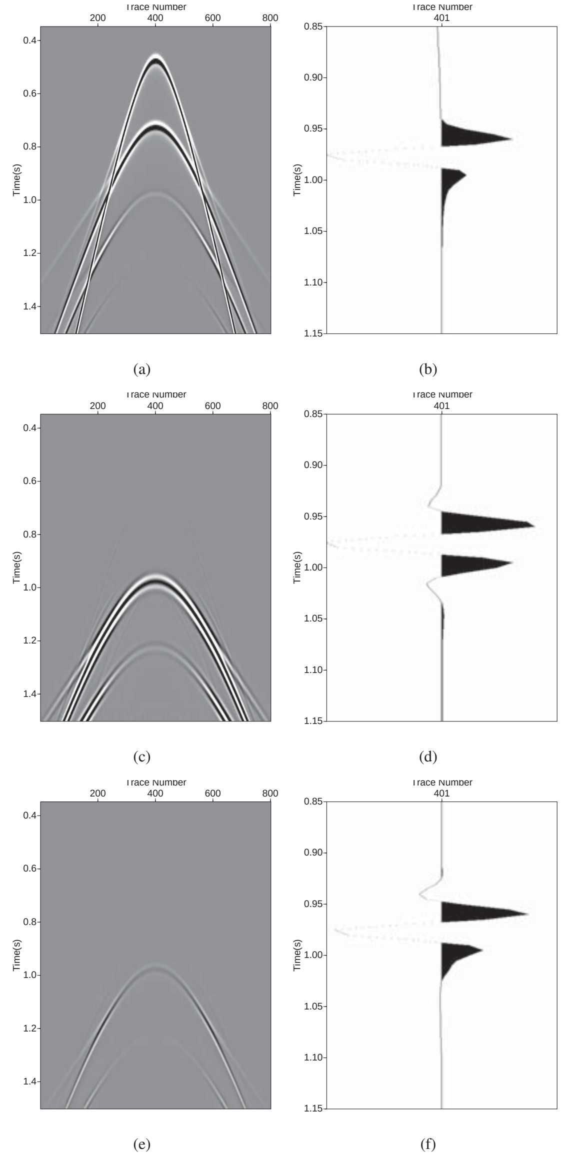

Figure 4: In the left column, (a) is the input data set (two primaries and first-order internal multiple), (c) is the internal multiple prediction without deconvolving the wavelet, and (e) is the internal multiple prediction with deconvolution of the wavelet. The right hand column shows only the first-order internal multiple (corresponding zero-offset traces). We see that removing the wavelet moves both the amplitude and shape of the predicted first-order internal multiple to the actual.

Fu et al. (2010) concluded that "Their (ISS internal multiple algorithm) performance was demonstrated with complex synthetic and challenging land field data sets with encouraging results, where other internal multiple suppression methods were unable to demonstrate similar effectiveness."

In general, strong reflectors at any depths are significant sources of internal multiples, especially where geologic bodies with different seismic properties are in contact. Typical examples are alternating sequences of sedimentary rocks, salt layers, basaltic layers or coal seams, which can give rise to short-period internal multiples.

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PREDICTION AND SUBTRACTION

Multiple removal is often described as a two-step procedure: prediction and subtraction. The subtraction step is meant to try to compensate for any algorithmic compromises, or real world conditions, outside the physical framework behind the prediction. In multiple-removal applications, the subtraction step frequently takes the form of energy-minimizing adaptive subtraction. The idea is that a section of data (or some temporally local portion of data) without multiples has less energy than the data with multiples. One often hears that the problem with multiple attenuation is not the prediction but the subtraction. In fact, the real problem is excessive reliance on the adaptive subtraction to solve too many problems, with an energy-minimizing criteria that can be invalid or fail with proximal or overlapping events. The breakdown of the energy-minimization adaptive subtraction criteria itself can occur precisely when the underlying physics behind, e.g., high-end inverse scattering series multiple prediction (that it is intended to serve) will have its greatest strength and will undermine rather than enhance the prediction. (Please see Figure 1.) Statistics based non-energy minimization adaptive subtraction approaches are presented in Liu and Dragoset (2013) and Kaplan and Innanen (2008). The latter reports showed encouraging results. Weglein (2012) presents a non-energy minimization adaptive criteria that is derived from, and aligned with, the properties of the free surface algorithm. We would encourage further research and development of fundamentally new adaptive criteria to address this outstanding and high priority issue.

Progress to take the algorithm for internal multiple attenuation towards elimination is reported in W. Herrera (Herrera et al., 2013) and Y. Zou (Zou et al., 2013). The latter work developed ideas first suggested in Ramírez and Weglein (2009). When there are two or more internal multiple generators, the leading order internal multiple attenuator can generate spurious events. C. Ma (Ma et al., 2013) and H. Liang (Liang et al., 2013) have provided algorithms with all the advantages of the leading order attenuator but without the artifacts.

P. Terenghi (Terenghi et al., 2012) developed and H. Ayadi (Ayadi et al., 2013) tested a method that mitigates the computational challenge of 3D ISS internal multiple attenuation. Musil and Kostov (2008) describe a 2.5D free surface multiple elimination algorithm. Extending the latter technique to internal multiples would be worthwhile.

PREREQUISITES

The currently most effective multiple attenuation methods require a reasonable source signature and deghosting, and Green's theorem methods have been developed for that purpose (see Zhang and Weglein (2005); Zhang and Weglein (2006); and Mayhan et al. (2011)).

We cite references here that demonstrate the impact of Green's theorem deghosting on free surface multiple elimination (Figure 3), and the wavelet deconvolution on internal multiple prediction (Figure 4) (Yang et al., 2013). L. Amundsen (Amundsen, 1993; Ikelle and Amundsen, 2005) pioneered P+Vz deghosting, and J. Zhang (Weglein et al., 2002; Zhang and Weglein, 2005, 2006; Zhang, 2007) pioneered and J. Mayhan (Mayhan et al., 2011, 2012; Mayhan and Weglein, 2013) developed Green's theorem deghosting algorithms. Advances in acquisition (e.g., dual sensor or over/under cables) have allowed these Green's theorem methods and subsequent processing to reach their potential.

SUMMARY

The toolbox approach views the collection of available methods for attenuating multiples and recognizes that each method has strengths and limitations and, for a given prospect and play, that one chooses the appropriate method from a cost-effectiveness perspective. It is always important to keep in mind that in the broader perspective and ultimate consideration within the cost-effectiveness calculation and driver, that the cost of seismic processing is dwarfed by the cost saving from avoiding drilling dry holes.

There is a documented shift and trend in the changing relative emphasis of, e.g., Radon, Feedback, and Inverse Scattering Series methods that is attributable and closely tied to the trend and changes in the exploration and production strategies, interests and portfolios of petroleum producers and companies that provide services. Those same influences and factors determine the priority of open issues and the pressing need to address them.

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