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Imaging with Doubly-scattered Waves - A North Sea Case Study

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SUMMARY

There are many geologic structures of interest that are not illuminated with standard surveys and singly scattered waves. In many situations, however, these structures are illuminated by multiply-scattered waves. In this case study, we illustrate the illumination of a salt flank above a chalk layer using doubly scattered waves. Our method uses one-way methods, allowing us to use a standard image to locate a reflector suitable for generating doubly scattered waves. This image is incorporated into a two-pass one-way method resulting in images of comparable quality to those obtained with reverse-time migration.

Introduction

In two related papers, Farmer et al. (2006) and Jones (2008b,a), show how so-called prismatic reflections (double-scattered waves) can be included in a reverse-time migration procedure to improve the location of salt flanks in a North Sea data set. We use the same data set to demonstrate that similar results are obtained with the one-way approach we introduced in Malcolm et al. (2009). There are several advantages to using a one-way approach for this imaging problem. The first is speed, imaging both doubly and triply scattered waves in a one-way framework requires approximately twice the computation time of a standard one-way migration. Second, in our approach a standard image is used as the near-horizontal generator of multiply-scattered waves. This removes the requirement that this horizon be included in the background velocity model and thus allows for more flexibility in the generation of multiply scattered waves. Third, in a one-way approach separate images are produced from doubly and triply scattered waves; the total image is simply the sum of these contributions. It is then possible to interpret these images separately, and to highlight and remove artifacts from each image. Our method shares similarities with other two-pass one-way methods such as those suggested in Hale et al. (1991); Xu and Jin (2006); Zhang et al. (2006), and the multiple-forward, single-back-scatter method used to image with duplex waves in Jin et al. (2006); Xu and Jin (2007). There have also been several studies using duplex waves and ray theory Broto and Lailly (2001); Marmalyevskyy et al. (2005); Cavalca and Lailly (2007); Kostyukevych et al. (2009). Although this case study focusses on duplex waves, the same theory can be applied to imaging with internal multiples. This is fundamentally different from methods that convert multiples into primaries, either explicitly Berkhout and Verschuur (2006) or through interferometry Schuster et al. (2004); Jiang et al. (2007); Vasconcelos et al. (2007), but can result in images of similar quality.

The Algorithm

The basic structure of our technique for imaging with multiply scattered waves is straightforward. The procedure is broken into the following steps, illustrated in Figure 1,

1. Form a standard image, assuming singly scattered waves.

2. Propagate the surface data down into the subsurface (with a one-way method), multiply the wavefield by the image, formed in 1, and store the resulting composite wavefield at each depth (Figure 1(a)).

3. Propagate the composite wavefield up to the surface (Figure 1(b)), forming an image at each depth by applying the imaging condition to the two composite wavefields for internal multiples, and to one composite wavefield and the standard downward continued wavefield for doubly-scattered waves (Figure 1(c)).

As in reverse-time migration, including multiples requires the specification of a layer (or multiple layers) that generate the multiples (see the discussion in Jones et al. (2007)). While this information must be included directly in the velocity model for reverse-time migration, and for the methods of Jin et al. (2006); Xu and Jin (2007), in our method this information is included separately, and is obtained directly from a standard image. This means that only the regions of the image that have significant reflectivity contribute to the generation of multiply-scattered waves, and that it is not necessary to specifically decide all layers that may generate multiples. Of course, it is still possible to exclude multiples from specific layers by simply muting the input image to not include those layers. It is thus not necessary that there be a single coherent reflector, although there must be something that physically reflects the energy toward the salt flank.

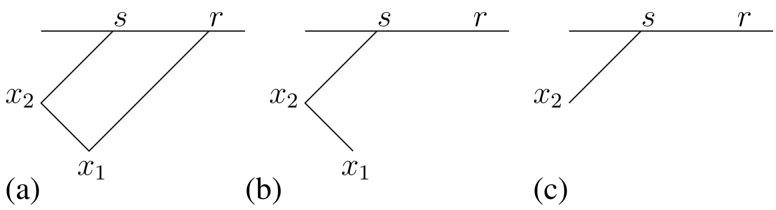

Figure 1 *The data shown in (a), are first downward continued (here illustrated on the receiver side) and multiplied by the image, at x_1 as in (b), after which the resulting composite wavefield is propagated up to the vertical reflection point at x_2 in (c) where an image is formed by applying the imaging condition to the up-going composite wavefield and the standard downgoing wavefield on the source side.*

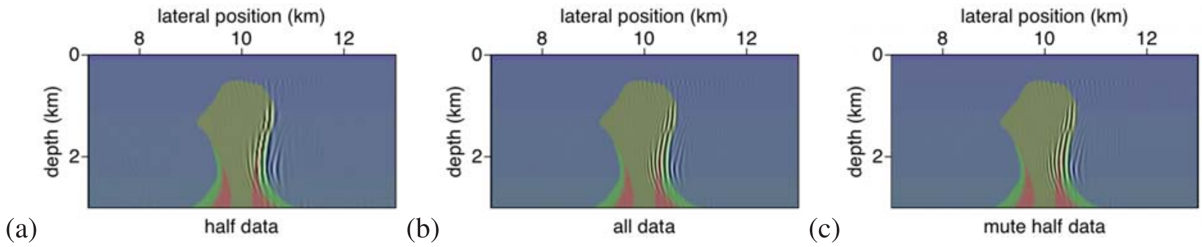

Figure 2 *The effect of grid size on the final image. (a) Using a receiver spacing of 25 m we get a good image of the vertical salt-flank. (b) Using a receiver spacing of 12.5 m gives the image a higher resolution, although the location and shape of the reflector do not change much. (c) Using the same grid as in (b) for the propagation, but with every second receiver muted (so an effective receiver spacing of 25 m with an actual receiver spacing of 12.5 m) gives nearly the same image as in (b) indicating that the additional data is not required but forming the image on a finer grid improves the image. All of these figures were made using a standard shot-record migrated image muted outside the interval 2.5-3.4 km for the input standard image.*

Effect of Sampling

To illustrate the importance of sampling in the lateral direction, we now work with a synthetic designed to mimic the structures seen in the real data set discussed in the following section. Part of this velocity model appears in the background of Figure 2, the region of the model not shown consists of near horizontal layers. For this and the real data example, we use a phase-shift propagator, performing the phase-shift separately for each occuring velocity in a horizontal slice. This is similar to the PSPI propagator Gazdag and Sguazzero (1984) as well as to the propagators suggested in Ferguson and Margrave (2002). Resolving the different vertical layers in this model requires that the image be made on a relatively dense horizontal grid. This does not mean that more data is required than is used to make a standard image, only that the image must be formed on a fine enough grid to appropriately sample the lateral direction. This is illustrated in Figure 2.

Updating the velocity model

In this section we explore the possibility of using doubly scattered waves to improve the velocity model near a salt structure that is not well imaged. The data are from a North Sea field; this data set is discussed in more detail in Farmer et al. (2006); Jones et al. (2007), where a similar set of procedures are applied in a reverse-time migration framework. What this study adds is, first the removal of the requirement that the salt itself be included in the velocity model, and second the requirement that hard boundaries be included in the velocity model. The first requirement is removed by using only waves that travel outside the salt to image its boundaries. This is similar to the result in Jones et al. (2007) that used reverse time

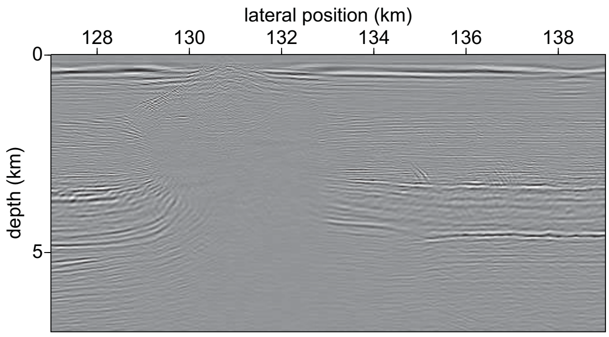

Figure 3 *Standard image made with the sediment model.*

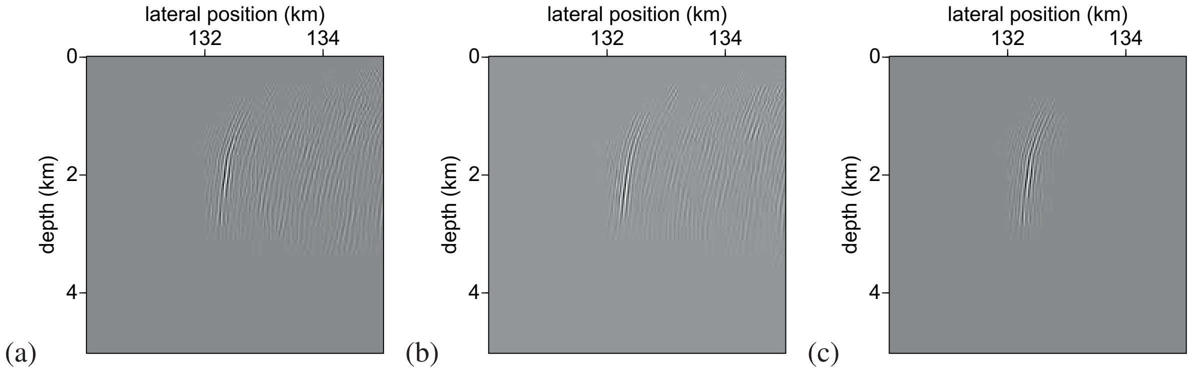

Figure 4 *This is the double-scatter image made with the (a) the sediment velocity model or (b) the one-dimensional velocity model. In (c) a double scattered image made with the surgically muted data, and the sediment velocity model is shown. In all of the figures, a muted version of the image shown in Figure 3 was used as the input single-scattered image.*

migration to image the salt flanks with duplex waves. The second requirement is removed by separating the smooth background velocity model from the sharp reflectors. By using both an image and a velocity model, we are able to reduce the requirements on the level of detail present in the migration velocity model. Figure 3 shows an image made with all 315 recorded shots on a 2D line extracted from a 3D volume, for each shot 120 offsets are recorded with a minimum offset of 160 m and 25 m spacing, the shot spacing is 50 m.

To make an optimal image of the salt flank, we followed a several step procedure. We first made an image of the salt flank, using the image in Figure 3(a), muted above 3 km as the input single-scattered image, resulting in the images shown in Figures 4(a,b). We then modelled the doubly scattered waves between this imaged salt-flank reflector and the top of chalk slightly deeper than 3 km. From these modelled data, we designed a mute to keep only double scattered waves in the data and muted all data arriving before one wavelength before the first-arriving doubly scattered waves. We then applied this mute to the data set and made an image of the flank of the salt, as shown in Figure 4(c). This figure is then added to that in Figure 3 to form the final image shown in Figure 5.

Conclusions

We have shown that two-pass one-way methods are able to image near-vertical structures such as salt flanks on real data, allowing the improvement of the understanding of the shape of these salt structures. Imaging with doubly scattered waves does not require particularly large offsets, but it does require data recorded at some distance from the structure of interest. Sampling is particularly important when imaging vertical structures with small amplitude doubly scattered waves.

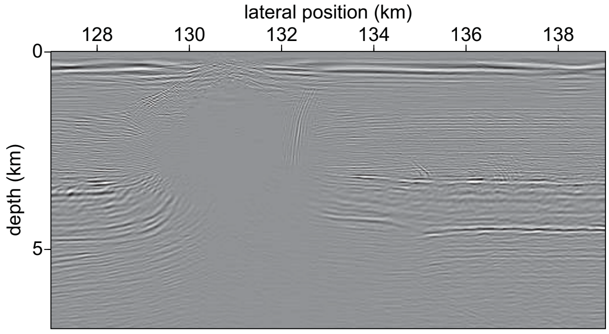

Figure 5 *The total image including both singly and doubly scattered waves to image the salt flank.*

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