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A shift in time: time-lapse detection using interferometry

David C. Henley
CREWES, Univ. of Calgary Geoscience Dept.

Summary

We use a joint application of raypath interferometry to detect subtle reflection time differences (time sag) between a 2D 'baseline' survey and a 'time-lapse' survey over an active CO2 injection experiment. We are able to detect a consistent time sag anomaly for this experiment, even though an unambiguous reflection amplitude anomaly has never been convincingly demonstrated. The success of this detection is likely due to the precise alignment of CMP images facilited by the raypath interferometry technique, as well as to its nonstationary near-surface corrections, where corrections for deep reflections are decoupled from those for shallow reflections.

Introduction

The use of seismic imaging to evaluate the removal or replacement of fluids in reservoir rocks continues to be of great interest to the hydrocarbon industry, as well as to the development of carbon capture and storage (CCS) technologies. Usually, the method employed is a comparison of repeated seismic reflection surveys deployed over the site of the fluid removal/injection, where the survey repetitions occur at regular time intervals. Comparisons are most often performed by subtracting seismic images corresponding to the individual surveys, where the acquisition and processing for each image is as similar as possible. Most often, the image difference sought as an indicator of fluid movement is a change in the reflectivity amplitude of a rock layer boundary associated with the fluid-induced change in rock properties of the reservoir layer. Hence, much of the processing flow for the seismic image data is devoted to preserving relative amplitudes, ensuring a common bandwidth, and properly aligning the images before subtraction. Even when great care is taken to repeat seismic surveys using the same source and receiver stations, the near-surface conditions can change significantly between surveys, due simply to seasonal changes. This means that conventional near-surface correction procedures yield different 'statics' solutions for different surveys, so we cannot use a common solution to help tie the two surveys in time. The result is often a small travel time mismatch between two surveys, due to the different solutions having slightly different means. Even though this mismatch may be only a fraction of a sample interval, efforts are usually made to eliminate it before image subtraction, so that the image differences will reflect only true reflection amplitude differences, not mismatched reflection events.

Another type of difference can also appear in a time-lapse CMP image; slight increases in two-way travel time for reflection events beneath the produced/injected reservoir zone, due to seismic velocity decrease in the reservoir. This is the so-called 'time sag' anomaly, and it can be difficult to observe, since the travel time increases are often very small and can be masked by differences in statics solutions for the two images to be compared. However, subtractive differences between two slightly mismatched images can be significant in amplitude, if the waveforms are similar. Thus, by adopting a slightly different processing strategy, in which we attempt to equalize event amplitudes between corresponding traces in two images, we can enhance and observe the amplitude differences due strictly to time mismatch. A requirement for the success of this strategy is the exact alignment in time of the two images. While the resulting time sag anomaly is a less direct indication of fluid changes in the reservoir above, it can still yield valuable information, particularly if the reflection amplitude anomaly at the reservoir boundary is weak and hard to observe.

As we indicated above, when conventional statics methods are used to correct two vintages of seismic data, the solutions may differ enough that it is difficult to match images well enough to detect the very small time sag anomaly (often a fraction of a sample interval). In light of this, we chose to apply our raypath interferometry technique to derive and apply near-surface corrections to time-lapse images. In so doing, we can ensure perfect alignment of the two images; and because raypath interferometry applies nonstationary corrections, time/phase changes for deeper reflections are independent of those for shallower ones, allowing for very subtle event time differences between images.

Method

We have been using the technique called raypath interferometry for several years to apply near-surface corrections to sets of seismic data where conventional surface correction methods like statics corrections either fail completely or provide only marginally useful solutions (Henley, 2012a, Cova et al, 2014), because the conventional assumptions are violated by the data. Raypath interferometry is based on the generalization of surface consistency to 'raypath consistency' and the relaxation of the 'single reflection arrival' assumption to include a distribution of wavefront arrivals associated with every reflection detected at a surface location (Henley, 2012a). Raypath consistency introduces nonstationarity to the surface-corrections, allowing proper correction of PS converted wave data (Cova et al, 2014); and the arrival distribution, or 'surface function' accommodates the scattered and multi-path arrivals common in areas with complex surface layers (Henley, 2012a). Importantly, surface consistency is a special case of raypath consistency; and the discrete reflection arrival is a special case of the arrival distribution. This means that raypath interferometry can be used to apply surface corrections to *any* data set, even those which satisfy the simplest assumptions and can be more easily corrected using conventional statics techniques (Henley, 2012b).

The steps in raypath interferometry are as follows:

- Transform input data, typically source gathers, to a ray-parameter domain
- Form common-ray-parameter gathers
- Use trace-mixing/eigenvector filtering to create smooth 'reference wavefield' panels
- Use conditioned cross-correlations between ray-parameter traces and reference wavefield as match filters to apply surface corrections to ray-parameter traces.
- Transform ray-parameter traces back to source gathers, now corrected for the near-surface.

Because of the interferometric operation, the wavelets associated with each source point will be made more consistent, as well. Crucially, no time shifting of any kind is applied to any of the input traces; hence there will be no net shift in the CMP stack of the traces, as there can be with conventional statics solutions.

For comparing two seismic surveys acquired over the same profile, raypath interferometry is uniquely suited for applying the near-surface corrections because of its 'no net shift' property, as well as the nonstationarity of its solutions, in which corrections to deeper reflections are independent of those to shallower ones. Thus, we can subtract the CMP image of a 'baseline' survey from the CMP image of a 'time-lapse' survey without having to explicitly align them in time, and the reflection time differences between the images will thus be related to physical phenomena rather than processing differences. We can enhance this outcome even more by using the same reference wavefield for both surveys, which increases the reflection character similarity between surveys and further ensures no net time shift between them, as well.

Examples

We first discovered the potential to use raypath interferometry for time-lapse analysis quite by accident, during a numerical model study in which we studied various factors affecting the detectability of a time-lapse anomaly, such as acquisition parameters, processing parameters, intrinsic noise levels, etc. (Henley et al, 2012, 2016). We processed data from the baseline model and time-lapse model in exactly the same way, using conventional statics to provide surface corrections, and alternatively using raypath interferometry. Figure 1 shows the difference of the CMP stacks of the time-lapse and baseline models after conventional statics (and after hand-shifting the baseline image for proper time registration). The time-lapse amplitude anomaly in the model can be readily seen (white arrow), but the time-sag anomaly beneath is less prominent. If we compare this with Figure 2, where we show the CMP stack difference after applying raypath interferometry to both surveys, we see the striking result that the amplitude anomaly is visible but much less prominent than the time-sag extending to several reflections beneath the anomaly zone.

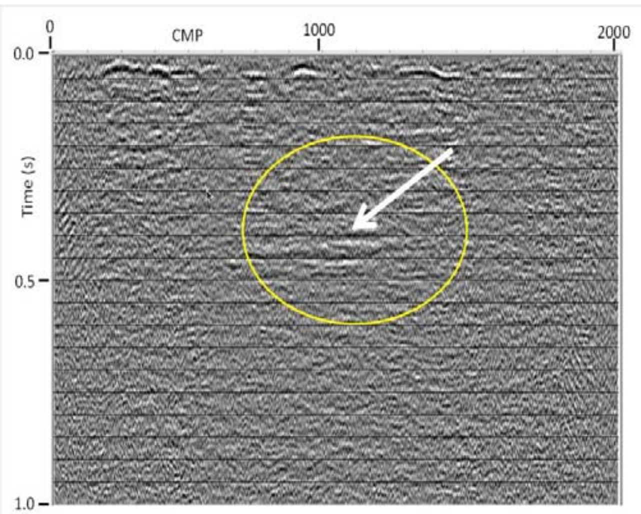

FIG. 1. Numerical model difference anomaly (conventional statics methods)

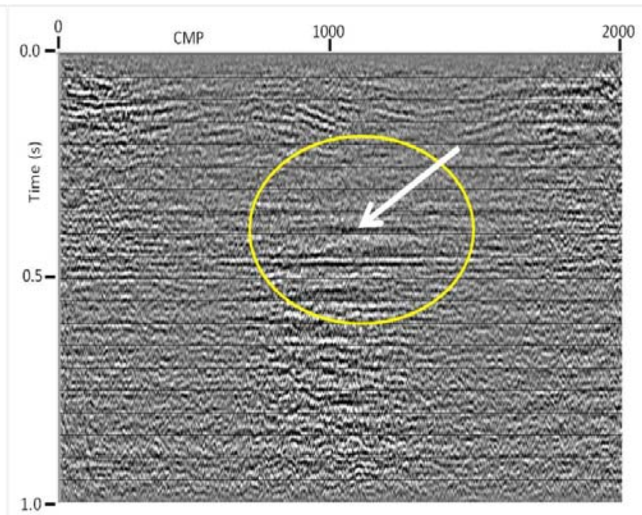

FIG. 2. Numerical model difference anomaly (Raypath interferometry)

This result prompted us to revisit a real time-lapse survey in which CREWES participated a number of years ago. The Violet Grove time-lapse experiment was performed over the period 2005-2007 to investigate the seismic detectability of CO2 injected into the porous Cardium formation. A 2D seismic line was acquired in 2005, before start of CO2 injection, as a baseline survey, followed in 2007 by a time-lapse survey using the same source and receiver locations and processing as the baseline survey. Previous attempts to detect an unambiguous amplitude anomaly using various processing techniques (Alshuhail et al, 2007, 2008, Almutlaq and Margrave, 2012) were only marginally successful; hence we chose to apply the raypath interferometry technique to the pair of surveys to try to detect the associated time-sag anomaly. Figure 3 shows the difference image with no shift applied between the input CMP images for baseline and time-lapse surveys before subtraction. The continuous events in the fan-shaped region beneath the position of the injection zone are interpreted to be due to time-sag. To show that these events are *primarily* caused by time mismatch between events on the two input images, rather than event amplitude differences, Figure 4 displays the difference image when the baseline image is deliberately shifted by 1.6ms before subtraction from the time-lapse image. In this figure, the continuous events *outside* the region beneath the injection zone show that the time mismatch is now mostly outside the region beneath the injection. By applying different amounts of shift before subtraction, we can make various portions of the coherent events in the fan fade or vanish altogether. Note that on Figure 3, the best fit of the time-sag region is displaced laterally from the injection borehole location, indicating that the CO2 plume may be asymmetric.

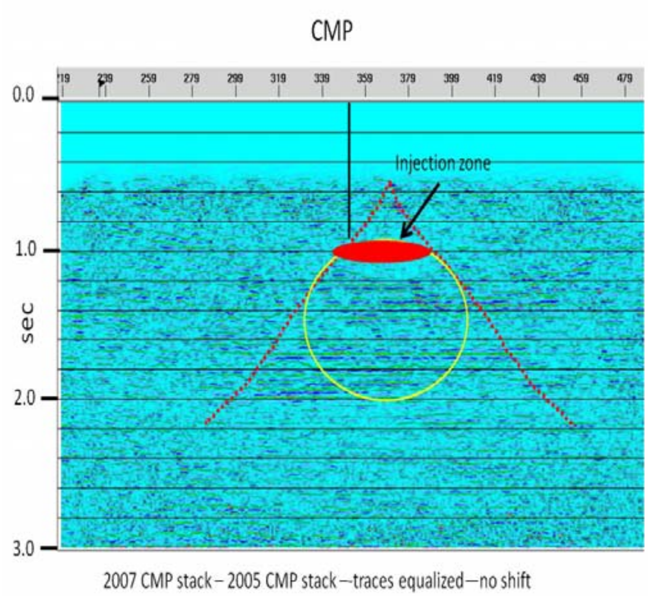

FIG. 3. Violet Grove time-sag shown by Raypath Interferometry

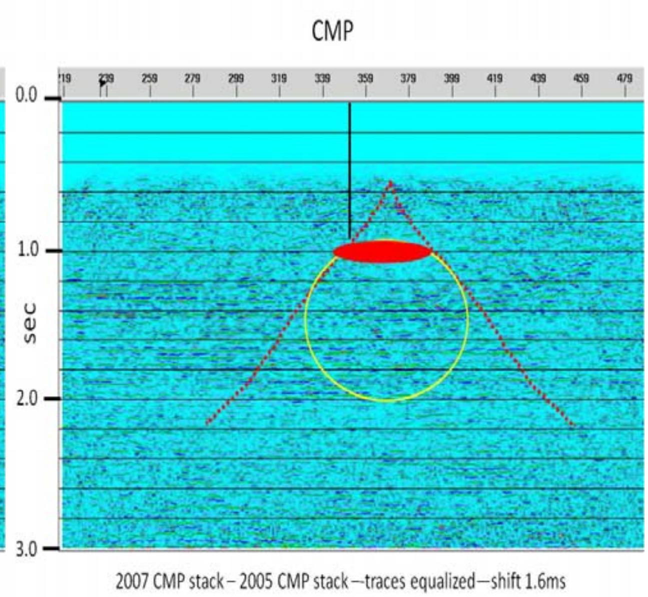

FIG. 4. Violet Grove time sag decreased by 1.6ms image mismatch before subtraction

Conclusions

Detecting changes in formation fluids using seismic methods always requires careful acquisition and processing. Sometimes, the change in reflection amplitude caused by formation fluid change is small enough that it is difficult to detect unambiguously. In such cases, there is a chance that a time-sag anomaly beneath the injection zone may be more detectable. We have shown that using a technique like raypath interferometry, that ensures exact alignment of CMP images and applies nonstationary surface corrections, we can detect time-sag as small as a fraction of a sample interval.

Acknowledgements

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References

Alshuhail, A., and Lawton, D.C., 2007, Time-lapse surface seismic monitoring of injected CO2 at the Penn West CO2-EOR site, Violet Grove, Alberta, CREWES Research Report Volume **19**(2007).

Alshuhail, A., Lawton, D.C., and Chabot, L., 2008, Pembina Cardium CO2 monitoring project: time-lapse seismic analysis, CREWES Research Report Volume **20**(2008).

Almutlaq, M.H., and Margrave, G.F., 2012, Violet Grove time-lapse data revisited: a surface-consistent matching filters application, CREWES Research Report Volume **24**(2012).

Cova., R., Henley, D.C., and Innanen, K.A., 2014, Using ray-path domain interferometry to address non-stationary S-Wave statics, SEG Technical Program Expanded Abstracts 2014.

Henley, D.C., 2012a, Interferometric application of static corrections, Geophysics, **77**, No. 1, pp Q1-Q13.

Henley, D.C., 2012b, Interference and the art of static correction: raypath interferometry at Hussar, CREWES Research Report Volume **24**(2012)

Henley, D.C., Wong, J., and Manning, P.M., 2012, Time-lapse by the numbers: elastic modeling of repeatability issues, CREWES Research Report—Volume **24**(2012).

Henley, D. C., Wong, J., and Manning, P.M., 2016, Time lapse survey repeatability: an elastic modeling study, CSEG Recorder Volume **41**, No. 9 (December 2016), pp 36-39.