Zero-offset modelling and simulated migration by one-way wavefront construction

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Abstract

Assuming a zero-offset configuration of sources/receivers, we present an approach to forward modelling based on a one-way wavefront construction process progressing upward from a selected target reflector. Subsequent simulation of migration amplitudes along this target reflector yields reliable estimates of amplitudes from a zero-offset depth migration and a quick (but less accurate) indication of small-offset depth migration amplitudes. The one-way wavefront construction process is based on theory permitting quantities related to the two-way wave propagation (accumulated reflection/transmission coefficients, geometric spreading, and phase shift due to caustics) to be continued step by step in the upward direction of normal-incidence rays. The upward continuation yields in addition the isochron curvature matrix, which is essential for the migration amplitude simulation. Numerical tests demonstrate that one-way wavefront construction is far more efficient than conventional two-point raytracing, especially when the number of sources/receivers is large. This makes it feasible to compare several scenarios with respect to model parameters in reasonable time.

Introduction

This paper is focused on two major issues. First, we have aimed at performing efficient and consistent modeling of traveltimes and amplitudes of reflected waves in the special situation that each source point has only one associated receiver point, and, these two points coincide (zero-offset modeling). Second, we use the curvatures of isochrons (surfaces of constant two-way time) for efficient simulation of migration amplitudes (SMA) along a selected target reflector. The isochron curvatures are obtained as a byproduct of the forward modelling.

The wavefront construction method (Vinje et al., 1993; Vinje et al., 1996a-b) combines initial-value raytracing with interpolation and is especially well suited for computation of multivalued arrivals in a large number of receivers. As opposed to in the classic raytracing techniques, it is not common within the wavefront construction techniques to compute complete rays from sources to receivers. In zero-offset modeling, the natural and most efficient way to apply the wavefront construction method is in the direction from the selected reflector towards the receivers, i.e., as a one-way propagation with one-way traveltime as the variable along the rays. The wavefront construction process is initialized by defining the selected reflector as the wavefront for which the one-way traveltime is zero ("exploding reflector" initialization). The modeling corresponds in this case to the propagation of the hypothetical *normal wave* (Hubral, 1983).

The SMA method was introduced recently (Vinje, 2000; Laurain and Vinje, 2001; Laurain and Vinje, 2004), inspired by Schneider and Winbow (1999). A main motivation behind the SMA method is to reduce the risk of pitfalls in the interpretation of depth migration amplitudes, which may lead to drilling of dry wells. SMA is based directly on Kirchhoff migration, but differs from a complete migration in the following respects: (1) the seismic trace in Kirchhoff migration is replaced by a synthetic trace computed by raytracing; (2) the two-way traveltime function in Kirchhoff migration is replaced by a second-order approximation to the two-way time based on the knowledge of isochron curvatures (Mispel et al., 2003); and (3) the stacking of the pulse in the SMA method is done along the target reflector only within the contributing area.

In this paper, we present a one-way wavefront construction process carrying all the parameters needed for generation of two-way traveltimes, amplitudes, and synthetic seismograms, as well as for simulation of depth migration amplitudes. For simplicity, we consider only P-wave propagation. The velocity model is three-dimensional and may consist of a mixture of isotropic and anisotropic layers.

Method

In the receivers considered for the zero-offset modeling, the two-wave traveltime is easily computed by doubling the traveltimes resulting from the one-way wavefront construction process. The estimation of the two-way amplitude is, however, not equally straightforward. A "brute force" solution is to let the wavefront construction process be followed by a classic initial-value raytracing process, where complete normal-incidence rays are obtained on the basis of ray parameters interpolated to the receiver locations. However, for a large number of receivers, the computation time of the separate amplitude calculations can be many times longer than the computation time of the wavefront construction process (Figure 1). In addition, the initial-value raytracing process may fail if the errors in the estimated ray parameters are too high. Therefore, a key issue has been to design the zero-offset modeling as a pure wavefront construction process, without the need for a subsequent separate process for amplitude calculation that involves tracing of complete normal-incidence rays.

Assuming a perfectly elastic medium, the three main factors influencing the two-way P-wave amplitude are the accumulated reflection/transmission coefficient, the geometric spreading, and the phase shift due to caustics. Based on the reciprocal property of normalized reflection/transmission coefficients (Cerveny, 2001), we use a recursive formula for the two-way accumulated reflection/transmission coefficient in the upward direction of the normal-incidence rays. Using the theory of ray propagator matrices (Cerveny, 1985; Hubral et al., 1993), one can obtain the two-way ray propagator matrix, geometric spreading, and phase shift due to caustics solely by one-way calculations (Iversen, 2004). By implementing these relations carefully in the one-way wavefront construction process, we have sufficient information in the receivers for generation of synthetic seismograms corresponding to two-way wave propagation. Knowing the one-way and two-way ray propagator matrices for the normal-incidence ray, we obtain the isochron curvature matrix needed by the SMA method.

Examples

Consider a layered velocity model with anisotropy of type VTI (Figure 2). The model has three main layers separated by two interfaces. The lower interface is syncline-shaped and serves as the initial wavefront (exploding reflector) of the one-way wavefront construction process (Figure 3). The resulting synthetic seismograms (Figure 4, left) can be compared to seismograms for the case that anisotropy has been removed (Figure 4, right).

An example of output from the zero-offset SMA method is shown in Figure 5. The model is in this case based on a seismic data set from the North Sea (Rosland and Drivenes, 2000).

Concluding remarks

For some years now, raytracing methods have been highly acknowledged in studies of the seismic-wave illumination of potential and existing hydrocarbon reservoirs. With the SMA method, one can estimate the relative importance of the various effects contributing to the prestack depth migration amplitude along a selected target reflector. We have presented zero-offset approaches to forward modelling and simulation of migration amplitude based on one-way (upward) wavefront construction. These approaches are by no means substitutes for modelling and simulated migration for a complete offset range, but are useful in the respect that results can be generated in very short time.

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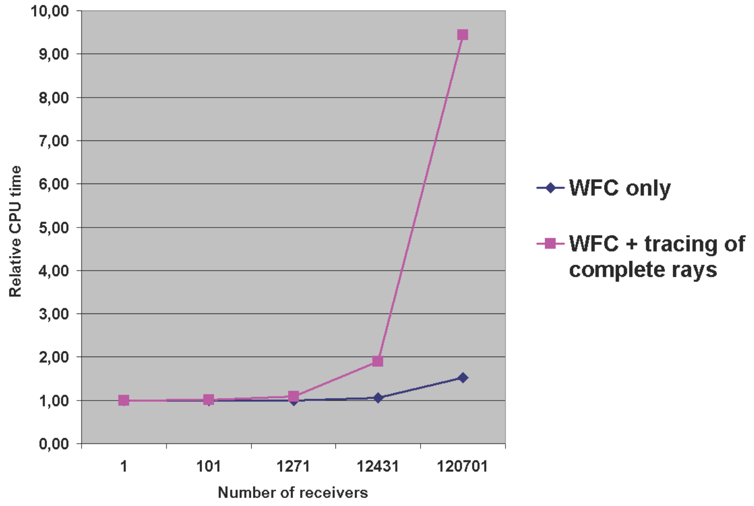

Figure 1 — Comparison of CPU times of the wavefront construction (WFC) method alone (blue) and WFC succeeded by tracing of one complete ray for each arrival (magenta).

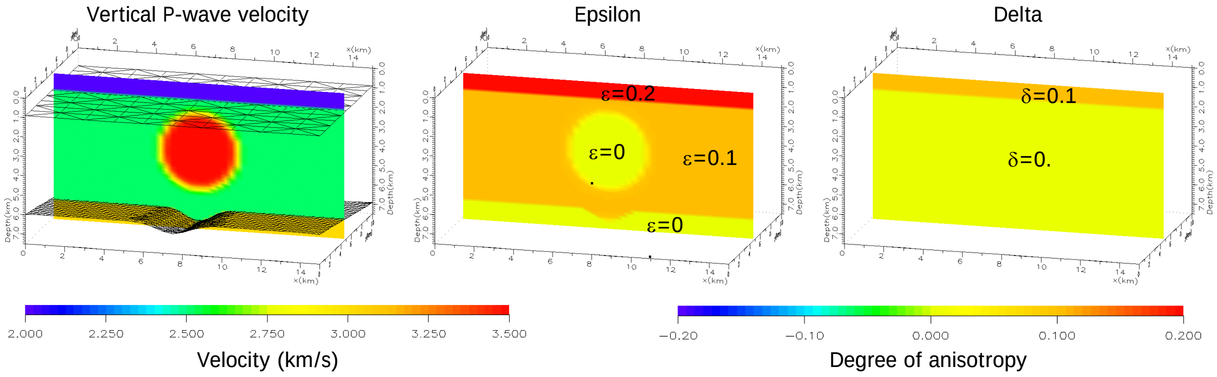

Figure 2 — Vertical cross sections (at y = 5 km) for parameters of the VTI model.

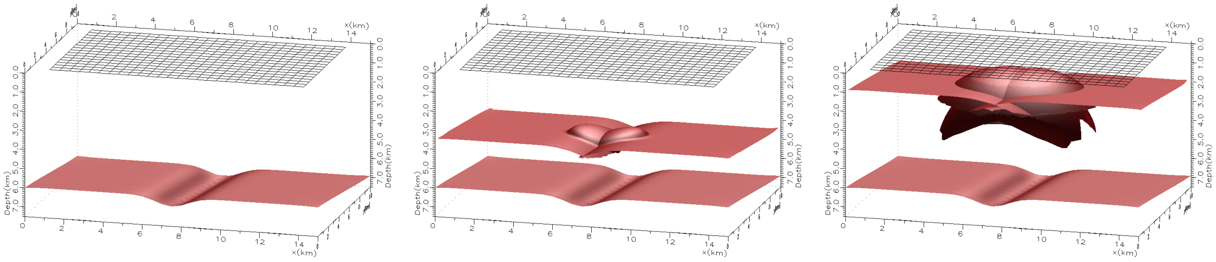

Figure 3 — Propagation of the normal-wave wavefront after one-way time 0.0 s (left), 1.0 s (middle), and 2.0 s (right). The extent of the receiver grid is indicated.

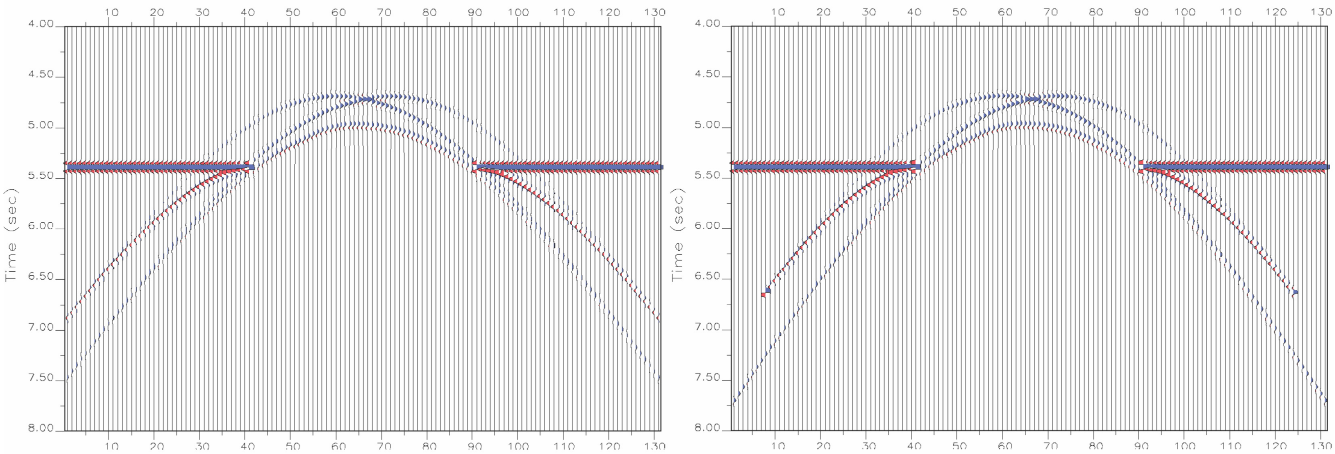

Figure 4 — Synthetic seismograms generated by one-way wavefront construction in the VTI model (left) and in the isotropic model (right). The receiver line is at y = 5 km.

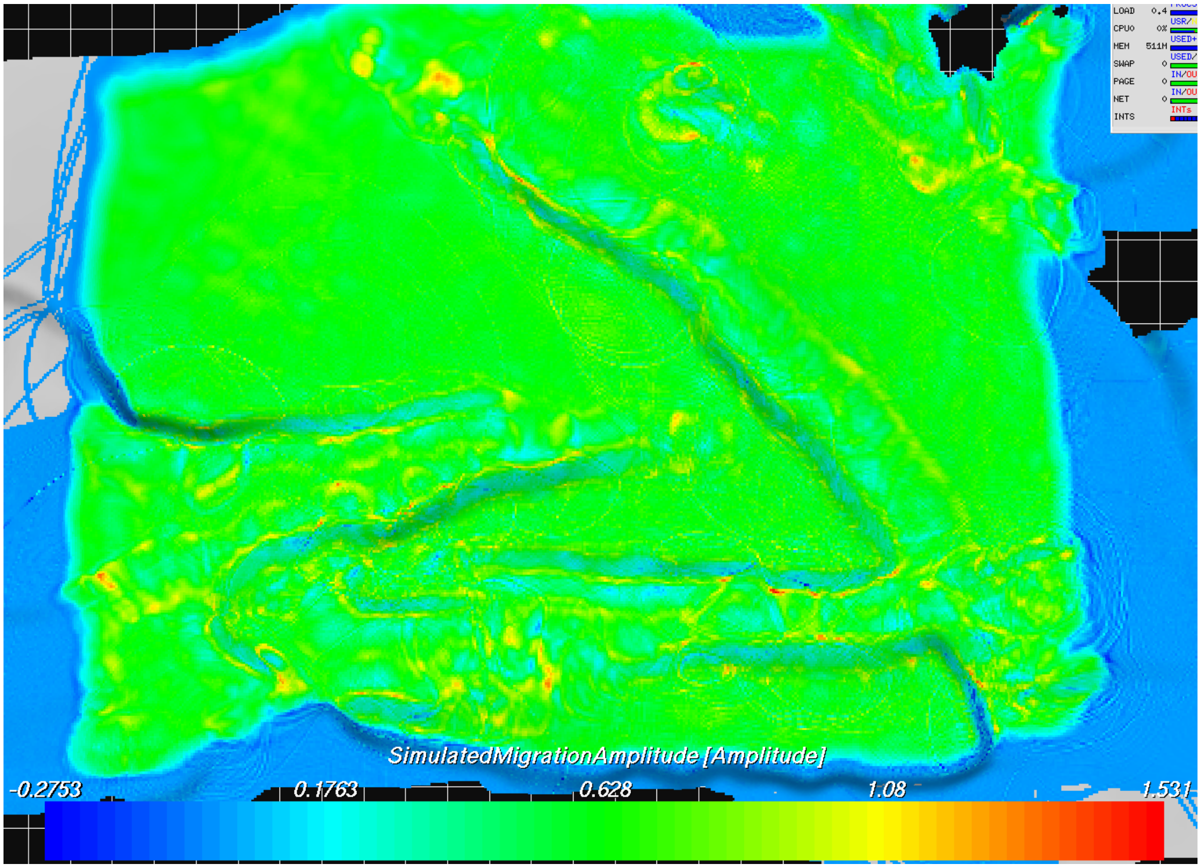

Figure 5 — North Sea model example: Zero offset SMA map for target reflector.