A non-differencing approach to seismic monitoring: Implications for difficult carbonate reservoirs

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Summary

Application of time-lapse seismic data to reservoir monitoring and/or carbon dioxide sequestration programs still faces challenges arising from data repeatability and routine processing practices. Emphasis has therefore been placed on structurally imaging the subsurface rather than preserving seismic wavelet characteristics. Our need for high-resolution seismic data and wavelet-oriented processing required attention to detail coupled with a non-differencing approach to interpretation to successfully monitor a weak time-lapse anomaly in a carbonate reservoir. Near-simultaneous processing flow for baseline and monitor data sets with special attention paid to preserving and enhancing monitor seismic wavelet characteristics and adopting an interpretation approach that would mitigate effects of less-than-perfect cross-equalization enabled us to detect and monitor a very weak (~10%) CO_2 flood anomaly. Conservative cross-equalization, though desired for preserving weak TL anomalies, renders data differencing unsuitable for most subtle time-lapse anomalies. Higher-resolution data improves the signal's sensitivity to fluid effects on time-lapse seismic and lessens the risk associated with monitoring thin and inhomogeneous carbonate reservoirs. However, high-resolution data is more susceptible to repeatability errors during differencing. Improvement in detectability of change using our non-differencing approach stems from enhanced emphasis on data quality and repeatability, use of areal textures on seismic horizon attribute slices, avoiding the noise amplification from differencing, and textural changes of time-lapse signatures from weak fluid effects.

Introduction

According to Calvert (2005), there is "still some way to go in the tool [time lapse seismic] itself, to make it faster, cheaper and more sensitive to small production effects." On the way to improving the time-lapse seismic tool lies the important task to better understand the interplay between thin-bed effect "fluid-composition related time thickness wavelet variations" in high resolution data, reflectivity changes resulting from fluid injection or field development, and interpretative differencing and noise effects. In some situations a better understanding of the effects of those characteristics may provide improved opportunities for fluid detectability as well as challenges, depending on the situation and selected processing and interpretation scenarios.

Repeatability problems necessitating cross-equalization when differencing time-lapse data volumes have been broadly discussed (e.g., Hall et al., 2006; Rickett and Lumley, 2001; Ross and Altan, 1997). Coleou, Hoeber, and Lecerf (2002) introduced a spatial co-filtering geostatistical technique into the 4-D processing sequence to increase repeatability and optimize the 4-D signature when differencing.

Higher-resolution seismic datasets are required to monitor thin targets and mandate tighter cross-equalization standards that are both difficult to meet and have the potential to eliminate weak time-lapse anomalies, such as those expected for low compressibility reservoirs. Lumley et al. (2003) reported the persistence of significant non-reservoir differences in all cross-equalization scenarios. A common approach to minimize non-repeatable energy effects and optimize the differencing potential of datasets is to apply a variety of match filters to the data sets (e.g., Ross et al., 1996). Several issues arise pertinent to application of match-filters, such as over/under-matching, instability of the filter, and strong dependence on design gates (e.g., Lumley et al, 2003). Because of the pervasive problem of non-repeatable energy, overlooking weak reservoir signature attenuation due to over-matching is a significant possibility. Therefore, after conservative cross-equalization in time-lapse analysis, non-differencing detection techniques (e.g., Beyreuther, Cristall, and Herrmann, 2005; Raef et al., 2005b) provide a promising and viable alternative in difficult scenarios.

In this paper, we introduce a variation to the parallel progressive blanking (PPB) approach (Raef et al., 2005a) that improves the method's performance by constraining the blanking to data with less repeatability by focusing the high-resolution zone of the color scale on energy with a consistency of no less than 85% after conservative cross-equalization. Seismic monitoring of a CO_2 flood in Kansas (USA) using this approach was validated against production data and material balance used in reservoir simulation. The preferential flow direction and extent was consistent with dominant seismic lineaments mappable on all time-lapse images. Our non-differencing approach has many advantages, such as it

1. minimizes the impact of post cross-equalization residuals of non-repeatable data by blanking filtering and color focusing on the near (± 10%) repeatable data,
2. utilizes both spatial textural characteristics and subtle anomalous attribute values, and
3. is less data processing intensive, allowing improved turnaround time for integrating results into reservoir management programs.

Compared to differencing using common cross-equalization approaches, this is especially true for data of moderate quality and quantitatively weak anomalies.

Cross-equalization, PPB Approach, and Differencing

The results of a bulk mistie/cross-equalization analysis (Figure 1) of amplitude time shift and phase differences between a baseline and monitor datasets for time lapse EOR-CO_2 monitoring in this carbonate reservoir revealed significant and erratic phase differences. This phase inconsistency is difficult to compensate for and, combined with other bulk cross-equalization residual differences, makes data-differencing unsuitable for this study. In our efforts to minimize the effects of phase inconsistencies, attribute horizon interpretations were made using both parallel progressive blanking (Raef et al., 2005a) and horizon attribute differencing applied after amplitude and time-shift mistie corrections.

Established TL-seismic practices have been designed around the concept that TL-seismic change due to production must be large enough to be detected as a magnitude difference over a considerable spatial extent. In the case of a weak TL-seismic signature, which is often the case for carbonates and tight sandstones, the TL-anomaly is not likely to maintain a sufficient magnitude over a considerable spatial extent. This low amplitude change is a result of being at or below the non-repeatable noise and residual cross-equalization differences. By focusing a high-resolution band of color (Figure 3) on data zones where the signature can be observed as a significant areal textural change compared to baseline data, the PPB approach of delineating time-lapse anomalies addresses situations where the reservoir signature is inconsistent or very close, or even at the level of the background noise. Apart from the use of a high-resolution color scale band, uniform (blanking) color is applied to what “highly nonrepeatable” is more likely to be detrimental for reservoir signature when differencing. Our modification of the application of the PPB approach used here on time-lapse attributes maps focuses on two aspects:

1. Preconditioning attribute data by preserving only the highly repeatable (less than about 15% energy repeatability) (Figure 2), which enhances the performance of the PPB approach.
2. To minimize textural artifacts, the width/resolution (Figure 3) of the high-resolution color zone is conditioned to span at least 30% of the data range. This, however, does render time-lapse textural changes difficult to discern or hard to verify relative to the baseline horizon control attribute map.

The improvements in quality of the textural time-lapse anomaly surrounding the CO_2 injector (Figure 3) are obvious when compared to previous applications of this method (Figure 2a&c in Raef et al., 2005b). As a result of the aforementioned modifications, the usefulness of this modified PPB approach is apparent for difficult cases where direct differencing (Figure 4) of seismic attribute maps has proven inadequate. The PPB scale was applied to Figure 4c to examine anomaly textures; when doing so, the anomaly outline is discernable (shown in Figure 3c).

Conclusions

A weak time-lapse reservoir signature complicates TL-seismic monitoring due to mingling of low amplitude signal with background noise. A conservative cross-equalization is necessary in the case of weak time-lapse anomalies (carbonates and tight sands), and therefore differencing does not produce a consistent and interpretable change in character. Conservative cross-equalization produces large residuals, which make time-lapse differencing ineffective in the case of weak anomalies.

Reservoir-specific modifications made to the PPB approach have been shown to improve its performance by scanning for the optimum (interpretative step) high-resolution band in preconditioned data (excluding low repeatability). More research and testing with a variety of small change datasets are necessary to establish objective (less interpreter-dependent) and repeatable criteria for a fine-tuned PPB approach.

Acknowledgments

Support for this research was provided by the U.S. Dept of Energy, project #DE-FC26-03NT15414. We would also like to thank Murfin Drilling Company for their cooperation and assistance in the field.

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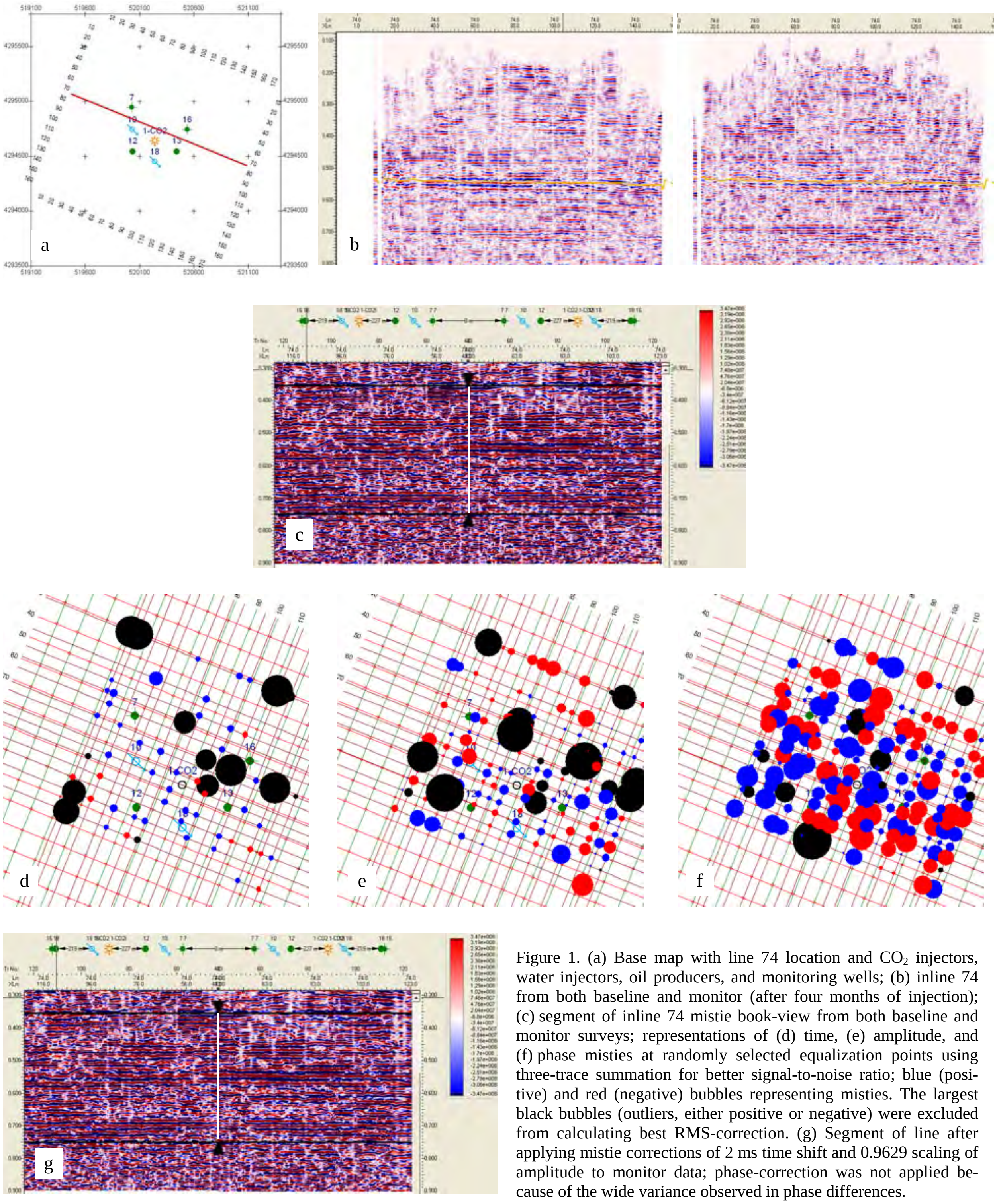

Figure 1. (a) Base map with line 74 location and CO_2 injectors, water injectors, oil producers, and monitoring wells; (b) inline 74 from both baseline and monitor (after four months of injection); (c) segment of inline 74 mistie book-view from both baseline and monitor surveys; representations of (d) time, (e) amplitude, and (f) phase misties at randomly selected equalization points using three-trace summation for better signal-to-noise ratio; blue (positive) and red (negative) bubbles representing misties. The largest black bubbles (outliers, either positive or negative) were excluded from calculating best RMS-correction. (g) Segment of line after applying mistie corrections of 2 ms time shift and 0.9629 scaling of amplitude to monitor data; phase-correction was not applied because of the wide variance observed in phase differences.

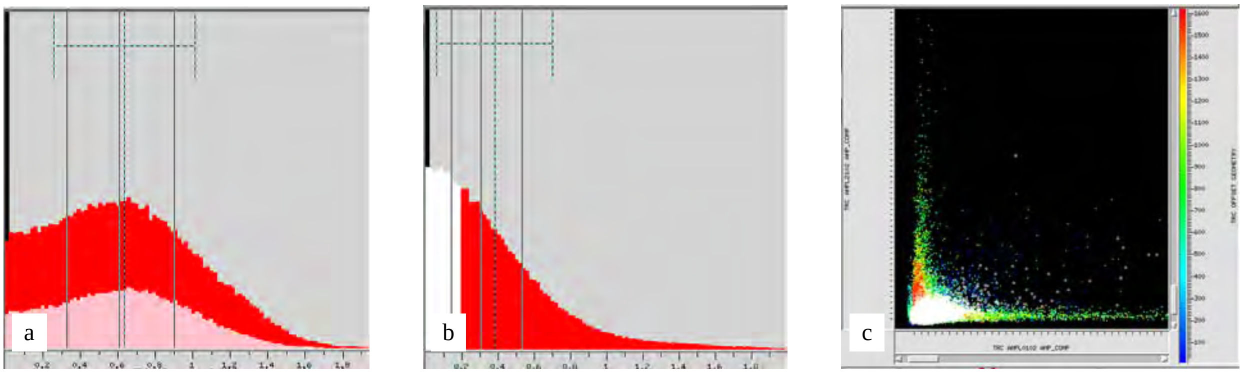

Figure 2. Lack of repeatability represented as normalized RMS error (a) before and (b) after amplitude balancing and cross-equalization. (c) Cross-plot of amplitudes after amplitude balancing and cross-equalization and data with good repeatability is shown as white.

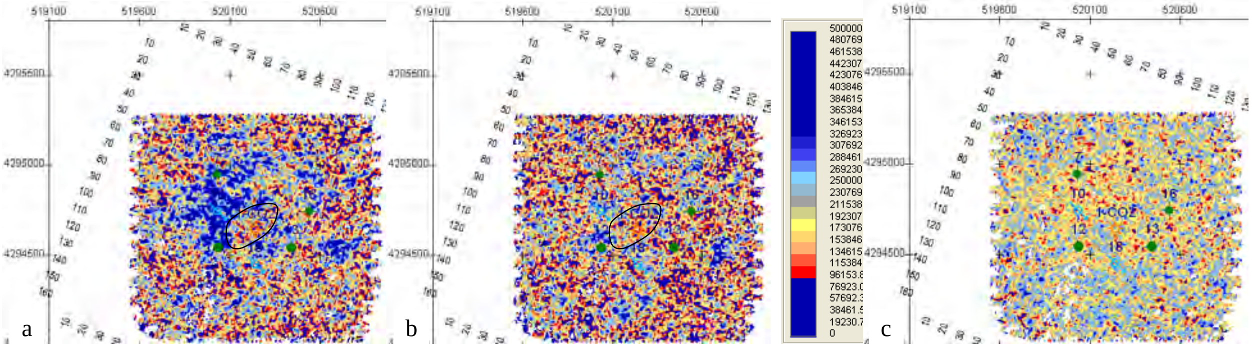

Figure 3. Normalized horizon amplitude envelope maps from (a) base and (b) monitor (four-month time lapse) surveys. Area of textural anomaly (as seen outward from CO2-injector) around CO_2 injector manifests time-lapse signature of the injected CO_2. Compared to images in Figure 2a&c in Raef et al. 2005b, the CO_2 anomaly is more discernable; (c) when applying PPB color scale to a difference the texture anomaly outline is more visible; solely on the basis of difference the TL anomaly is not evident.

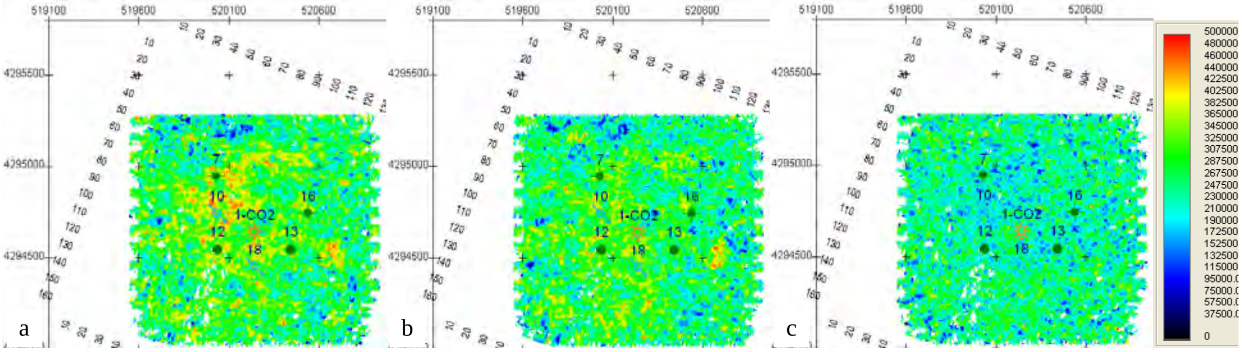

Figure 4. Horizon normalized amplitude maps for (a) baseline and (b) monitor data; (c) difference horizon amplitude map with non-outstanding anomaly despite the discernable difference around the CO_2-injector when visually examining baseline with monitor horizon amplitude maps. The difference may provide interpretative value when it is examined within the PPB flow (see Figure 3c).

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