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3D Multiple Attenuation and Depth Imaging of Ocean Bottom Seismic Data

J. Mispel* (StatoilHydro ASA), B. Arntsen (StatoilHydro ASA), A. Kritski (StatoilHydro ASA), L. Amundsen (StatoilHydro ASA), M. Thompson (StatoilHydro ASA), O. Sandvin (READ Well Services) & L. Jahren (READ Well Services)

SUMMARY

In 3D Ocean Bottom seismic surveys (3D-OBS) both pressure and vertical particle velocity is recorded. This presents the opportunity to decompose the recorded wavefields in up- and down-going components and apply to 3D common receivers gathers a designature/demultiple algorithm to attenuate free surface multiples. This single processing step replaces several steps in conventional processing usually encompassing τ-p predictive deconvolution and Radon demultiple.

Using a 3D-OBS data set from the Gullfaks Sør field in the North Sea, the new 3D designature/demultiple approach, together with 3D common receiver depth migration, is shown to result in seismic images of better quality than by the traditional processing sequence.

Introduction

The major motivation in the early 1990's for going to the added effort and expense of placing the seismic sensing system on the ocean bottom was to record shear waves in addition to pressure waves to more reliably characterize the rock and its contained fluids than is possible from conventionally towed-streamer recordings.

However, three-dimensional ocean bottom seismic (3D-OBS) surveys have other advantages compared to standard towed-streamer seismic surveys, which may be unsuitable for obtaining the very best reservoir images, especially in geologically complex areas. 3D-OBS - although more expensive - offers the distinct advantage of flexible acquisition geometries. True 3D data acquisition is realized by using a stationary seabed sensing system combined with a survey vessel shooting over a predetermined grid on the sea surface. Every subsurface point on the target can thus be illuminated from all directions and a large number of angles (Thompson et al., 2007).

To obtain accurate and detailed images, however, suppression of multiple energy while preserving the character of primaries is required. By utilizing that the complete wavefield is recorded in the 3D-OBS experiment Amundsen et al. (2001) proposed an efficient deterministic designature/demultiple solution to the free-surface multiple problem that does not require any knowledge of the source signature nor the subsurface. The essence of the method is to design a demultiple operator from the inverse of the downgoing part of the acoustic wavefield (downgoing pressure or downgoing component of the particle velocity).

In today's 3D-OBS surveys with dense source-side sampling but coarse crossline receiver sampling, the designature/demultiple method is run on 3D τ-p transformed common receiver (CR) gathers. The 3D τ-p transform is implemented as a discrete Radon transform that is rapidly computable and invertible by means of FFTs. For most seismic applications, it is sufficient to transform data to a triangle sub-domain of the concentric squares grid (Ikelle and Amundsen, 2005).

3D Designature/Demultiple of 3D-OBS data for Layered Earth

Amundsen et al. (2001) derived an integral relationship between the recorded pressure and particle velocity data (p, v_m) in the *physical* OBS experiment, containing all free surface related multiples, and the desired designatured OBS data with those multiples absent, ($\tilde{p}, \tilde{v}_m$). Here p is the pressure and v_m is the m'th component of the particle velocity. The desired data are those data that would be recorded in a *hypothetical* OBS experiment from a monopole or dipole point source with desired signature, $\tilde{a}$, in the case when the water layer extends upward to infinity. The geology below the water layer is the same in the physical and hypothetical OBS experiment.

Amundsen's integral relationship does not put any restrictions on velocity variations below the water. Nevertheless, the relationship simplifies significantly in a horizontally layered medium due to the fact that the seismic response is laterally shift invariant with respect to source location. It then follows that any component of the designatured/demultipled field can be obtained by spectral deconvolution between the field itself and the downgoing part of the pressure p. In the frequency-wavenumber domain the designature/demultiple of the m'th component of the particle velocity reads (Amundsen et al., 2004)

$$\tilde{V}_m = \frac{V_m}{P^{(d)}} \tilde{P}^{(dir)},$$

while the designature/demultiple of the upgoing pressure recording becomes

$$\tilde{P}^{(u)} = \frac{P^{(u)}}{P^{(d)}} \tilde{P}^{(dir)},$$

where e.g., for a monopole point source,

$$\widetilde{P}^{(dir)} = -\frac{\widetilde{a}}{2ik_z}\exp\left[ik_z\left(z_r - z_s\right)\right]$$

is the direct wavefield from the desired source. The phase shift corrects for difference in source and receiver depth levels, and k_Z is the vertical wavenumber. Observe that $\left(P^{(d)}\right)^{-1}$ is the multidimensional operator that acts (i) as a deterministic designature operator and, (ii) as a deterministic free-surface multiple attenuation operator. This designature/demultiple scheme may be implemented as frequency-wavenumber domain or τ-p domain algorithms.

Presently the typical 3D4C-OBS surveys have dense source-side sampling but coarse cross-line receiver sampling. Therefore it is better to run the designature/demultiple method on τ-p transformed CR gathers. Compared to published techniques for 3D free-surface demultiple for streamer data, this designature/demultiple method is very fast. To our knowledge, this is the only deterministic free-surface demultiple method that directly can be applied to 3D4C-OBS surveys with today's geometries.

3D Common Receiver Depth Migration

Most prestack depth migration algorithms can be expressed as a wave field extrapolation step followed by an imaging condition. In our case, the primary reflection data *p* is approximated with the demultipled upgoing pressure $p \approx \widetilde{p}^{(u)}$. Using the frequency-wavenumber formulation given in the preceding section, the demultipled upgoing pressure can be computed independently for each CR gather. By using reciprocity we can replace the CR gather with a common source gather, where the 3D-OBS receiver becomes the source, and the sources become new receivers. In this way we can use Claerbouts shot-profile approach for imaging 3D-OBS compressional waves.

Our implementation is based on the method presented by Sollid and Arntsen (1994) and uses a numerically optimized technique for the wave-equation finite-difference extrapolation operators as suggested by Mittet (2001). The wave field extrapolation is done separately for the data and the source wave field and an image is obtained by cross correlation of the two extrapolated wave fields.

Demultiple and Imaging of the Gullfaks Sør 3D-OBS Data

The Gullfaks Sør field is located in the Norwegian sector of the North Sea and was discovered in 1978. A 3D-OBS survey was acquired in 2002, with a layout consisting of 16 cables separated by 400m. Each cable contained receivers with a group distance of 25m. The shot area is effectively a 50x50m grid covering the same area as the cable layout with 6km additional coverage in the inline direction and 2km extra coverage in the crossline direction.

The main steps of the initial pre-processing of the data are displayed in Fig. 1. 3D CR depth migration using the approach described in the previous section was then applied with the velocity model derived from streamer data and a maximum frequency of 28 Hz. Post-processing included only t^2 amplitude scaling and depth-to-time conversion using the migration velocities. The left images in Fig. 2 and 3 show an inline and a crossline from the final stack.

The raw data were then reprocessed using the designature/demultiple approach described in the first section, implemented in the τ-p domain assuming a layered earth (see sequence on the right in Fig. 1). The multidimensional spiking deconvolution operator was computed from amplitude-frequency and phase-frequency matched pressure and vertical component of particle velocity. The desired source signature chosen was a zero-phase wavelet. The 3D depth imaging algorithm with post-processing as described before was then applied. Figures 2 and 3 show comparisons of results from inline 1751 and crossline 2601 processed with both demultiple methods.

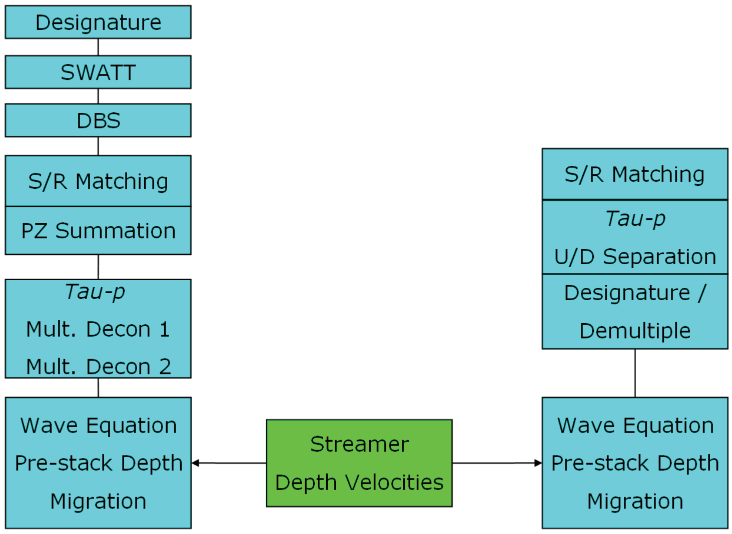

Figure 1: Simplified (Left) standard pre-processing scheme and (Right) Amundsen-type pre-processing scheme.

The change in quality is noticeable. There is less noise between the two main reflectors at ca. 1.8 and 2.7 sec; in particular the multiple train visible in the rectangular box in Fig. 2 is better attenuated. Also strong multiples in the area with tilted fault blocks below 2.8 sec. are apparently better removed (see Fig. 2 and 3). The first-order multiple, marked by a blue line in Fig. 3, is much better attenuated compared to standard processing.

In general, the inlines processed using the designature/deconvolution approach are less noisy and contain reflectors with better continuity in the target area.

Conclusions

A new and simpler processing sequence for 3D-OBS data has been presented. The sequence fundamentally contains only two major steps: Pre-processing using 3D designature/demultiple followed by 3D depth imaging using a common receiver FD method.

The 3D designature/demultiple stage does not need any information about the source array (except location), about the sea floor parameters and the subsurface below the sea floor, about any variations in the water layer from the local density and acoustic velocity, or about the state of the sea surface. Implicitly in the demultiple process is a designature process that removes the source array effects from the recorded data. Using the layered earth assumption, the demultiple/designature can be applied very efficiently to each separate CR gather individually with a cost comparable to PZ summation. The imaging step consists of 3D depth migration and is applied directly to each individual CR gather. An explicit FD migration algorithm is used, which is cost-effective due to the large number of traces in each gather.

Because the overburden down to the Base Cretaceous level does not show significant lateral variation we find that the layered model designature/demultiple scheme works satisfactorily on 3D-OBS seismic data. The P-wave depth sections from the Gullfaks Sør seismic survey show that the designature/demultiple algorithm provides images with less multiples and better continuity of target reflectors than the conventional multiple attenuation approach.

Acknowledgments

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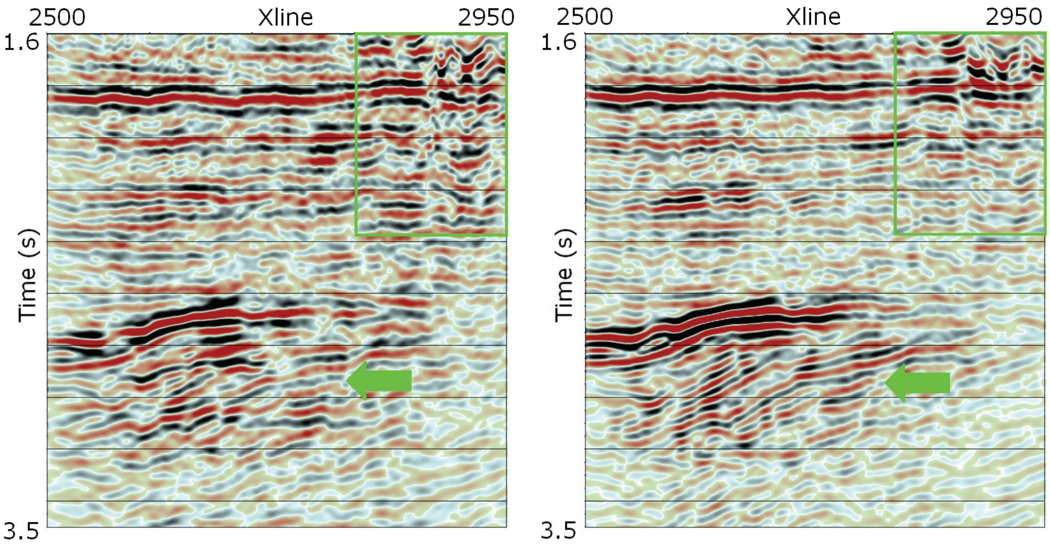

Figure 2: (Left) Inline 1751 after standard pre-processing and (Right) after Amundsen-type demultiple.

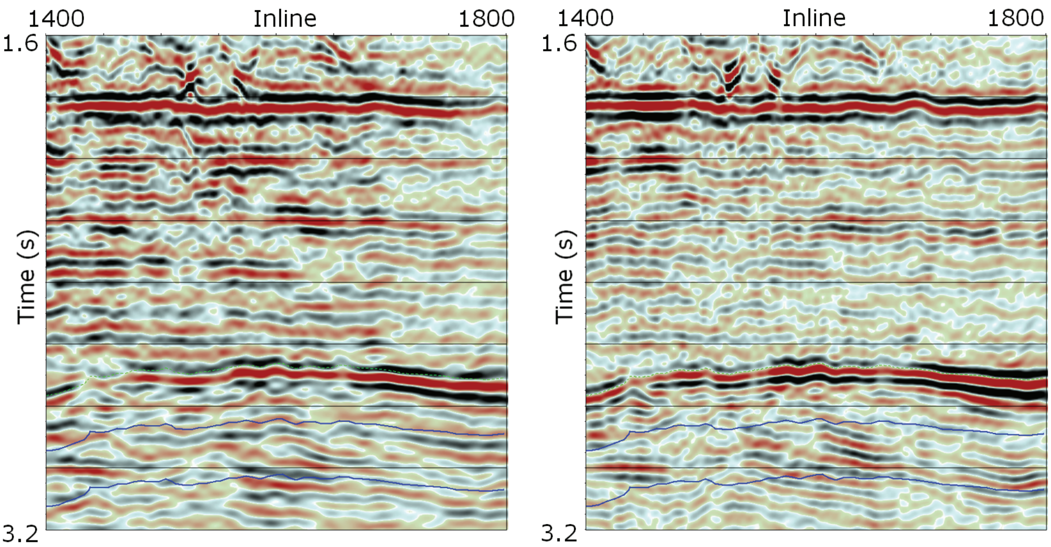

Figure 3: (Left) Crossline 2601 after standard pre-processing and (Right) after Amundsen-type demultiple. The blue lines mark the time of the first- and second-order multiple.