Simultaneous time-lapse processing for optimal repeatability

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ABSTRACT

In amplitude friendly simultaneous processing of time-lapse seismic data, we introduce a strict QC scheme that steers the processing towards optimal time-lapse repeatability. We compute NRMS errors between stack traces for different phases after each main step of simultaneous processing. A processing step is considered acceptable only when its overall NRMS error value is lower compared to the value of the previous step. We demonstrate this QC scheme with a real time lapse dataset.

INTRODUCTION

A number of concepts used in this report need some clarification.

The concept of simultaneous processing of multi-vintage time-lapse datasets is well defined in Lumley, et al, 2003. The premise is to process multi-vintage datasets as one dataset, especially when they are acquired for 4D analysis purposes. We believe simultaneous processing offers the ultimate opportunity to improve time-lapse repeatability through seismic data processing. Simultaneous processing should be considered even when two different vintages of data were not designed with time-lapse analysis in mind. For example, when computing a near-surface velocity model and refraction statics for land seismic data, simultaneous processing can utilize first break arrivals from more than one dataset. Not only is the statistics for the model inversion enhanced, but also, one common solution of the near surface model can eliminate the chances of very different refraction statics solutions from the same earth. Different near surface model and refraction statics can make it very difficult to create meaningful time-lapse differences without aggressive cross-equalization in later processing steps. Atkinson (2011) shows such an example where a survey with careful 4D design ends up having different stack volumes.

Simultaneous processing also extends the meaning of surface consistency. The surface consistency concept is based on the assumption of near vertical ray paths of reflected seismic waves at near surface. It assumes a constant operator (such as a static time shift, an amplitude scalar or an earth wavelet response) at each surface location. In seismic data processing, it is more realistic to treat a source and a receiver differently even when they are located at the same surface location. Surface consistency becomes "source-receiver consistency". Moreover, in simultaneous processing of a multi-vintage 4D dataset, even two sources (or two receivers) located at the same location should be treated differently due to different source or receiver configurations for different vintages. The source-receiver consistency concept is further extended to mean "vintage specific source-receiver consistency". In this report, the phrase "surface consistent" is used in this extended definition.

The NRMS (normalized root-mean-squared) error between two traces is a standard measure of repeatability (Calvert, 2005, Atkinson, 2011). It is defined as the RMS value of the difference between two input traces normalized by the average of the RMS values

of the two input traces. The RMS values are computed in a common time window and a common frequency band. By definition, NRMS values are always between 0 and 2. For two very similar traces this value is close to zero, and for two similar traces with different polarity the NRMS value is close to 2. Often one NRMS error value is used between two vintages of a 4D survey. This value can be an average of the NRMS values computed for a selected portion of or the whole survey. Computing NRMS measurements on common CDP range of stack volumes is a common choice.

We use the term "amplitude friendly" processing for processing sequences that preserves the relative amplitude information in the prestack data. In simultaneous time-lapse processing, we believe the amplitude friendly processing sequences should be strictly followed to ensure the time-lapse characters be preserved even at the prestack stage.

There are quite a number of main processes in simultaneous processing that work differently from those in "parallel processing" (Lumley et al, 2003), where different vintages of a 4D survey are processed as separate surveys but using "exactly" the same flow. In simultaneous processing, surface consistent residual statics are determined for the objective of producing the best common CDP stacks from traces of all vintages. Other surface consistent operators, such as decon operators and amplitude scalars, are also computed by treating different vintages as a unique dataset. Stacking and migration velocities are also determined for creating the best common stack images, at least for zones expected to be time-lapse invariant.

The next section gives the details of how we implement the NRMS QC-ed simultaneous processing flow.

SIMULTANEOUS PROCESSING WITH NRMS QC

The essence of our simultaneous amplitude friendly time-lapse processing is the addition of an extra QC component to conventional amplitude friendly processing flow. The QC component includes the computation of NRMS errors from stacks of different vintage data, after each key processing step. A processing step is accepted when it increases the 4D repeatability from the previous step.

The computation of the NRMS errors is straightforward. However, we should carefully choose the time window and frequency band for NRMS computation. The time window should be restricted to times shallower than the target zones where non-repeatability should be preserved. A fair length of good quality data should be included. Too short a window or low quality data in the window, may jeopardize the statistical reliability of the NRMS error computation. The frequency band for NRMS computation should contain the frequencies with high signal to noise ratio. The band should be wide enough to contain a large majority of the reflection signal, but not include frequencies with too low signal-to-noise ratio. It is reasonable to consider using different frequency bands for data before and after deconvolution.

NRMS computation should be considered at each of the following steps in the processing flow:

  • Starting point: raw data or data with geometrical spreading correction;

- Refraction statics application;
- Surface consistent amplitude correction;
- Groundroll removal and other pre-decon noise attenuation;
- Surface consistent deconvolution;
- Surface consistent amplitude correction;
- Velocity and residual statics update;
- Post-decon noise attenuation;
- CDP trim statics;
- Poststack noise attenuation;
- Poststack migration;
- PSTM stack;

NRMS repeatability measurements can change significantly at any one of these steps. There could be other processing steps specific to individual 4D surveys that should be in the list. For example, a phase matching between different source types can make significant differences in repeatability.

DATA EXAMPLES

We have processed a 4D survey using our simultaneous amplitude friendly time-lapse processing. The seismic data was acquired for the purpose of time lapse analysis. The geophones are buried for all phases. The dynamite sources were located at exactly the same surface locations, but with possible difference in hole depth and dynamite amounts between different phases of the time lapse survey. The processing starts with exactly matched source and receiver surface locations.

There are 3 phases in this 4D survey, Figure 1 shows a number of trace "triplets" from a relatively clean part of the datasets. One triplet contains three traces from three different phases and from the sources at a same surface location and recorded from the same receiver. The traces displayed in Figure 1 are raw data with geometrical spreading correction applied. The repeatability and the lack of it are quite easy to identify. Note that when repeatability is evident in terms of wavelet shapes, the amplitude levels of the traces quite often are different. Different triplets also seem to have different amplitude levels. These amplitude differences can be corrected, at least partially, by surface consistent scaling as shown in Figure 2.

From the changes shown in Figure 2, it is expected that the repeatability will be improved on the stacks after surface consistent amplitude correction. The curves in Figure 3 clearly show such improvement. Figure 3 also contains the NRMS errors computed from stacks after refraction statics application. Refraction statics did not improve the repeatability substantially for this survey. There is a strong correlation between good repeatability and high CDP stacking fold (for NRMS curves in Figure 3 and later figures as well). This implies that noise in the survey does not repeat between different phases.

As in Figure 3, only the NRMS errors between phase 1 and 2 are shown. The NRMS errors between phase 1 and 3, and phases 2 and 3 display similar trends and we will not show them in this report.
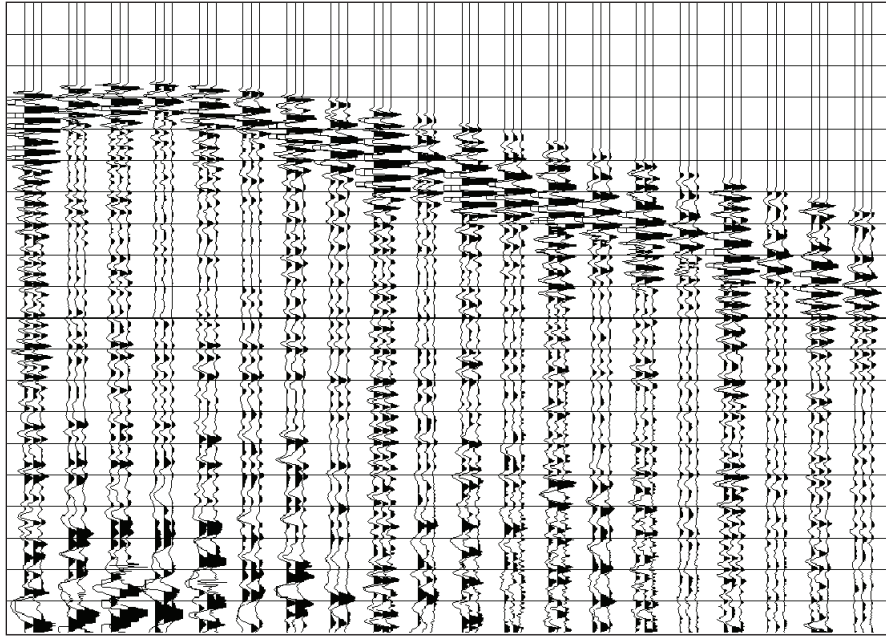
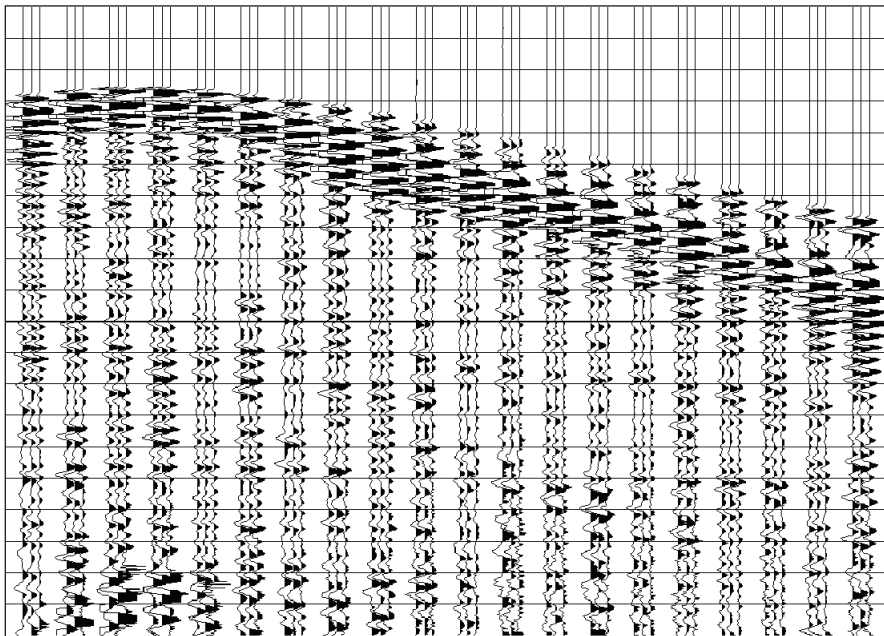FIG. 1. Trace triplets from raw data with geometrical spreading correction.

FIG. 2. Trace triplets from data with surface consistent amplitude correction
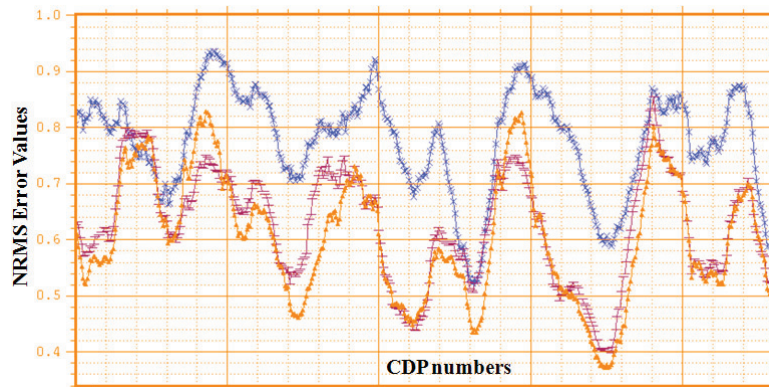
FIG. 3. NRMS error values computed between stack traces from phase 1 and 2 of the 4D survey at a range of CDPs. The horizontal axis is the CDP numbers. The CDP range displayed in this figure includes a number of stacked lines, where periodic high-low fold changes correspond to the center-edge changes between the lines. The blue line is from stacks after geometrical spreading correction, the brown line is from stacks after surface consistent amplitude correction, and the yellow line is from stacks after refraction statics correction. Note that surface consistent amplitude correction has a significant repeatability improvement over raw data. The rapid variation of these NRMS values is due to the stacking fold variation and the non-repeatable noise.

Deconvolution is a process that changes amplitude, phase and spectral content of traces the most. It is expected that the NRMS error will change dramatically after deconvolution. The NRMS curves shown in Figure 4 are from data before and after deconvolution. At high stacking fold CDP locations, deconvolution does not reduce the repeatability, and at some places it improves the repeatability. However, it significantly reduces the repeatability at low fold locations. This again, is due to the non-repeatable noise in broader bandwidth.
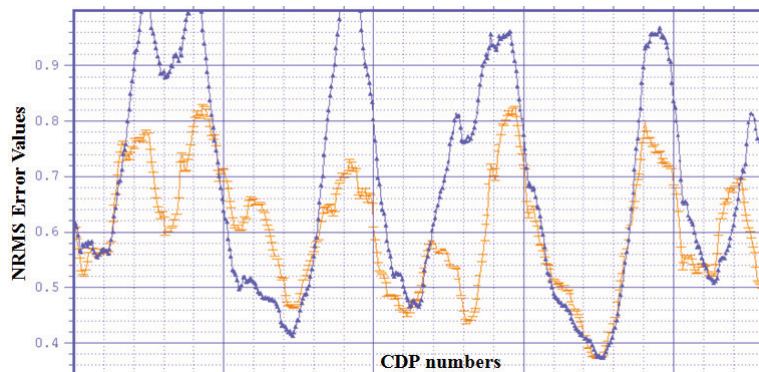

FIG. 4. NRMS error values computed between stack traces from phase 1 and 2 of the 4D survey at a range of CDPs. The yellow line is from stacks after refraction correction, and the blue line is from the data after surface consistent deconvolution. Noise in broader bandwidth after deconvolution reduces the repeatability at low fold area but keeps good repeatability at high fold area.

Figure 5 shows residual statics and trim statics further improves the repeatability. Figure 6 shows further improvement from poststack processing. The poststack 3D f-xy prediction filter (also called f-xy decon) and interpolation to re-create traces at low fold locations from neighbouring high fold traces improved the repeatability. Note that the

interpolation process was in the original plan when the data were acquired; it is not a standard process for the sake of repeatability improvement. The interpolation successfully preserved the good repeatability of the high fold traces. Spectral balancing followed by another f-xy decon further improved the repeatability. This is expected after comparing the data in the spectrum domain. The amplitude spectra of traces from phase 1 and phase 2 are quite different, as shown in Figure 7. For the phase 1 traces, the amplitude level of frequencies from 15 to 30 Hz is relative lower than the amplitude level of frequencies from 30 to 50 Hz; however on the phase 2 traces, the spectrum is quite balanced from 15 to 50 Hz. Also, the amplitudes between 50 to 70 Hz on phase 1 traces are stronger compared to the amplitudes of the same frequency range on phase 2 traces. These differences suggest that some spectral balancing process is needed. As shown in Figure 8, time variant spectral whitening process made the spectra from these two phases much more balanced for the main signal range from 15 to 70 Hz. This frequency range is used to compute the NRMS errors. This is especially evident for the traces on the left portion of each panel.
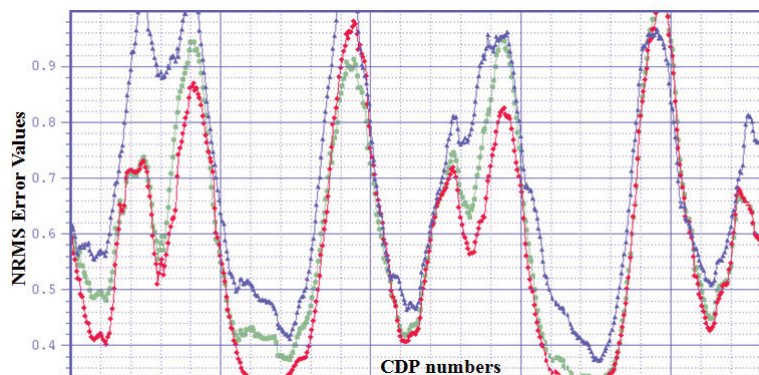

FIG. 5. NRMS error values computed between stack traces from phase 1 and 2 of the 4D survey at a range of CDPs. The blue line is from the data after surface consistent deconvolution; the green line is from the data after two iterations of residual statics correction; the red line is from data after the trim statics correction.
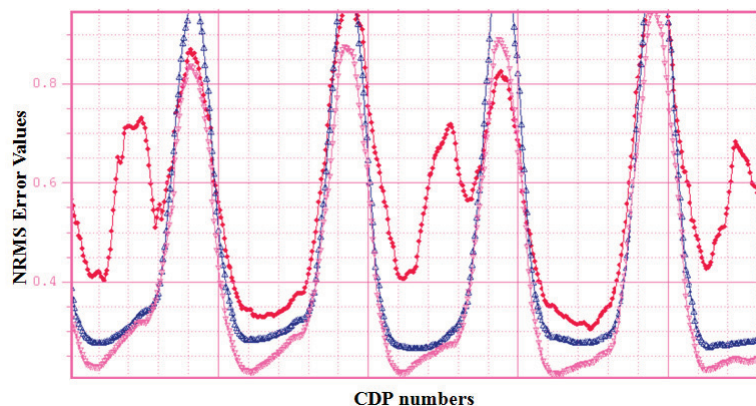

FIG 6. NRMS error values computed between stack traces from phase 1 and 2 of the 4D survey at a range of CDPs. The red line is from the trim stack; the blue line is after f-xy decon and trace interpolation; the pink line is from the data after spectral balancing and f-xy. Note that the NRMS value at the lowest point is reaching 0.2, and this indicates very good repeatability.
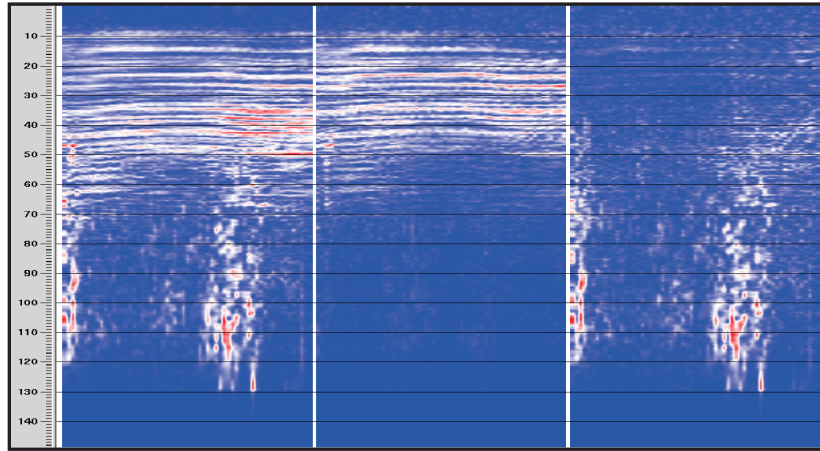
FIG. 7. The f-x spectra of one line of stacked traces after f-xy decon. The vertical axis is frequency in Hz. The left panel is from phase 1, the middle panel is from phase 2, and the right panel is from the difference stack between phase 1 and 2. Note that neither spectrum is well balanced between 15 to 70 Hz.
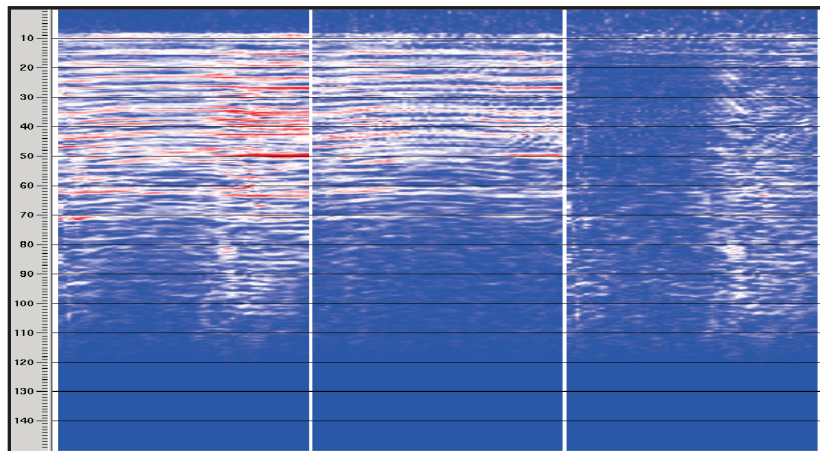

FIG. 8. The f-x spectra of one line of stacked traces after spectral whitening and f-xy decon. The vertical axis is frequency in Hz. The left panel is from phase 1, the middle panel is from phase 2, and the right panel is from the difference stack between phase 1 and 2. The panels are better balanced between 15 to 70 Hz, and this improved the similarity between these two phases, especially on the left half of the panels.

Figure 9 shows a number of triplets from final migrated stacks. The repeatability of the three phases is evident. We found that for this dataset the migration process does not improve repeatability.

As a summary of the entire processing flow, Figure 10 displays the NRMS errors for all major processing steps where repeatability is improved. The NRMS error between two stack volumes is estimated by an average of the NRMS errors of individual stack traces over a range of high fold CDP locations. This display clearly shows the gradual improvement of the time-lapse repeatability. The 3-letter symbols represent the following processing steps:

OAC: offset dependent geometrical spreading correction
SC1: surface consistent amplitude correction
REF: refraction statics correction
SCD: surface consistent deconvolution
RS2: two iterations of residual statics correction
TST: CDP trim statics correction
FXY: f-xy decon on stacks
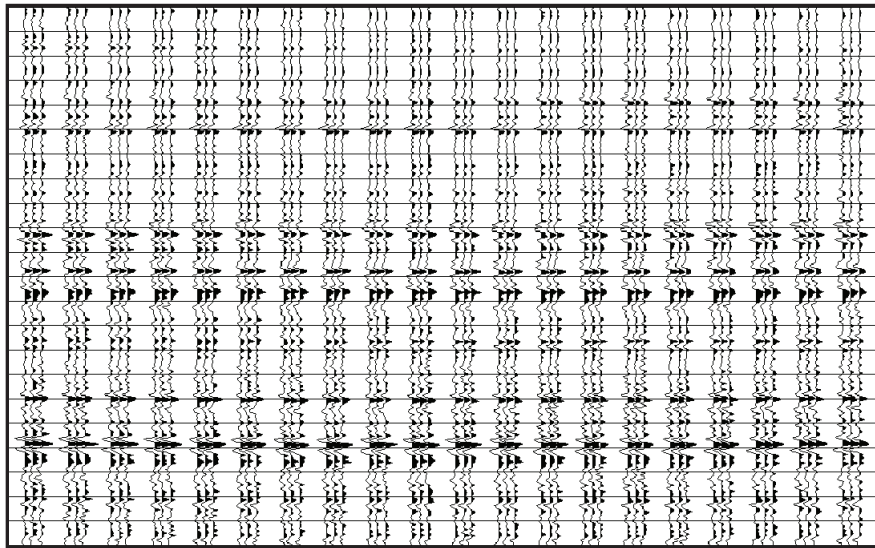TVSWFXY: spectral whitening and f-xy decon

FIG. 9. Trace triplets from final migration stacks. Traces from the same CDP locations are displayed in a group of three.
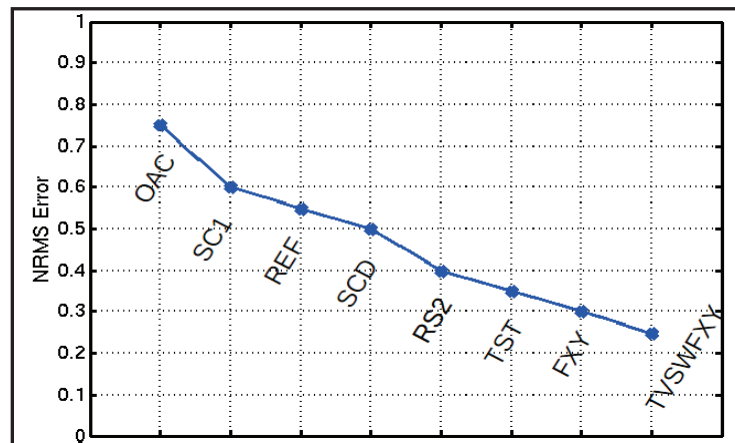

FIG. 10. Estimates of the average NRMS errors for entire stack volumes between phase 1 and 2 are displayed against a number of processing steps. Gradual repeatability improvement is clearly seen. The 3-letter symbols are explained in detail in the main text.

During the processing of this time-lapse dataset, we found that the process of surface consistent amplitude correction after deconvolution in a standard amplitude friendly flow unexpectedly reduced the repeatability almost uniformly across the entire survey. Further investigation indicated that the surface consistent scalars computed from prestack traces

are severely biased by the different noise levels in the different phases, especially in high frequency range where noise has been amplified by deconvolution. Overall, the amplitude levels of the noise background in phase 2 and 3 data are significantly higher than that of phase 1 data. We had to abandon the standard approach and recompute the surface consistent scalars from shot and receiver stacks. The application of the new set of amplitude scalars did not improve the repeatability but certainly maintained the previous repeatability level.

Prestack coherent noise attenuation steps in the processing of this dataset also marginally improved the overall repeatability. Experience with other datasets has shown noise attenuation plays a more significant role in improving the repeatability.

DISCUSSIONS

The data example shown here happened to be carefully designed for the time-lapse repeatability. We did not have trouble matching the geometry of different phases of the survey (we did eliminate a few shot records in one phase that were not available in the other phases). As discussed in Campbell et al (2011), advanced 4D processing tools such as 4D binning may be needed when acquisition geometry for different vintages does not match well. These tools can improve the repeatability of the data by selecting traces with better geometry repeatability at the very beginning of processing.

Conventional land data processing involves a substantial amount of time and effort to resolve statics issues. A suite of algorithms are devoted to solve statics problems, including earth velocity model based methods, surface consistent residual statics methods, and pure event alignment statics methods. Amplitude friendly processing requires more caution on the use of trace-by-trace amplitude/spectrum scaling, such as simple trace equalization, single trace decon and spectral balancing. Model based deterministic and surface consistent amplitude processing are becoming the standard choices. Time shift and amplitude are definitely the most important factors to quantify the similarity between two seismic wavelets. The third factor is the wavelet phase. Phase processing is only slightly addressed in the deconvolution process in standard land data processing. However, in 4D processing, phase differences between different vintages can significantly reduce the repeatability. We believe that spatially variant phase-matching operators can be constructed and they should further improve time-lapse repeatability. We have not applied phase matching of any sort in the data example shown here. Almutlaq and Margrave (2010) investigated developing surface consistent match filters (SCMF). We expect that SCMF is a more integrated matching processing with constrained amplitude scaling, time shift, and phase matching inherently included.

CONCLUSION

Time-lapse analysis requires a different emphasis on seismic data processing. Single vintage data processing simply aims at producing the best quality stack volumes or prestack gathers. However, a time-lapse survey aims at obtaining the most meaningful differences between different vintages in the survey (Calvert, 2005). This implies that reflection signal from zones without time-lapse effect should be repeatable and difference between vintages at these zones should be minimized. We propose a time lapse processing flow that requires not only the amplitude preserving simultaneous processing

of all vintages as one dataset, we also require a strict QC procedure to ensure each main processing step improves (or at least maintains) the repeatability of its previous step. We have shown in detail how this approach works for a real data example. It is very possible that some standard processing steps have to be modified to fit into the processing stream. Generally speaking, amplitude balancing, static time correction, and noise attenuation are the main steps where significant repeatability improvements are expected.

ACKNOWLEDGEMENTS

REFERENCES

Almutlaq, M. H. and Margrave, G.F., 2010, Towards a surface consistent match filter (SCMF) for time-lapse processing: CREWES Research Report.

Atkinson, J., 2010, Multicomponent time-lapse monitoring of two hydraulic fracture simulations in an unconventional reservoir, Pouce Coupe field, Canada: MSc thesis, RCP, Colorado School of Mines.

Calvert, R. 2005, Insights and methods for 4D reservoir monitoring and characterization: SEG/EAGE DISC course notes.

Campbell, S., Lacombe, C., Brooymans, R., Hoeber, H., and White, S., 2011, Foinaven: 4D processing comes up trumps: The Leading Edge, 30 , No. 9, 1034-1040.

Lumley, D., Adams, D. C., Meadows, M. Cole, S., and Wright, R., 2003: 4D seismic data processing issues and examples: SEG, Expanded Abstracts, 22, No. 1, 1394-1397

Pevzner, R., Shulakava, V., Kepic, A., and Urosevic, W., 2010, Repeatability analysis of land time-lapse seismic data CO2CRC Otway pilot project case study: Geophys. Prospecting, 59, 66-77.