A cross-equalization processing flow for off-the-shelf 4D seismic data

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SUMMARY

Seismic reservoir monitoring is a new technology that involves interpreting differences between different generations of 3-D seismic data in terms of changes in reservoir properties over time. A vast number of 3-D seismic surveys are repeated, in whole or in part, for reasons other than reservoir monitoring. In this paper, we cross-equalize two off-the-shelf migrated datacubes over a Gulf of Mexico field with favorable reservoir properties, to see whether their time-lapse nature can be exploited for reservoir monitoring purposes. Key elements in the processing flow include spatial realignment to a common grid, wavelet equalization by L_2 matched-filtering, warping to compensate for different stacking/migration velocities, and amplitude balancing. A balance is struck between global and local operators to ensure a clean cross-equalization result without inadvertently removing changes due to fluid production.

INTRODUCTION

Seismic reservoir monitoring aims to use multiple 3D seismic surveys acquired at different calendar times to directly image fluid movements, pressure/temperature fronts or other effects of production in the subsurface (e.g. Lumley, 1995). Unfortunately, different generations of 3D seismic can exhibit seismic differences unrelated to reservoir production, caused by different (or non-repeatable) seismic acquisition and processing artifacts. The aim of cross-equalization is to remove processing and acquisition differences between time-lapse seismic surveys, so comparison between them can be interpreted in terms of genuine fluid-related changes.

Since reservoir monitoring is a relatively new technology and individual case studies tend to vary significantly, the industry has not developed a standard 4-D processing flow. However, cross-equalization of post-stack seismic datasets typically includes the following generic elements:

1. Survey realignment to a common grid, including spatial and temporal re-registration to correct the effects of geometry errors, differential statics, or different velocity functions used for NMO and migration.
2. Bandwidth and phase equalization to compensate for different source wavelets, for example.
3. Amplitude balancing to scale the data to the same amplitude (or energy) level.

3-D seismic surveys are often repeated for purposes other than reservoir monitoring (improvements in acquisition technology, imaging different targets etc.). In these cases, additional processes may need to be considered to balance spatial frequency or dip-content, for example.

Gulf of Mexico example

Figure 4 shows panels from two very different marine datasets shot over a salt diapir in the Gulf of Mexico. The left-side of Figure 4 is very early 3-D, shot by Chevron in 1979. The right-side is contractor (spec) data from 1991/1992.

Classic G.o.M. rock physics means the reservoir would score well in a technical risk assessment (Lumley et al., 1997). However, questions of seismic repeatability cast doubt over the success of a 4-D project.

Improvements in 3-D technology over the 12 years between surveys have resulted in large differences in quality between them. For example, as well as having very different geometries, it is apparent that they have been processed very differently too. Most noticably the 1991 dataset was migrated with a turning-ray alogorithm, to image the overhanging salt-flank. The 1979 dataset contains a much lower dip range.

Ideally we would like to go back to the pre-stack seismic data, and perform some kind of inversion to estimate a common Earth model. If this not possible, we should at least reprocess one of the datasets to be consistent with the other. However, for these datasets (and many others) finding the pre-stack tapes is impossible, or at least prohibitively expensive. Even if the pre-stack tapes were available, the cost of reprocessing them will be high. As a result non-production related differences between these surveys have to be removed by cross-equalization in the post-stack domain.

In this paper, we demonstrate a powerful post-stack cross-equalization flow with the aim of determining whether *any* useful information can be obtained from these off-the-shelf processed datacubes. The processing flow is robust, and addresses non-stationarity through the use of spatially-variable operators.

SPATIAL REALIGNMENT

Unless two surveys have been shot with the aim of reservoir monitoring, it is likely that they will have significantly different geometry; and unless they have been processed for reservoir monitoring, they may also be binned very differently.

The left side of Figure 1 shows the areal coverage of the two Gulf of Mexico datasets, and their 34° difference in azimuth. The 1979 survey covers a larger area, but there is a significant overlap. The right side of Figure 1 shows a close-up of the bin-centers in part of the survey. The 1979 survey was shot and processed with bin-spacings of 82.5 ft (in-line), and 247 ft (cross-line); whereas the 1991 survey has 41 ft bin spacings in both the in-line and cross-line directions.

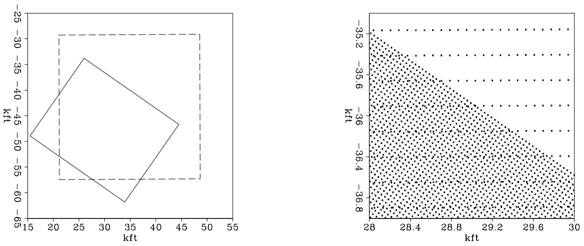

Figure 1: Post-stack geometries. Left panel: the spatial coverage of the 1979 survey (dashed-line), and the 1991 survey (solid-line). Right panel: close-up of the different bin-spacings between the 1991 (denser) and 1979 (less dense) surveys.

To compare the two surveys, the first step is to realign them both onto a common grid. In this case, we applied a spatial anti-aliasing filter in the (k_x, k_y) domain, and regridded the 1991 survey onto the 1979 grid. Since the 1991 survey was spatially-sampled so much more finely than the 1979 survey, a linear interpolation algorithm was used for the regridding, without causing artifacts.

MATCHED-FILTERING

Matched-filtering (Claerbout, 1991) can simultaneously estimate a correction for static, phase and spectral differences between surveys. A cross-equalization operator, $\mathbf{A}$, can be designed to minimize the norm of the residual,

$$\mathbf{r} = \mathbf{A}\mathbf{d_1} - \mathbf{d_2} \tag{1}$$

where $\mathbf{d_1}$ and $\mathbf{d_2}$ are the operator "design windows" of the two data sets to be matched. $\mathbf{A}$ is then applied to the whole dataset, including the area of interest.

In this paper, we solve for $\mathbf{A}$ as a time domain convolution operator by minimizing the residual, $\mathbf{r}$ in a least squares (L_2) sense. The degree of spectral matching, essentially the number of degrees of freedom, is then controlled by the length of the time domain operator. By working with a short operator of a similar length to the two wavelets being matched, the operator can provide the "right amount" of spectral shaping: a close enough spectral and phase match to compensate for differences in wavelets and residual statics between the two surveys, while avoiding an over-match that can zero out differences in the data sets caused by petrophysical changes during reservoir production.

Figure 2 shows the amplitude spectra for the two datasets before and after matched-filtering. The frequency content of the 1991 spectrum is much wider than the 1979 data, suggesting that the 1991 survey has the higher useful bandwidth. As an initial pre-processing step, we low-pass filtered the 1979 survey to 60 Hz and resampled from 4 ms to 6 ms to coincide with the 1991 survey.

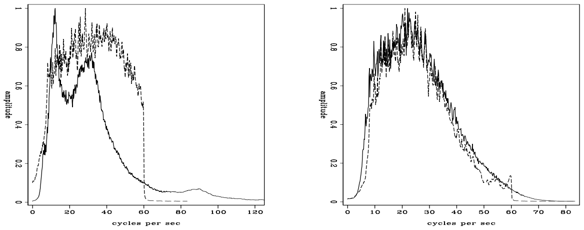

Figure 2: Amplitude spectra before (left) and after (right) matched-filtering. The solid line corresponds to the 1979 survey and the dashed line to the 1991 survey.

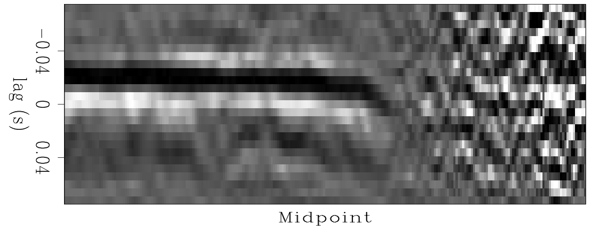

Figure 3: Matched-filters from an in-line slice. The salt begins at approximately $2/3$ of the way across the panel, coinciding with the noisy filters.

The matched-filtering operators, $\mathbf{A}$ were designed to map the higher quality 1991 survey to the 1979 survey. Figure 3 shows example operators. Separate filters were then designed for each trace, by considering a design window from 0.5 s to 2.0 s depth (above the reservoir zones) and three traces wide in the in-line direction. The filters show a consistent shape in the left-hand side of the Figure, but become noisy in the salt, where there are no reflectors. Just before the salt you can see the static shift associated with the filters change due to the different imaging of the dipping reflectors.

Close inspection of the matched-filters reveals an average phase-shift between 45° and 90°, and an average residual static correction of about one time sample (6 ms). The matched-filters equalize the amplitude spectra of the two datasets, as shown in the right of Figure 2.

As well as matching wavelets and small residual static shifts, a matched-filter also has an associated amplitude correction. However this amplitude correction may be significantly biased by the presence of noise in $\mathbf{d_1}$ (Rickett et al., 1997), so an additional amplitude balancing step is required.

AMPLITUDE BALANCING

Whether an AGC window or a more careful geometric spreading correction has been applied, two generations of seismic survey will, in general, have different time-varying gain functions applied to them. If not compensated for correctly, this may lead to a systematic leakage of non-reservoir events into the difference section. Although an amplitude correction may need to be time and space-varying, it should be constrained to vary very slowly, so it is not influenced by changes in the reservoir zone.

The simplest approach to amplitude balancing is to scale the data based on the r.m.s. energy in the two surveys. However, this assumes that the energy present in the noise fields are the same in both datasets, or of much smaller magnitude than the signal energy. As an illustration we can consider two normalized datasets, $\mathbf{d_1}$ and $\mathbf{d_2}$, to consist of some shared signal, $\mathbf{s}$, and uncorrelated "noise" components, $\mathbf{n_1}$ and $\mathbf{n_2}$, which include the reservoir difference anomaly we seek:

$$\mathbf{d_1} = \frac{1}{|\mathbf{s}+\mathbf{n_1}|}\left(\mathbf{s}+\mathbf{n_1}\right) \tag{2}$$

$$\mathbf{d_2} = \frac{1}{|\mathbf{s}+\mathbf{n_2}|}\left(\mathbf{s}+\mathbf{n_2}\right) \tag{3}$$

In order to rescale the signals to the same level, we need to apply a scale factor, ν to $\mathbf{d_1}$, where

$$\nu = \frac{|\mathbf{s}+\mathbf{n_1}|}{|\mathbf{s}+\mathbf{n_2}|} \tag{4}$$

or again assuming the noise fields are weakly correlated with the geological signal

$$\nu \approx \frac{\sqrt{\mathbf{s}^2+\mathbf{n_1}^2}}{\sqrt{\mathbf{s}^2+\mathbf{n_2}^2}} = \sqrt{\frac{1+\frac{1}{s_1^2}}{1+\frac{1}{s_2^2}}} \tag{5}$$

where s_1 and s_2 are the signal-to-noise levels in the two datasets. For high ($s_1 \gg 1$ and $s_2 \gg 1$), or similar ($s_1 \approx s_2$), signal-to-noise levels ν reduces to unity, and the equal energy condition is valid.

For the field examples in this paper, the equal energy condition was used to balance the filter amplitudes. This is a reasonable assumption for many examples, and does not require independent estimates of the signal-to-noise ratio.

WARPING

Different NMO and migration velocity functions may cause both the traveltime depth and spatial postitioning of imaged reflectors to differ between surveys. Moreover, the degree of mispositioning will vary throughout the 3-D seismic volume. Although static time corrections may provide a partial solution, static corrections will not co-locate reflectors imaged at different lateral positions, nor will they allow for dynamic (as opposed to static) time-shifts that vary as a function of traveltime depth.

Even small shifts (less than a sample interval in magnitude) may cause enough misalignment that false events appear in the difference sections. Without access to the full pre-stack data, there are a limited number of ways such differences can be corrected.

Residual post-stack migration (Rothman et al., 1985), or velocity continuation (Claerbout, 1986; Fomel, 1997), provide operators that map between different migration velocities. However, without detailed knowledge of the velocity fields used for NMO and/or migration, and in cases where the migration algorithms differ significantly between surveys, it will be difficult to determine the correct residual migration operator to apply *a priori*. Instead the operator may have to be estimated from the data.

As an alternative to standard residual migration, we use a 'warping' operator (Wolberg, 1990) to correct for kinematic differences between surveys. A 3-D shift vector, or 'warp-function' that maps one survey onto another can be estimated at every point in the data volume, and applied directly.

At node points throughout the seismic data-volume, we calculate local 3-D cross-correlation functions between surveys. Picking the maxima of these functions produces a sparse cube of 3-D shift vectors that map one survey onto the other. Before applying the warp, we median-filter, then smooth, then interpolate the warp-function to fill the volume. To apply the warp, we look back down the shift vector, interpolating a value at every point in the output space.

Grubb and Tura (1997) used a similar algorithm to estimate uncertainty in AVO migration/inversion results. They migrated the same dataset many times with slightly different velocity fields. They then co-located reflectors with a warping algorithm, which allowed them to separate the kinematic and amplitude effects of the different migration velocities.

Warping as residual migration

Warping provides a mapping between different migration velocities that is kinematically equivalent to velocity continuation for plane-wave events. Fomel (1997) showed this directly from the zero-offset velocity continuation equation, but it is apparent intuitively if you consider the effect map-migration (Claerbout, 1993) has on a planar dipping events. In this context, warping bears the same relationship to residual migration as 'map-migration' bears to conventional zero-offset migration. Map-migration and warping are both point-to-point operators; whereas conventional zero-offset migration and residual migration are based on a convolutional model. Warping, therefore, can be thought of as 'residual map-migration'.

The relationship between warp-function and velocity change can be derived from kinematic map-migration equations. The following three equations describe migration of a zero-offset planar event at $(\mathbf{x}_{\rm zo}, t_{\rm zo})$ dipping with slowness, $\mathbf{p}_{\rm zo}$, with velocity v:

$$t = t_{\rm zo}\sqrt{1 - v^2 p_{\rm zo}^2} \tag{6}$$

$$\mathbf{x} = \mathbf{x}_{\rm zo} - v^2 t_{\rm zo}\ \mathbf{p}_{\rm zo} \tag{7}$$

$$\mathbf{p} = \frac{\mathbf{p}_{\rm zo}}{\sqrt{1 - v^2 p_{\rm zo}^2}} \tag{8}$$

Differentiating with respect to v, and eliminating the zero-offset variables leads to the equations that describe residual map-migration along Fomel's velocity rays, providing a link between the warp-function and the residual velocity correction.

$$\Delta\mathbf{x} = -2vt\ \mathbf{p}\ \Delta v \tag{9}$$

$$\Delta t = vtp^2\ \Delta v \tag{10}$$

Using an algorithm based on map-migration may seem questionable when we are considering an amplitude-sensitive issue such as reservoir monitoring. However, for this application the shifts we apply are so small (a few sample points), that such an approach is valid.

Separating kinematics and dynamics

In some fields, notably those under steam-flood, reservoir changes have been shown to have large kinematic effects on the seismic response of the reservoir (Lumley, 1995). If the 'bricks' (3D design windows) used to calculate the cross-correlations are small enough, the shift-functions may themselves contain high-frequency information that provides information about fluid changes. Warping, therefore, may provide a way to separate the dynamic and the kinematic effects of production.

Conversely, if the cross-correlation 'bricks' are large enough, then the shift-functions will be smooth, and small localized changes due to fluid production will not influence the warp. This is the case in the data example presented here, since despiking and smoothing kept the shift-functions conservatively smooth. Despite this, warping led to a significant decrease in the overall amplitude of the difference section, and made direct comparisons between surveys simpler and more insightful.

RESULTS

Figure 5 shows the two datasets after cross-equalization. The time-slices correspond to depths above the producing intervals, where we would expect there to be no difference between the two datasets. Indeed, amplitudes in the two surveys are directly comparable suggesting a successful cross-equalization at this level in the subsurface. To fully assess whether the two datasets contain useful time-lapse information, a complete interpretation of the producing intervals is needed in conjunction with a study of production histories.

CONCLUSIONS

We have proposed a processing flow suitable for cross-equalizing off-the-shelf migrated seismic datacubes for reservoir monitoring and tested the flow on two seismic surveys from the Gulf of Mexico. After cross-equalization, amplitudes may be compared more directly making 4-D interpretation easier. The flow consisted of four basic elements, each of which has a physical basis: spatial realignment, matched-filtering, amplitude balancing, and warping.

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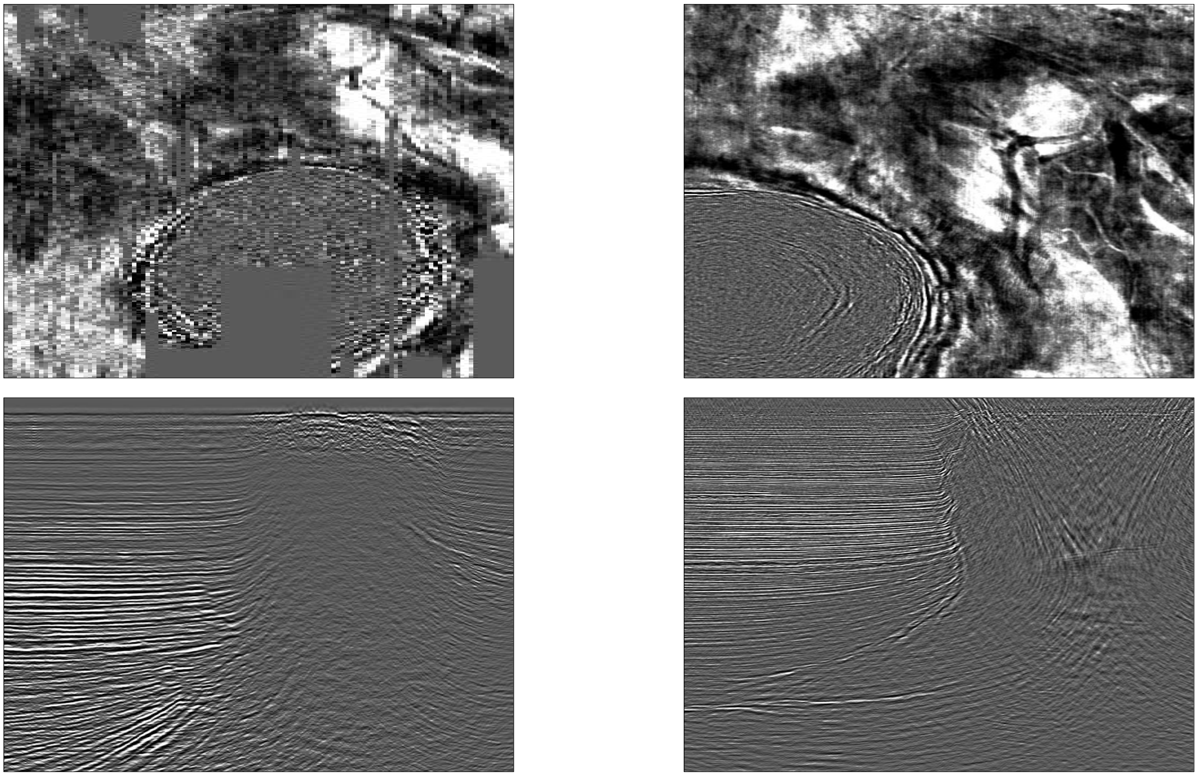

Figure 4: Before cross-equalization: panels from the 1979 survey (left), panels from the 1991 survey (right).

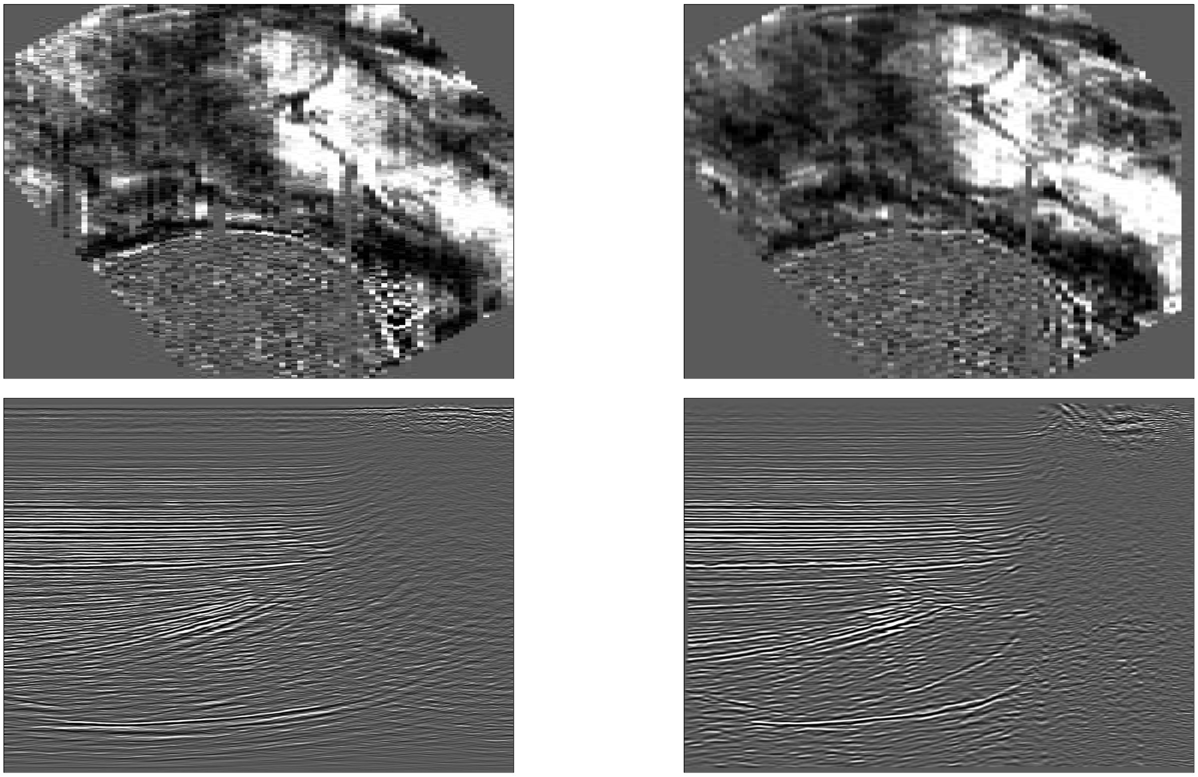

Figure 5: After cross-equalization: panels from the 1979 survey (left), panels from the 1991 survey (right).