Improved Geological Modeling and Interpretation by Simulated Migrated Seismics

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Summary

Using a combined Forward and Inverse operator (resolution function), a fast method is presented to construct a simulated migrated seismic section from a geological depth model. Unlike the 1D convolution model, the resolution function expresses both vertical and horizontal resolution. This gives an interpreter a powerful tool to create simulated migrated seismics, which includes migration effects. Further due to its low computational costs, different geological models can rapidly be evaluated.

Introduction

The seismic experiment is an important tool for "understanding" the subsurface geology. A prerequisite for such an understanding is a clear relation between the seismic image and the complex Geological Depth Model, see Figure 1. Let the collection of seismograms in general be given by the following representation:

$$\text{Data}(\mathbf{x}^{\text{R}},\mathbf{x}^{\text{S}},t)= \text{Forward Operator}\ \{\text{Geological Depth Model}(\mathbf{x})\},$$

where Data denotes the recording of the (raw or simulated) seismic experiment in time t, measured at position $\mathbf{x}^{\text{R}}$ due to a seismic source at location $\mathbf{x}^{\text{S}}$. The Forward Operator symbolizes either the seismic experiment in the field itself or stands for a computational procedure. To capture the geology from seismic measurements an Image Operator has to be applied

$$\text{Depth Image}(\mathbf{x})= \text{Image Operator}\ \{\text{Data}(\mathbf{x}^{\text{R}},\mathbf{x}^{\text{S}},t)\}.$$

The Depth Image should be representative for the Geological Depth Model. In the synthesis stage the geologist is concerned with the question how and to what extent geological details are visible in the seismic image. The following relation will be investigated

$$\text{Depth Image}(\mathbf{x})= \text{Image Operator}\ \{\ \text{Forward Operator}\ \{\text{Geological Depth Model}\ (\mathbf{x})\ \}\ \},$$

which is the compound operation of the aforementioned processes, as illustrated by the thick box in Figure 1. Commonly, the 1D convolution method (e.g. recently by Pratson and Wences (2002)) is used to create synthetic seismics. However, the 1D (convolution) method only expresses the vertical resolution, while the combined

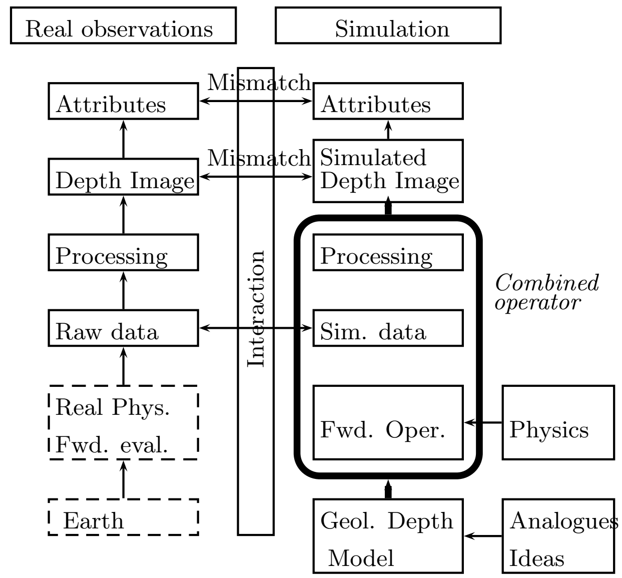


Fig. 1: "Simulation in a complete sense", modified after Petersen (1992). The combined operator, thick box, fits in this framework by acting as a direct transfer function from the Geological Depth Model to a simulated migrated Depth Image.

operator also expresses the horizontal resolution of primary waves. Compared to other forward and migration schemes (e.g. based on finite differences) the compound operator considerably saves on computational time and storage, because we do not have to output the full intermediate 3D recordings (Data($\mathbf{x}^{\text{R}}$,$\mathbf{x}^{\text{S}}$,t)). Together with geological modeling software this method will provide the interpreter with a new powerful tool that helps to understand migration effects on a geological model. More specifically, due to its low computational costs, different geological models can be rapidly evaluated, in order to minimize the "mismatch", see Figure 1.
The paper proposes the use of the combined operator to create simulated migrated seismics for enhanced seismic interpretation and modeling. Note that in the examples we will not apply the scheme to real data or deal with the question how the actual comparison between simulated migrated and real migrated seismics is performed.

Framework for combined operator

Figure 2 shows the framework to simulate a migrated seismic section. Input is a 3D (shared earth) geological depth model containing gridded wave velocities and

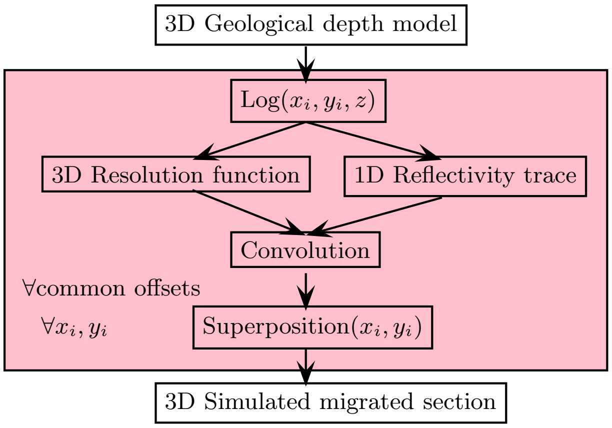


Fig. 2: Framework to obtain a simulated migrated seismic section. Summarized by convolving the resolution function with a reflectivity trace, followed by superposition of all convolution products for all reflectivity traces.

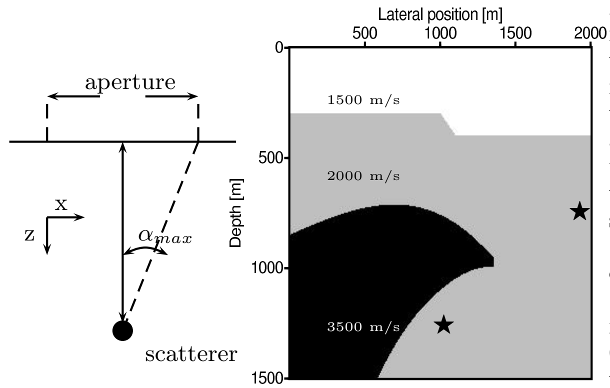
rock density data. The framework can be summarized by convolving the 3D resolution function with a 1D reflectivity trace, followed by superposition of all convolution products for all reflectivity traces. The resolution function is the result of the combined operator and will be considered in more detail in the next section. In the convolution step the resolution function is assumed to be constant over a specific vertical range. Zoeppritz's equations are used to calculate the 1D reflectivity trace. In case of a selected offset, ray-tracing is performed to obtain the angle of incidence and the wavelet is corrected according to Wapenaar (1999). Note that the propagation grid for the calculation of the resolution function is (mostly) decoupled from the reflectivity grid. This means that it contains a smoother or (piecewise) homogeneous velocity field, e.g. in case of an unknown overburden. The implementation performed in this paper is 2D, but there is nothing in the formalism that prevents us from using the same method in the 3D case.

Resolution function

The zero-offset response of a scatterer is acquired using the exploding reflector analogy and the Gazdag phase shift operator (Gazdag, 1978) as a one-way forward wavefield extrapolator. After phase shift migration the result is a so-called resolution function or "focusing cross", which is well known in migration (Berkhout, 1984). The one-way wavefield operators in the $\omega - k$ domain are chosen for their computationally efficient implementation (Fast Fourier Transform), ability to select a frequency range of interest and propagate through a large layer in one step (e.g. water layer). This implies, that the resolution function is derived by locally assuming the geological depth model laterally invariant. In the convolution the obtained resolution function is convolved with the reflectivity of the lateral invariant geological depth model. Note however, that the idea of the combined operator can easily be generalized, e.g. by using $\omega - x$ domain operators, but at the cost of increasing computational costs. In the following two examples the effects of acquisition and propagation on the representation of a resolution function will be considered. For the first example, Figure 3 (a) illustrates an acquisition setup. In a homogeneous medium with P-wave velocity of 2000 m/s, three equal strength point scatterers are located at 500,1500 and 2500 meters depth. During modeling, dz=2 and dx=5 meters. The Ricker wavelet has a center frequency of 40 Hz and a maximum frequency of 60 Hz. First we consider the acquisition setup with an "infinitely" large aperture and maximum propagation angle (α_{max}) of 90^o. Figure 4 (a) shows that the resolution functions are nearly one-dimensional and can be interpreted as point scatterers convolved with the used wavelet. It is important to notice that the 1D convolution model would have given almost the same result. In the second more common acquisition setup, $\alpha_{max} = 60^o$ and the aperture width is limited to 3000 meters (Figure 4 (b)). The 2D resolution functions are now "smeared" out compared to the first acquisition setup and vary with depth. This has two reasons: first less angle information is available due to the maximum angle of propagation. But second the limited aperture width makes that the effective receiver array becomes smaller with increasing depth. As a consequence the deeper point scatterers have less angle information available and thus less spatial resolution. In the second example, two resolution functions are examined which are obtained from a simple salt model, Figure 3 (b). The resolution functions are calculated at positions, x=1800,z=750 and x=1000,z=1250 meters. The modeling parameters are the same as in the previous example. For comparison, the resolution functions are also derived using $\omega - x$ operators (see above discussion). Starting with the shallowest resolution function, Figure 5 (a) shows that the resolution function is asymmetric. This can be explained by an acquisition effect. The right part of the "symmetric" aperture is missing due to the right boundary. By simulating this in the presented framework, at lower computational costs, a similar resolution function is obtained (see Figure 5 (b)). Now consider the scatterer at 1250 meters depth. As Figure 5 (a) shows, the resolution function is again asymmetric. This time, the shape is mainly related to a higher wave propagation angle of waves propagation through the salt. Taking the left α_{max} equal to 80^o and the right α_{max} to 60^o, also in the presented framework an asymmetric resolution function is obtained, see Figure 5 (b). This last example shows that for complex geological situations the local derived resolution function has to be constructed with care.

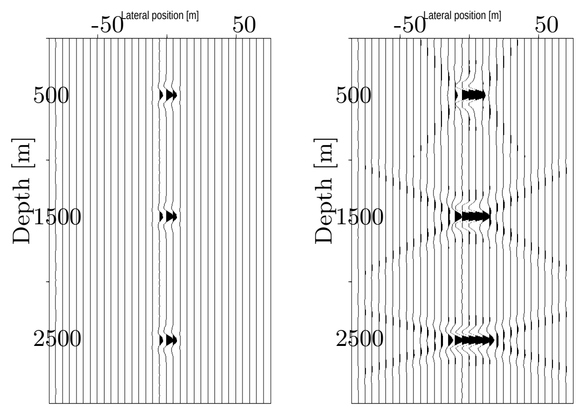
2D synthetic examples

In the first example the tuning phenomenon is investigated, see Figure 6 (a). The simulated migrated section (Figure 6 (b)) is created using the 2D resolution function at 1500 meters depth (Figure 4 (b)). For comparison in



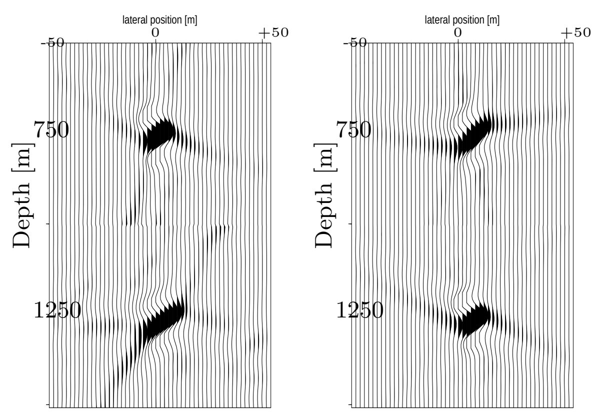
(a) (b)

Fig. 3: (a) Acquisition setup with a limited aperture and selection of the maximum angle of propagation (α_{max}). (b) Simple salt model, the asterisks denote the positions of obtained resolution functions.



(a) (b)

Fig. 4: Resolution functions. (a) Recording "infinite" aperture and all propagation angles. Note that almost the same result would be obtained with the 1D convolution model. (b) $\alpha_{max} = 60^o$ and an aperture width of 3000 meters. The 2D resolution function is "smeared" out and varies in depth.



(a) (b)

Fig. 5: Resolution functions at two different depths, see text for more details. (a) $\omega - x$ modeled. (b) $\omega - k$ modeled.

Figure 6 (c) the 1D convolution result is given. Comparison shows that the vertical resolution is approximately the same. The horizontal resolution differs, especially in Figure 6 (b) the end points are smeared out. Note, that this simulated result can also be used to derive attribute responses (see Figure 1). This could then be used to understand the attribute response or provide a way to compare real and simulated migrated data. In the second example, seismic sections of the Graben model (Figure 7 (a)) are created. Figure 7 (b) shows the results of the presented method, using a resolution function at 1200m depth from trace 1200m. During modeling α_{max} is 60^o and the convolution uses an operator length of 61 points. For comparison, Figure 7 (c) and (d) show the 1D convolution method and prestack migrated finite difference modeled shot-records, respectively. Note that the $\omega - x$ migration uses the true velocity model. Comparing the zoomed in seismic sections, starting with the double arrows, detect the similarities between Figure 7 (b) and (d). However at different computational costs, hours and 30 seconds, respectively. Second compare, the single arrows. Figure 7 (b) and (d) again show resemblance, which lacks in the 1D method, Figure 7 (c). However, note that following the reflector in Figure 7 (b) and (d) the match decreases. This can be explained by keeping in mind that, the reflectivity is also derived under a zero-offset assumption and that the resolution function is only valid within a certain vertical range. Depth-dependent resolution function at different lateral positions, like in Figure 4 (b), would improve the match.

Discussion

The presented method is an extension to the commonly used 1D convolution model to create simulated seismic of a Geological Model. Using a combined operator (resolution function), we present a fast method to create a simulated migrated seismic section. This enables an interpreter to understand migration effects and further to rapidly evaluate the response of different Geological Models.

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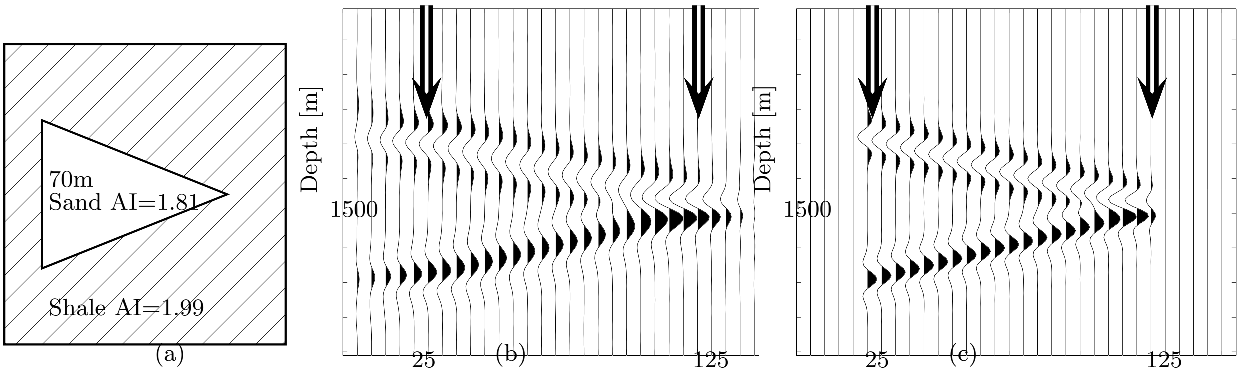

Fig. 6: (a) Sand wedge model. (b) Simulated migrated image of sand wedge placed at 1500 meters depth. (c) For comparison the 1D convolved sand wedge. The simulated migrated image shows a decrease in horizontal resolution (arrows) and approximately same the vertical resolution.

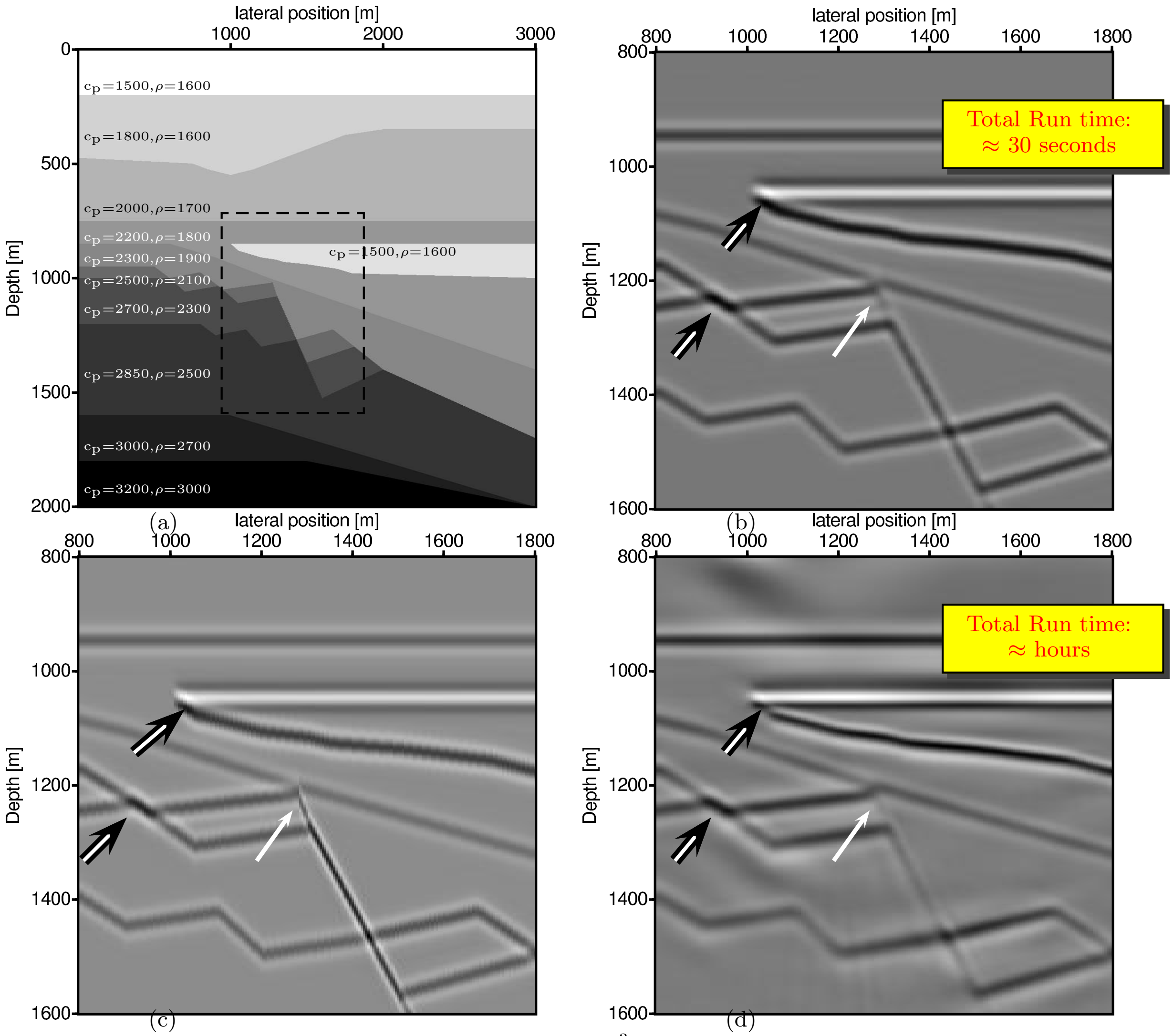

Fig. 7: (a) Graben model. Velocities in m/s and density in kg/m^3. The following zoomed in sections: (b) Simulated migrated section using resolution function at 1200m from velocity trace at 1200m. (c) 1D method. (d) Finite difference modeled and migrated section using the true velocity model. See text for more details.