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Tube-Wave-Related Repeatability Diagnostics for Cross-Well Time-Lapse Seismic

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SUMMARY

We apply tube-wave monitoring method to a time-lapse cross-well dataset from Mallik field. Raw waveforms are used for analysis thus avoiding any smearing of 4D response introduced by pre-processing. We perform extensive modeling that includes effects of a source borehole and confirms nature of most prominent arrivals as being tube-wave related. Modeling proves that strongest conversion of tube wave into P and S waves occurs at the sharp acoustic boundary. While tube-wave related arrivals exhibit strong time-lapse response, it appears that it is mainly caused by non-repeatable acquisition. i.e. different source and receiver positions between the surveys. We show that tube-wave related arrivals provide unambiguous diagnostic of the time-lapse repeatability of cross-well surveys that could not be extracted from first arrivals.

Introduction

In cross-well surveys it is typical to consider direct transmitted P-waves as a signal and all other arrivals as noise. Tube (Stoneley) wave represent abundant and very strong "noise" arrivals that are usually suppressed by various processing techniques. In contrast, recently proposed tube-wave monitoring concept (Korneev et al., 2006) suggests making use of these tube-wave-related arrivals for reservoir monitoring. Mallik cross-well time-lapse dataset was selected to verify this concept. Watanabe et al (2004) performed cross-well tomography using first P-wave arrivals and concluded that no change in velocity can be detected. Bakulin et al (2006) speculated that later tube-wave related arrivals exhibit substantial time-lapse effect. In this study we show how to use tube-wave related arrivals to verify the repeatability of source-receiver geometry between different surveys. Such powerful diagnostics are useful for both tube-wave monitoring as well as conventional cross-well surveys. Applying these diagnostics to Mallik dataset, we discover that majority of time-lapse differences in tube-wave related arrivals can be explained by slight geometric non-repeatability of the data that remains unnoticed if one analyzes first arrivals only.

Mallik experiment

Cross-well time-lapse surveys were conducted at the Mallik field, Canada as a part of the 2002 Mallik Gas Hydrate Production Research Well Program (Bauer et al., 2005 and references therein). Two cased boreholes were used for observations, both located 42.5 m away from production well. Detailed description of the experiment is given by Bauer et al (2005). Multiple source and receiver positions covered depth from 800 to 1050 m with depth spacing of 0.76 m. To achieve such a fine sampling interleaved receiver arrays were utilized since receiver spacing along the cable was 1.5 m. Piezoelectric source excited the signal in one well while hydrophone array recorded response in another well. Baseline and three time-lapse surveys have been conducted during the course of methane production test that included thermal stimulation of gas-hydrate-bearing zone in the central well (Bauer et al., 2005).

Bakulin et al (2006) confirmed previous conclusions that first arrivals display no time-lapse changes but discovered that later tube-wave-related arrivals exhibit strong time-shifts and some amplitude changes. Nevertheless, they did not answer the question whether time-lapse anomalies in tube-wave related arrivals are due to genuine reservoir changes or an artifact of some acquisition non-repeatability that existed for all survey. For instance, baseline survey was abandoned due to positioning problems (Bauer et al, 2005). Consequent three surveys are more repeatable since first arrivals are almost identical on all of them (Watanabe et al, 2004). Bakulin et al (2006) speculated that in this case later arrivals may still exhibit time-lapse changes due to longer travel path and slower velocity. However on the same accounts, good repeatability of first P-wave arrivals can not guarantee the repeatability of the later tube-wave related events. In thus study we design a completely new set of repeatability diagnostics based on redundancy of tube-wave-related arrivals. They allow to unambiguously distinguish geometric non-repeatability and genuine time-lapse changes.

Mispositioning during single cross-well experiment

To illustrate the problem, we take the first survey, select fixed source position at 914 m depth, plot two common-shot gathers (CSG) with even traces and odd traces as an individual panels (Fig. 1) and then subtract them from each other (Fig. 2a). It should be noted that actual borehole receiver array contained only ten hydrophones and therefore 80-trace seismogram consists of least eight different cable positions. Although even and odd traces should be separated by 0.76 m spacing, we observe almost full subtraction of traces 1 to 50 (Fig. 2a). This suggests absence of any depth shifts for these cable positions. This artifact is likely caused by incorrect positioning of borehole array when it was moved down the hole and essentially the same receiver positions have been re-acquired again. Remaining 30 traces exhibit some small time shift but it is unclear whether they are separated exactly by 0.76 m. To estimate the actual depth shift we subtracted seismograms with even traces from the seismograms with odd traces while introducing a time shift equal to 1/10, 2/10, 3/10 etc of the time sampling interval (dt=0.125 ms) After inspection, we concluded that time shift equal to one time sample (0.125 ms) leads to a complete subtraction of tube-wave arrivals on traces from 51 to 80 (Fig. 2b). Taking into account that tube-wave velocity is almost constant in a cased boreholes (1400 m/s) we estimate that even and odd traces were actually shifted by 0.15 m in vertical direction instead of nominal 0.76 m.

Repeatability diagnostics based on tube-wave-related arrivals

Since source/receiver position for wireline borehole surveys can not be trusted even within a single survey, then in a time-lapse world our task is to distinguish between four possible scenarios based on the data alone (without trusting the actual trace headers):

1) Perfectly repeated acquisition geometry and no time-lapse effect
2) Perfectly repeated acquisition geometry and present time-lapse effect
3) Non-repeatable acquisition geometry and no time-lapse effect
4) Non-repeatable acquisition geometry and present time-lapse effect

For the data of interest we can rule out the trivial first scenario and therefore we focus on distinguishing between remaining three scenarios. Let us start with the third scenario. For certainty, let us consider configuration when source and receiver elevation differ by 10 m and distance between wells is 85 m (Fig. 3a). Let us further assume that second receiver is depth-shifted by 0.15 m with respect to first one and formation between wells is homogeneous (at least between top and bottom interfaces on Fig. 3c). In this case the difference between direct P-wave arrivals for these two receivers is only 0.008 ms. This is a very small amount and is unlikely to be detected using direct P-waves.

Now let us consider tube-wave related arrivals (Fig. 3b) for the same third scenario. First, let us focus on the TPT arrival that propagates as an up-going tube wave in a source borehole, hits the interface between layers and converts into horizontally propagating P-wave and then converts into down-going tube wave in the receiver borehole. Difference in TPT arrival time between two receivers is 0.107 ms, which is much large than 0.008 ms, comparable to the time sampling and can be easily detected. If we consider another TPT arrival traveling in the opposite direction (say converted at the lower rather than upper interface) then time-shift between two receivers will be the same 0.107 ms but with a negative sign (Fig. 3c). Similar logic applies to any cross-well arrival that travels as T-…-T (i.e. TST, TPST etc.) Due to data redundancy, we observe abundant tube-wave arrivals of both directions. This allows us to easily verify whether this "no time-lapse, constant depth-shift between receivers" scenario takes place in a three-step procedure. First, we search for a positive time-shift that can be introduced into monitor dataset in order for the down-going tube-wave arrivals to fully subtract out between the surveys. In a second step, we search for a negative time-shift that minimizes the difference between up-going tube-wave arrivals. In a third step we verify that these time shifts are of equal magnitude (Fig. 3c).

In case of a second scenario, we would not be able to find a single time-shift magnitude that would make both up-going and down-going tube-wave arrivals to cancel out especially if the data exhibits TPT and other arrivals converted at different geological interfaces. In the forth scenario, when geometry is not repeated but time-lapse effect has taken place, the time-shifting procedure above will lead to some increase in repeatability of tube-wave arrivals due to compensation of geometrical effects, but we will be unable to achieve a perfect subtraction between time-lapse data due to genuine reservoir changes.

To apply this diagnostic to Mallik data, let us select only odd receivers from first and third surveys that appear repeatable based on overlaying the first arrivals (Watanabe et al, 2004; Bakulin et al, 2006). Then we find that in order for down-going tube waves to fully subtract out we need to introduce a time shift of $dt_{DTW} = -0.125$ ms (Fig. 4a). Likewise, for up-going tube waves to cancel out we need to introduce $dt_{UTW} = 0.125$ ms (Fig. 4b). Since

dt_{DTW} and dt_{UTW} are equal and opposite in sign and residual wavefield after subtraction is small, we conclude that differences between two datasets are mainly caused by the non-repeatable locations of the borehole receivers and therefore most likely third scenario takes place. There may be some small time-lapse effect present but with a signal-to-noise ratio at hand and unrepeated receiver positions, this is difficult to quantify.

Conclusions

We present a field example of cross-well tube-wave monitoring at Mallik gas hydrate site. This method relies on arrivals that travel as tube waves inside source and receiver borehole and as body or other wave type between the wells. Such arrivals are abundantly present and easily identified in Mallik dataset and they exhibit time shifts between the repeated surveys. Utilizing tube-wave arrivals traveling up and down the well we design new set of sensitive repeatability diagnostics revealing that for Mallik dataset these time shifts are chiefly caused by non-repeatable receiver positions between time-lapse surveys and not by genuine reservoir time-lapse effects. These diagnostics can be useful for conventional and any other types of cross-well surveys where similar arrivals can be identified.

References

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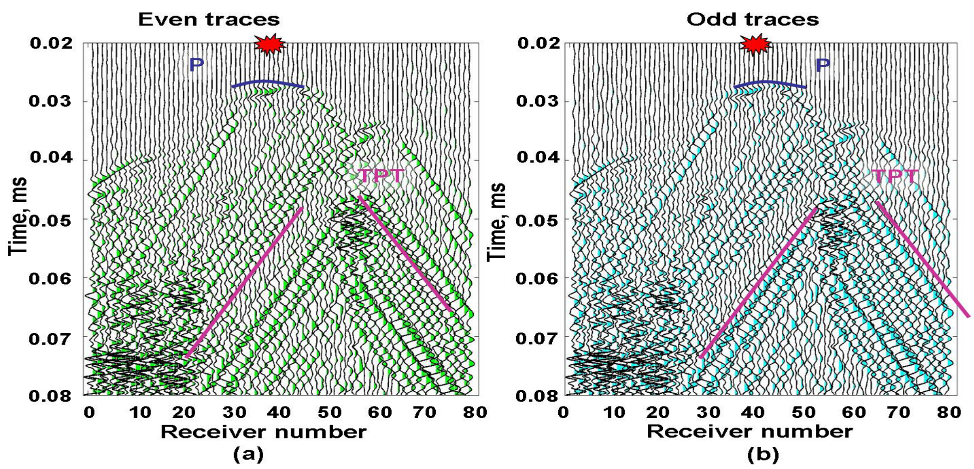

Figure 1. CSG from the first repeated survey with the source at 914 m depth was diveded into two seismograms: with only even traces (a), with only odd traces (b).

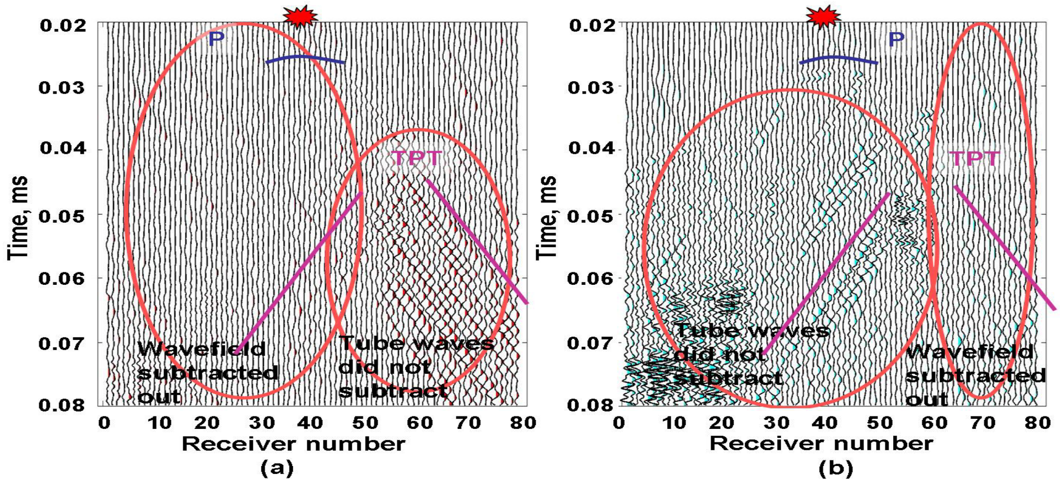

Figure 2. Difference between even and odd traces for common-shot gather at 914 m from the first survey: (a) without time shifting; (b) with time shift of 0.125 ms (one time sample).

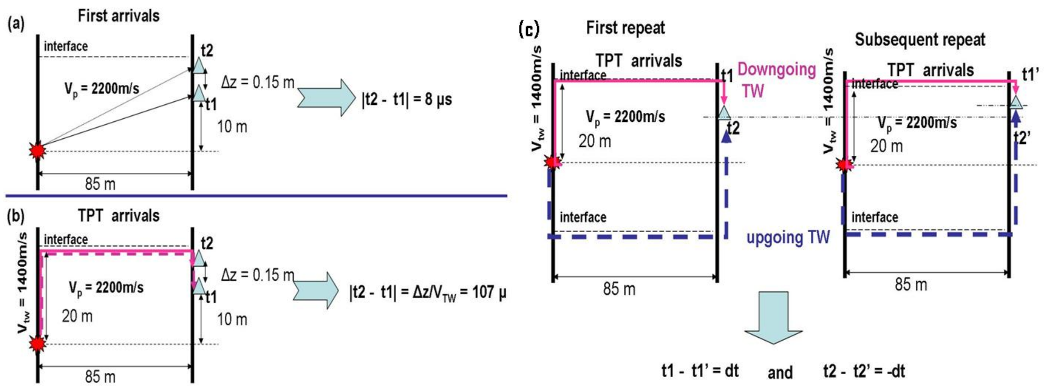

Figure 3. Estimating difference in travel times for two closely spaced receivers in a cross-well survey: (a) for direct P-wave and (b) for TPT arrival. (c) Up-going (blue) and down-going (magenta) TPT arrivals experience positive and negative time delay of the same magnitude, if source is fixed, but receiver position is not repeated

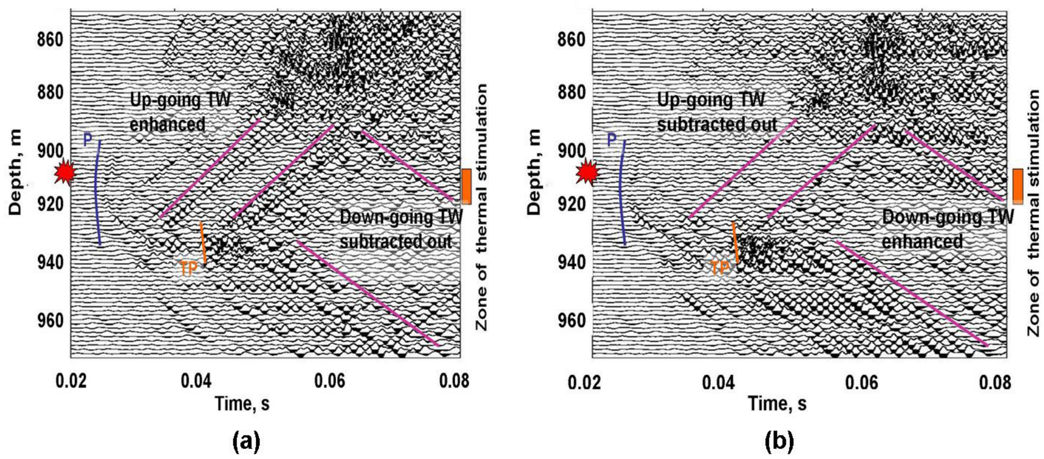

Figure 4. Difference beween common-shot gathers from first and third time-lapse surveys after introducing a timeshift of : (a) -0.125 ms, (b) 0.125 ms.