IMAGING OF STEEP FLANKS BY FOCAL SOURCES
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Abstract
One-way recursive wavefield extrapolation and migration has many advantages over other wavefield extrapolation methods. The method can handle complex models and is robust. However, the extrapolation of turning waves is one important omission of one-way wavefield extrapolation. In this paper a new hybrid approach for the imaging of steep salt flanks is presented. CFP redatuming is used to redatum the data to a vertical array, and one-way wavefield extrapolation, using a rotated velocity field, is used to image the steep flank. A simple example is given for a synthetic dataset calculated for a model which includes a steep flank.

Introduction
Virtual sources can be simulated in the subsurface using a source array at the surface (Berkhoff 1992, Rietwiijk et al. 1992). These virtual sources can be focused (combined) again to illuminate specific parts of the subsurface. In the last section of Chapter 5 of Thorbecke (1997) an idea to image steep salt flanks was illustrated and briefly discussed, but has never been worked out. The last year this idea has been worked out in a slightly different way.

In short the idea boils down to the fact that an (vertical) array of focal points (FP’s), with corresponding CFP gathers and CFP operators, is used to redatum surface data to the array of focal points. In Figure 1 two kinds of focal point arrays are shown, a vertical and a curved array. The response of this array is used to illuminate steep salt flanks. The CFP redatuming, followed by imaging is worked out in this abstract and illustrated by imaging of a steep flank of a synthetic data set.

To redatum a data set, recorded at the surface, to a vertical array, focusing operators are needed that contain the propagation effects between the vertical array and the acquisition positions at the surface. A first focusing step creates CFP gathers which have virtual source positions on the vertical array and real detectors on the surface. After this first step a second focusing step is used, using the same focusing operators, but now with CFP gathers as input. After this second focusing step the focal points acts as a source position (where the focusing operator is confined (n = m) with the focal point) and the other points in the vertical array, are receiver locations (where the focusing operator is bi-valued (n ≠ m) with the focal point). The CFP gather and the redatumed CFP gather are represented by

\[
P_j(z, z_0) = P_j(z, z_0) \delta(z - z_0)
\]

\[
P_j(z, z_0) = F_j(z, z_0)
\]

respectively. The constructed gathers \(P_j(z, z_0)\) can be migrated using a standard one-way shot record migration program, where the velocity model is rotated to become aligned with the new positions of the vertical array.

Zhang and McMechan (1997) used a similar approach, and also used a rotated velocity model of 90° to extrapolate the energy associated with turning waves, but they did not use a (CFP) redatuming step as introduced in this abstract. The redatuming step has two advantages:

• a smaller aperture is needed to migrate the reflection energy from the steep flank,
• the energy after redatuming is better focused, which makes the (steep) imaging condition better defined and more stable.

The redatuming has one disadvantage: the vertical array is not imaged by these migration methods. In the one-way result (a) the bottom of the salt and the bottom of the salt flank are clearly visible. In the Kirchhoff migration (Figure 3a) the salt flank is not imaged by these migration methods. The last year this idea has been worked out in a slightly different way.

Example: salt flank model
To illustrate the CFP approach a synthetic steep flank model, shown in Figure 2a, is used. In this model 534 shots were modeled (using an acoustic finite-difference program) with a fixed-spread acquisition, ranging from 0 to 8000 m, and a source and receiver spacing of 15 m. The model consists of a background model with a vertical velocity gradient and a salt-like structure on the right hand-side of the model. The recorded wavefield from shots on the left hand-side of the model, will contain energy from reflected turning waves. The dotted line in Figure 2a indicates the vertical positions of the focal points (FP’s), each FP being connected to a CFP-gather. The vertical distance between the FP positions in the vertical array is chosen \((\Delta z = 15 \text{ m})\). These vertical FP positions will become the new acquisition plane. The snapshot in Figure 2a show that the reflection of the steep flank contains multiple arrivals. Figure 2b shows a shot record with a source position in the outer left part of the model \((x = 105 \text{ m})\). The reflection from the top of the salt and multiple arrivals from the steep flank are clearly visible.

The two-stack depth migration results, using the modeled shots, are shown in Figure 3. The true model as used in the FD modeling, was also used in the one-way migration. For the Kirchhoff migration a smoothed model was used for the modeling of the rays. The Kirchhoff migration (Figure 3a) images the steep flank close to 90° degrees and the one-way based scheme (Figure 3b) close to 70°.

If one has measurements from buried detectors, then the first arriving event in these measurements (Xiao et al., 2006) can also be used to constrain and verify the calculated focusing operators. The focusing operators, used to construct the CFP gathers at the vertical array of Figure 2a, are calculated using a ray-based modeling program. These calculated focusing operators will correctly follow the turning waves through the model. The velocity model used for the ray-based modelling only contains the background model, a depth velocity gradient of 0.4 m/s per meter ranging from 0 to 6000 meter and starting at \(z = 0\) with 1500 m/s. Usually the velocity gradient along the side(s) of a salt structure is well known. On positions of the vertical array, where the focal point coincides with a reflecting boundary, the calculated operator can be verified using the CFP principle of equal traveltime. If one has measurements from buried detectors, then the first arriving event in these measurements (Xiao et al., 2006) can also be used to constrain and verify the calculated focusing operators.

FIGURE 1: An array of focal points can be used as a redatuming surface. This array can be designed to illuminate the structure in an optimum way. In this abstract we use a vertical array of focal points as shown in the left picture.

The focusing operation, used to construct the CFP gathers at the vertical array of Figure 2a, are calculated using a ray-based modeling program. These calculated focusing operators will correctly follow the turning waves through the model. The velocity model used for the ray-based modelling only contains the background model, a depth velocity gradient of 0.4 m/s per meter ranging from 0 to 6000 meter and starting at \(z = 0\) with 1500 m/s. Usually the velocity gradient along the side(s) of a salt structure is well known. On positions of the vertical array, where the focal point coincides with a reflecting boundary, the calculated operator can be verified using the CFP principle of equal traveltime. If one has measurements from buried detectors, then the first arriving event in these measurements (Xiao et al., 2006) can also be used to constrain and verify the calculated focusing operators.

FIGURE 2: Salt dome model embedded in a medium with a vertical velocity gradient. The vertical array at \(z = 6000\) shows the 533 locations (\(\Delta z = 15\)) of the FP’s, each FP being connected to a CFP-gather. Note the complex, multi-valued, wavefront from the reflection of the steep salt flank in the snapshots (a). Multiple arrivals in the turning wave event occur around 6 s. in the shot record from the far left side of the model (b).

FIGURE 3: Pre-stack depth migration results using original shots records (not redatumed) with Kirchhoff migration (a) and successive one-way wavefield migration (b). In the one-way results parts of the steep flank are imaged due to the presence of diffraction energy originating from course blocks in the finite difference model.

The constructed CFP gather in Figure 4a, includes reflection energy from the steep flank which has propagated through the vertical gradient medium. The reflection event in the CFP gather around 4 s. originates from the steep flank of the salt. After constructing all CFP gathers at the defined vertical array, the redatuming step is completed by using the focusing operators a second time. Applying this redatuming step to all CFP gathers gives a new pre-stack volume. For one redatumed source position the constructed shot record is shown in Figure 4b. This redatumed CFP gather can be interpreted as the response of a source at \(x = 6000, z = 1500\) with receivers at the vertical line \(x = 6000, z = 15 - 7959\). In this redatumed shot record multi-valued arrivals from the synthetic structure of the flank are visible and indicated with an arrow. The application of this redatuming process gives 533 shot records, each with 533 receivers and one virtual source position on the defined vertical array.

FIGURE 4: CFP gather for focal points at depth of 1500 m after the first (a) focusing step and after redatuming to the vertical array at \(z = 6000\) (b). Note that the horizontal axis in a) represents surface position of the real sources, and in b) the horizontal axis represents depth positions of virtual positions on the array.
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By adding the sources within a modified common receiver gather together, a plane wave response is constructed and shown in Figure 7a. This response is migrated through a rotated velocity model shown in the background of Figure 7e. The plane-wave migration result in Figure 7c shows that indeed energy from the steep flank has been preserved and can be imaged with one-way operators using a 90° rotated velocity model. This simple plane wave test already indicates that turning wave energy has been preserved in the CFP redatuming.

To verify the velocity model (or focusing operators) of the salt flank structure the redatumed data set can also be used to construct CFP gather with FP's on the flank, and check the ‘principle of equal traveltime’. In Figure 8a a focal point (blue star) on the flank of the salt dome is chosen at $x = 3000, z = 7330$, a focusing operator is calculated, and CFP gather constructed. Figure 8b shows the CFP gather with its focusing operator overlaid. Note that the operator verification, using the reflections from the steep flank, can lead to accurate focusing operators. Migrating the redatumed CFP gathers with a pre-stack depth migration algorithm gives the image shown in Figure 8c. For comparison in Figure 9b the same area for the pre-stack depth migration result (Figure 3b) is shown for surface shot record migration. The same one-way wavefield extrapolation operators are used (Thorbecke et al., 2004). Note the better imaging of the steep flank of the salt structure. The reflection of the flank is too steep to be imaged with one-way operators and recorded data at the surface. One-way extrapolation operators, applied on recorded data at the surface and using a regular grid, cannot handle turning waves, so the energy of the turning waves, which are visible in Figure 2b, is suppressed by the one-way operators and not imaged in Figure 9b. Note that reflections of the top and bottom of the salt, which has travelled through the salt, are nicely imaged. Note also that parts of the steep flank are imaged due to the presence of diffraction energy originating from corner blocks in the finite-difference model. This imaged diffraction energy is visible as horizontality oriented events which are not aligned with the steep flank.

Redatumed CFP gathers can be used to image complex geological structures which contain steep flanks. The proposed procedure consists of three steps. First a shot or vertical or curved array of focal points with their CFP gathers is constructed. Second the CFP gathers are redatumed to the array positions. The redatumed CFP gathers represent a fixed acquisition spread along the array of focal points. Thirdly, these redatumed CFP gathers are input to standard velocity analysis and then migrated by a standard shot record migration program. Note that the position of the structure can be verified by using the principle of equal travel time. The obtained migrated image will show information of high angles and overturned waves when these are present in the data. For an optimal imaging and detailed velocity analysis the virtual array can be designed for any specific geological structure.

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References