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Measurement and Dynamic Wavefield Correction for Time-dependent Water-velocity Changes

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SUMMARY

Changes in water velocity produce significant 4D noise in time-lapse images. To be addressed accurately, the water-velocity problem requires two major ingredients: 1) water velocity must be estimated accurately at all acquisition times and for all shot/receiver locations, 2) time-variable corrections to the data must be dynamic to treat the full wavefield accurately. We present a new approach to parameterization of water-velocity changes which minimizes sensitivity to water depth, allowing data redundancy to be exploited to increase robustness and precision of water velocity estimation. Dynamic correction of the wavefield is then achieved by designing 3D time-variable phase-shift operators that extrapolate data through the water column with a time-variable water velocity and re-extrapolate back to the acquisition datum with a stationary (reference) velocity. This is applied in a tau-px-py least-squares modeling process. Application of the method to deep-water OBN data shows significant improvements in data repeatability, decreasing 4D noise and increasing focus and clarity of the 4D signal.

Introduction

Changes in water velocity during the life of a seismic survey create busts in the seismic record for shots adjacent in space but separated in time (Wombell, 1997). Water-velocity changes can be as high as 10 m/s, creating busts of tens of milliseconds for deep-water data. These busts are dynamic and vary with offset and arrival time. Furthermore, the location and magnitude of the busts are non-repeatable, and create a significant level of 4D noise in time-lapse surveys. Even in cases where the shot and receiver positioning is highly repeatable, 4D noise in the acquired data can be strong due to non-repeatability of arrivals that have passed through a changing water column (Figure 1).

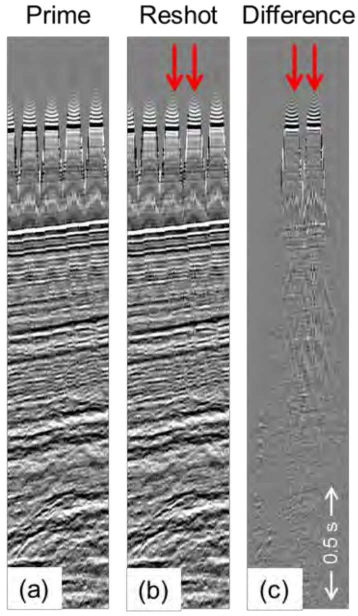

Figure 1 *(a) Baseline OBN stack. (b) Stack with two receivers (red arrows) replaced and reshot. (c) Difference between (a) and (b). Energy in the difference is dominantly caused by changes in water velocity.*

The water-column problem has been known for many years and typically addressed with static time-shifts of the traces. Static shifts can be modified for offset-dependence (Mackay et al., 2003), or converted to dynamic corrections using normal-moveout style equations. Lacombe et al. (2006) use normal-moveout transforms applied first with a variable water velocity that models the acquired data, and then removed with a different, reference, water velocity. Normal-moveout based methods are attractive in their simplicity and robustness. However, they model all arrivals as primary reflections, and it is difficult to accurately correct back- or side-scattered energy. Calvert (2005) describes a generalised concept for full dynamic correction using wavefield extrapolation to the water bottom with a time-variable water velocity, then extrapolation back to the acquisition datum at the desired reference velocity. To be accurate for the full wavefield the extrapolations must be conducted in 3D and with time-variant operators, correctly handling busts in the recorded data. Since real wavefields do not propagate with busts in the wavefronts it is not straightforward to conduct this style of extrapolation.

The following sections describe how time-variant 3D extrapolation operators can be constructed in practice, and used as part of a least-squares modelling process to estimate the seismic wavefield as it would have been if it were acquired with a stationary water velocity. The method is demonstrated in 4D using deep-water ocean-bottom node (OBN) data. Accurate measurement of time-dependent water velocity is also addressed, with a new method able to estimate velocities from seismic data to an accuracy level similar to specialised Pressure Inverted Echo Sounders (PIES: Wang et al., 2012).

Method

Average water velocity can be calculated from picked traveltime measurements (usually the direct water-wave or its first multiple) after ray-tracing to determine the path-length of the arrival. By repeating this for a range of shots a time series of average water velocity can be obtained. However, in deep-water the speed of sound is depth dependent, and this creates a strong correlation of measured average velocity with the water depth at the location of measurement. This depth dependence is apparent as a low-frequency trend in Figure 2a, in which the acquisition time correlates with water depth due to a gradual progression of the shot carpet from shallower to deeper water. Depth-dependence prevents meaningful averaging of redundant water-velocity measurements made on receivers at different water depths. To minimise the effect of depth dependence on the velocity time series, and to exploit the full redundancy of the data, time- and depth-dependent water velocities are re-parameterised in terms of a velocity perturbation. This allows averaging in a running-window of acquisition time, such that water-velocity estimates become statistically more accurate (Figure 2b).

The velocity perturbation is parameterised in terms of a depth-dependent reference velocity function, $v\ (z)$, and a perturbation function, $f(z)$, that alters the reference profile in a defined depth interval (Figure 2c). The perturbation function is scaled by a time-dependent factor $q(t)$ such that the time- and depth-dependent water velocity becomes $v_w(z,t) = v_0(z)[1 + q(t)f(z)]$. The perturbation is restricted in depth to reflect real changes of salinity and temperature that occur in the ocean. With picked traveltimes, ray-tracing through $v_w(z,t)$ produces a time series of perturbation scalars, $q(t)$, that are insensitive to water depth. The measured $q(t)$ is averaged in time intervals to exploit the redundancy of the data and increase the robustness and precision of the final time series. In Figure 2b, $q(t)$ is used to evaluate water velocity at the same depth as the PIES instrument for comparison, although $q(t)$ can be evaluated at any depth.

The effect of time-variable water velocity on the wavefield is corrected using a 3D extrapolation approach with time-variable operators. This is achieved by least-squares modelling of data in the 3D tau-px-py domain, where data is naturally decomposed into plane waves. The tau-px-py transform operators are modified to incorporate the effect of time-dependent water velocities such that the model itself is free of these effects. Once a clean model is obtained, it is reverse transformed back to the data domain with a stationary water-velocity profile used in the operator. The output is then the seismic wavefield as it would have been recorded with stationary water velocities. The time-variable transform operators are written as the adjoint pair $\boldsymbol{d} = \boldsymbol{L}^r\boldsymbol{\psi}$ and $\boldsymbol{\psi} = \boldsymbol{L}^f\boldsymbol{d}$ for model $\boldsymbol{\psi}$ and data $\boldsymbol{d}$. The forward transform operator is written

$$i\omega[(x \quad y) + \quad _e(p \quad)] \,, \tag{1}$$

for horizontal coordinates x,y, corresponding slownesses p_x,p_y, angular frequency and where 1. The function Δt_e models time variability in the transform. The effect of is to form plane waves by slant-stacking across a busted, or corrugated, plane through the data. The problem hinges on quantifying Δt_e so that the plane-wave transform correctly incorporates water-velocity changes. By carrying out two wavefield phase-shift extrapolations, one in the measured water velocity and one in the reference velocity v_0, we obtain

$$(p \qquad) \quad [- \ (\qquad)] \ (1 \ -) + [\Delta \qquad](1 \ -) \,, \tag{2}$$

where $(\qquad)$ are the components of the 3D slowness vector in the reference water velocity and $(\Delta x, \Delta y, \Delta z)$ are the components of a displacement vector from the shot to the point at which the specular ray crosses the seafloor. The tau-px-py model is derived in a least-squares sense using sparseness weighting (Hermann et al., 2000) to deal with aliasing in the transform. A rugose waterbottom is handled by allowing $(\Delta x, \Delta y, \Delta z)$ to vary across shots and as a function of the slowness coordinates in the model domain. The different kinematics of primary and multiple arrivals are handled by jointly finding primary and multiple models that reverse transform and sum to describe the input in a least-squares sense. The separation of primaries and multiples is helped by an initial set of weights derived from a multiple model. The effect of changing water velocity on multiples is

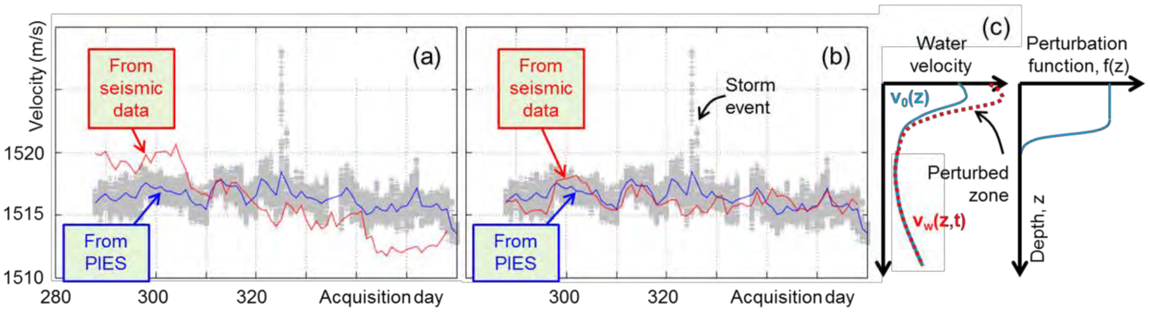

Figure 2 *(a) Measured (red) water velocity from seismic data using velocity parameterisation. (b) Using the depth-insensitive perturbation parameterisation depicted in (c). Blue lines are a running day-average of Pressure-Inverted Echo Sounder (PIES) measurements (grey).*

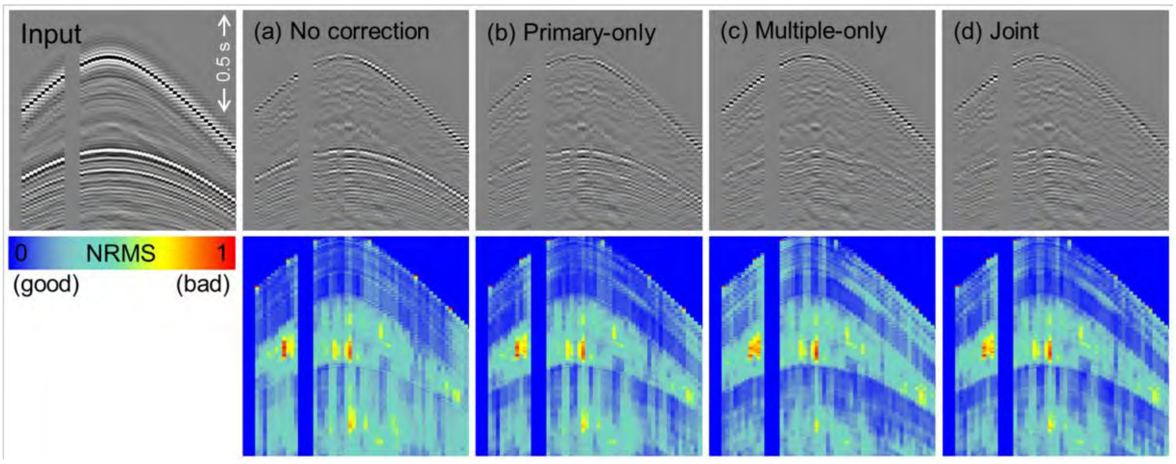

Figure 3 *Baseline OBN receiver gather (hydrophone) with 4D difference to monitor data (top) and NRMS plots (bottom) after different flavours of dynamic wavefield correction.*

described by increasing the extrapolation distance to account for three passes through the water layer.

Results

Results of the dynamic correction process are illustrated first using a single OBN receiver gather redeployed and re-shot with receiver positioning repeated to <2 m and shot positioning repeated to <8 m (Figure 3). The primary-only correction produces a slight repeatability improvement to primaries (most visible in the NRMS plots). With multiple-only correction, a more significant improvement is observed but this time to the multiples. The improvement is greater for multiples because energy passes through the water column three times, creating larger 4D non-repeatability in the data. The multiple-only correction degrades the 4D match of primary arrivals, however, since these are over-corrected. The joint primary and multiple correction is used with separated wavefields (Osen et al., 1999) as weight functions. This improves the repeatability of multiples while maintaining the repeatability of primaries.

The second example (Figure 4) uses deep-water OBN data shown after migration of the hydrophone component. The baseline and monitor surveys are co-processed through a fast-track flow without 4D matching filters applied. With no water-column corrections the main 4D fluid-production signal around an injection-well is visible on horizon extractions. Application of measured water-velocity corrections using static trace shifting actually degrades the 4D signal quite significantly. Meanwhile, dynamic correction increases 4D repeatability, sharpens the main 4D fluid-production signal in the horizon extraction, and also adds nearly 3 dB to the shallow 3D image as the data become better modelled by the water-velocity profile used in the migration (inset detail). With dynamic correction the 4D repeatability also improves both above and below the shallow anomalies (arrows) believed to be some form of shallower 4D fluid changes.

Conclusions

Water-velocity changes in 4D surveying require accurate time-dependent velocity measurements in an area covering the receiver and shot arrays. Data must then be dynamically corrected for the effects of measured water-velocity changes. By describing water velocity in terms of a perturbation time series it is possible to decouple time-dependence from depth-dependence and exploit the redundancy of shots and receivers to increase the precision of water-velocity estimation from seismic data. Time-variable 3D wavefield extrapolation through the water column and then back to the acquisition datum with a stationary water velocity allows a dynamic wavefield correction to be made to the data to increase its repeatability. Application of this as a tau-px-py least-squares modelling process produces data free of the effects of time-variable water velocities. This process is tested using 4D data from deep-water OBN surveys, and shown to improve the repeatability of the data.

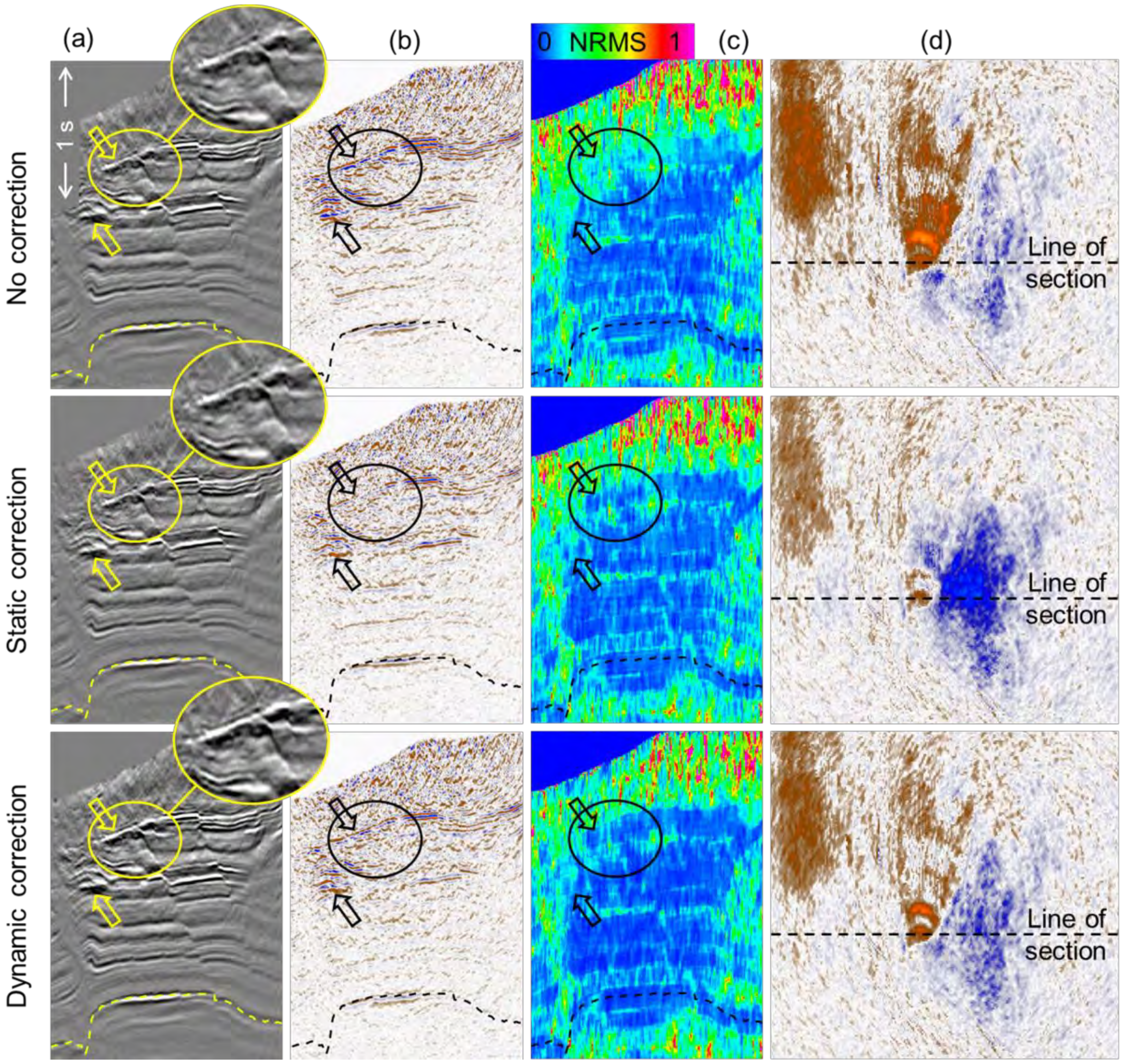

Figure 4 *Baseline images (a), 4D differences (b), NRMS (c) and amplitude from the 4D difference extracted on the dashed line (d). Inset detail highlights relative amplitudes on the baseline image.*

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