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Dip-angle Image Filtering for 4D Processing of Towed-streamer and OBN Datasets

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SUMMARY

Ocean-bottom data are often acquired in the development and production stages of an oilfield's lifecycle to guide well placement and water injection strategy. Although well suited to time-lapse monitoring, this type of ocean-bottom survey will miss the first time-step in which a field is explored, appraised, and undergoes initial fluid production. To capture this time step it is necessary to 4D co-process ocean-bottom data with the exploration dataset, usually surface towed streamer. Our example from the North Sea benefits from flexible trace pairing to produce high-fold subsets of the input data that generate more similar images than would otherwise be available. However, residual multiple generates significant 4D noise, as does un-cancelled migration operator from the very different, irregular, survey geometries. Migration to: (1) common-offset, (2) scattering-angle, and (3) dip-angle output domains provide opportunity to explore similarity-filtering strategies with the data. The scattering- and dip-angle gathers respond well to similarity filtering, but results show greater spatial resolution, signal continuity, and coherence when dip-angle gathers are used. Dip-angle is an intuitive domain in which to locate and attenuate un-cancelled migration operator in 4D, which is advantageous as migration noise is a major source of 4D noise in these data.

Introduction

Towed-streamer surveys and ocean-bottom surveys have few acquisition parameters in common, and a 4D comparison defies the conventional wisdom that success in 4D requires acquisition repeatability (Calvert, 2005). Nevertheless, both datasets contain information about the Earth's subsurface, and one would expect a meaningful 4D comparison could be made if they were processed and imaged appropriately. Several authors have tried this with methods including least-squares migration (Ayeni & Biondi, 2010), pre-migration time shifts and amplitude matching (Duffaut *et al*., 2003; Helgerud *et al*., 2012), and sub-surface 4D binning (Haacke *et al*., 2013). A more pragmatic view allows the migration to produce different images, but then subjects the output to a filtering process that enhances the similarity between baseline and monitor such that 4D signal is more easily discernible (e.g. Hatchell *et al*., 2012; Huang *et al*., 2014). Finally, Theriot (2015) describes a method of post-migration pre-stack matching that reportedly serves well in difficult cases. In this technique, the baseline and monitor images are partitioned by scattering angles, from which match filters can be produced that vary smoothly in time, space, and scattering-angle.

This contribution describes the use of dip-angle gathers for the purpose of post-migration 4D matching. While the scattering-angle domain partitions an image by the angle between the source and receiver rays (Figure 1a), the dip-angle domain partitions the image by the angle of the migration operator from the vertical (Audebert *et al*., 2003). The dip-angle domain differs from the scattering-angle domain quite significantly in terms of the migration output, although both domains sum to the same final result if no post-migration processing is applied.

One particular advantage of the dip-angle domain is the intelligent selection of data via dip-controlled muting (Klokov & Fomel, 2013). We argue that another particular advantage for 4D processing is the ability to apply similarity filters on the dip-angle gathers to select parts of the migration operator that are in common between baseline and monitor, and parts which diverge due to major differences in acquisition geometry: e.g. a different receiver datum (Figure 1b). The effect of different acquisition geometries produces an intuitive difference in the expression of un-cancelled migration operator when considered in the dip-angle domain. Since un-cancelled migration operator is a very significant cause of 4D noise, this is an advantage to be levered energetically.

Method

The baseline dataset consists of legacy narrow-azimuth Towed Streamer (TS) data with 4 km maximum offset, 6 cables separated by 50 m towed at 6 m depth, and with shots every 18.75 m in-line. Subsurface bins of 12.5×12.5 m hold a nominal fold of 106. Meanwhile the monitor dataset is a modern Ocean-Bottom Node (OBN) survey with receivers on a 300 m square grid and shots on a 25×25 m carpet. Although the source array configurations, volumes and depths are different (towed at 5 m and 6 m depth respectively), modern deghosting and designature techniques (e.g. Wang *et al*., 2015) are effective in addressing these issues during pre-processing.

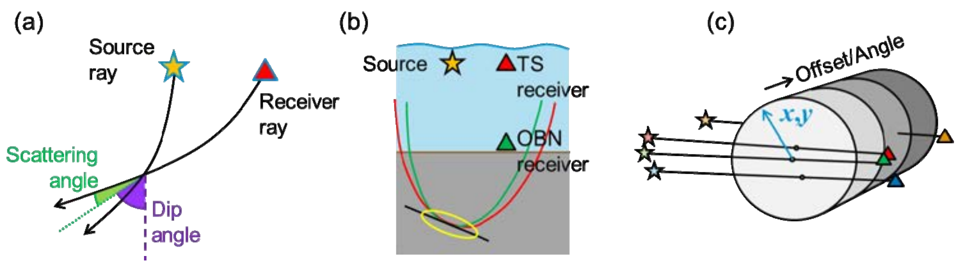

Figure 1 *(a) Definition of scattering- and dip-angles. (b) The 4D image is formed at dip-angles where the baseline (red) and monitor (green) migration operators tangentially overlap (yellow ellipse). Away from this area, the migration operators diverge when the receiver datum is significantly different. (c) Flexible pairing allows each trace in the monitor dataset to find its best match from the entire baseline dataset, searching across space and surface offset or subsurface angle.*

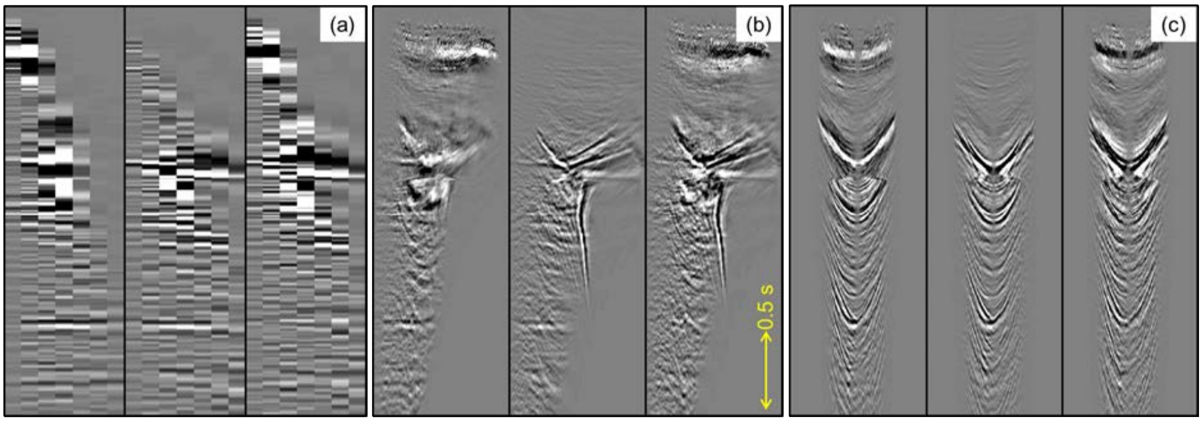

Figure 2 *(a) A single image-point gather from common-offset Kirchhoff migration with towed-streamer baseline (left), OBN monitor (middle) and 4D difference (right). Data is plotted after application of post-stack match filters. (b) Equivalent image point partitioned by scattering-angle in range 0 – 60 degrees. (c) Partitioned by dip-angle in range -89 – 89 degrees.*

The survey area is located in 95-110 m of water in the North Sea, in an area notorious for strong water-layer multiples that migrate on top of and all around the target horizons. Both datasets are subjected to strong 3D multiple attenuation techniques from the standard modern toolbox. Although attenuation of the multiples is significant, residual multiple contributes to high levels of 4D noise.

A key pre-processing step is the 4D binning of data to produce subsets with similar properties as input to the migration. Instead of binning in the conventional sense, with common mid-point bins used to associate traces, we follow a flexible pairing approach (Figure 1c) in which each input OBN trace is allowed to search across the full TS dataset to find the trace that matches it best as measured by a windowed cross-correlation after normal moveout. Flexible pairing is allowed to select the same TS trace to match different OBN traces, which is a philosophical choice to maximize similarity where possible. After flexible pairing, poorly matched traces are removed by thresholding the cross-correlation value.

Finally, the TS and OBN data are imaged with pre-stack Kirchhoff migration to three different output domains (Figure 2). The first of these is the common-offset domain, in which input data is partitioned by surface scalar offset. The second is the scattering angle domain, and the third is the dip-angle domain. In the latter two the image is partitioned according to the properties of the migration operator rather than the acquisition properties of the input data.

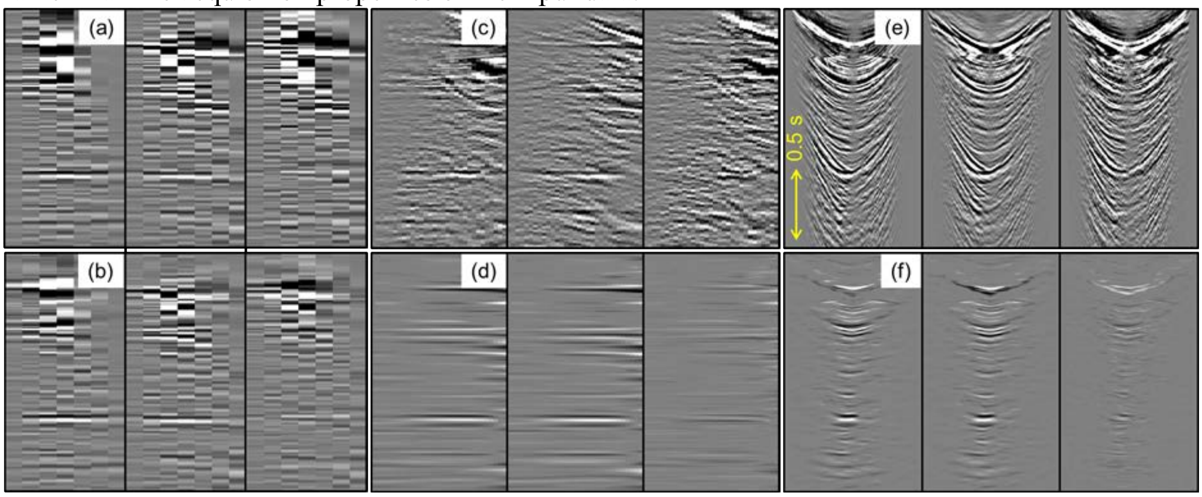

Figure 3 *A single image-point gather for Towed-streamer (left), OBN (middle) and 4D-difference (right): (a) input common-offset data, (b) preconditioned and similarity-filtered common-offset data, (c) input scattering-angle data, (d) preconditioned and similarity-filtered scattering-angle data, (e) input dip-angle data, (f) preconditioned and similarity-filtered dip-angle data.*

Each output gather is further processed to enhance similarity between baseline and monitor (Figure 3). In this step the additional redundancy of traces in the scattering- and dip-angle domains, compared with the common-offset domain (for which the offset classes are wide due to the sparse OBN geometry), is advantageous to filter design and implementation.

The similarity filter is a point-by-point cross-correlation weight calculated after preconditioning of the gathers to suppress non-flat energy. Preconditioning is tailored to suit each type of gather. The scattering-angle gathers work well with AVO-preserving wavenumber-filters applied to each time sample, while the dip-angle gathers benefit from an f-k filter applied to the full gather. These preconditioning processes have almost no effect on the stack. A post-stack match filter is then designed on a strong overburden horizon and applied to the pre-stack gathers. This is done after similarity filtering to ensure the match is made on clean signal. Finally, a 0-30 degree mute is applied to all gather types, which are then stacked.

Results

After f-k filtering the dip-angle gathers reveal stationary parts that form the image, which include main bands of signal at the dominant geological dip, but also energy from conflicting dips at higher angles. There are clear areas in which the TS and OBN data are the same, and clear areas in which they are different, due mainly to different residual multiples and un-cancelled migration operator. The similarity filter removes a lot of energy deemed non-repeatable between the images, with a 30 degree dip-angle mute making a further minor improvement.

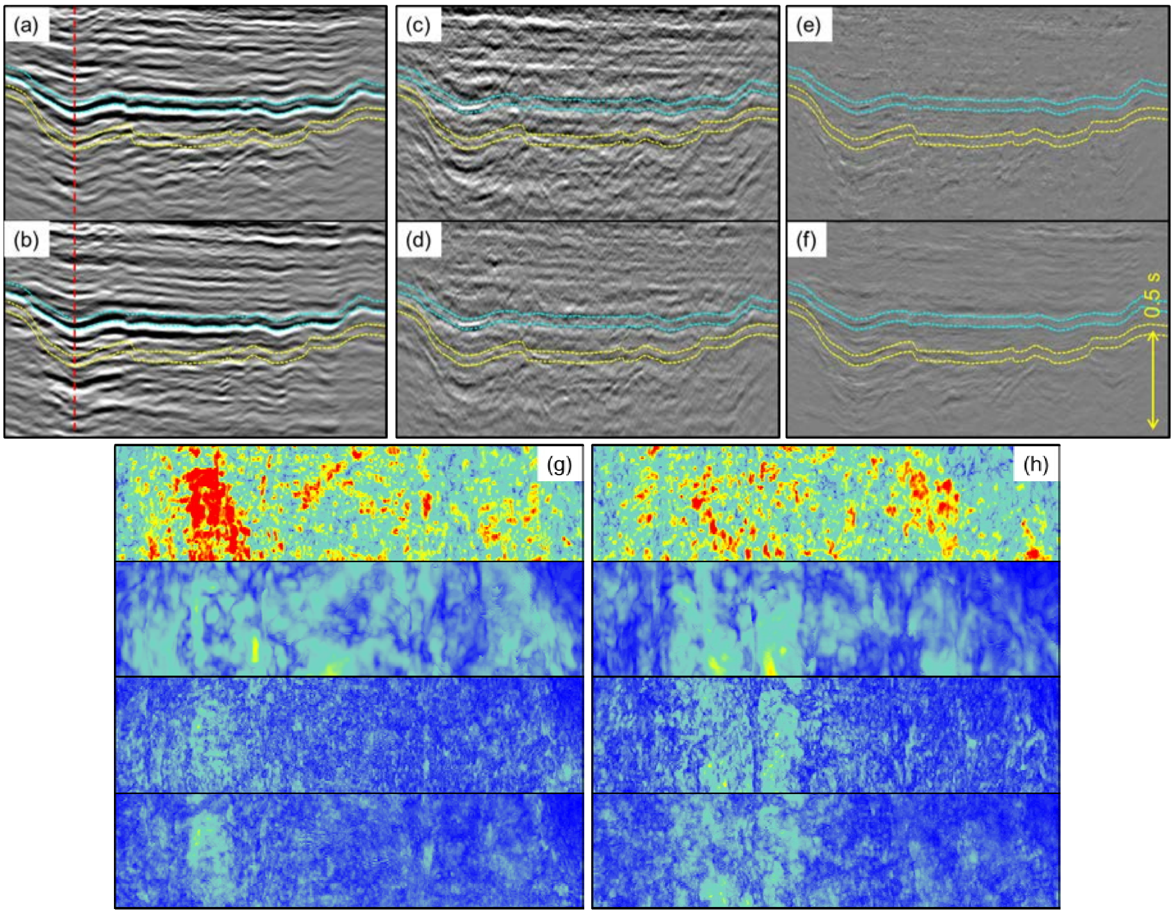

Figure 4 *Stacked baseline (a) and monitor (b) images, then 4D differences after match filtering in the overburden: (c) raw common-offset data, (d) common-offset data after similarity filtering in gathers, (e) scatting-angle data after similarity filtering, (f) dip-angle data after similarity filtering. The lower panels show maps of peak absolute amplitude extracted in the blue interval (g) and in the yellow interval (h) with sub-panels arranged vertically (top-bottom) to correspond with sections (c-f) respectively.*

In stack form and in horizon attribute extractions, results (Figure 4) show evidence of faulting and 4D signal coincident with reservoir lithology in all but the raw 4D differences. The patterns of signal in Figure 4h suggest sweep related to the two main injectors lying off the bottom of the maps. Whereas the filtered common offset data appear to indicate a high level of connectivity, the scattering- and dip-angle data show evidence for reservoir heterogeneity that may be significant in explaining field behavior and influencing future development decisions. The dip-angle results also show an overall improvement in the continuity and coherence of the 4D image compared with other results.

Conclusions

Tests with towed-streamer baseline and sparse Ocean-Bottom Node monitor data in this North Sea study show significant advantages of scattering-angle and dip-angle migration outputs for similarity filtering. This is particularly intuitive in the dip-angle domain, where filtering targets residual multiple and un-cancelled migration operator that produce the bulk of 4D noise. Similarity filtering in this case provides an improved spatial resolution and a greater level of coherency and continuity in the output than when applied to common-offset or scattering-angle gathers.

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