Tube-wave monitoring at Mallik field: comparing modeled and experimental time-lapse responses

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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. Data displays clear time-lapse changes in tube-wave related arrivals, while shows no change in first arrivals. Modeling suggests that to explain the data the reservoir changes have to occur at a deeper interval than previously anticipated, below the perforations. Excellent agreement between modeled and experimental data provides us with good confidence in our results. This study represents first application of tube-wave monitoring concept.

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 perform detailed modeling of the Mallik experiment, identify the exact nature of the prominent arrivals displaying time-lapse change and suggest a spatial location for reservoir changes that semi-quantitatively explains the time-lapse anomaly.

Experiment

Time-lapse cross-well acquisition was acquired 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). Three repeated surveys were acquired from 6 to 8 of March 2002 shortly after thermal stimulation and during methane production from gas-hydrate-bearing layers. Two cased boreholes were used for observations, both located 42.5 m away from production well (Bakulin et al., 2006). Detailed description of the experiment is given by Bauer et al (2005). Multiple shots and receivers covered depth from 800 to 1050 m with a very dense spacing of 0.76 m. Fluid-coupled piezoelectric source excited the signal in one well while hydrophone array recorded response in another well. 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. Strong temperature changes have been observed by distributed temperature array. Bakulin et al (2006) confirmed previous conclusions that first arrivals display no time-lapse changes

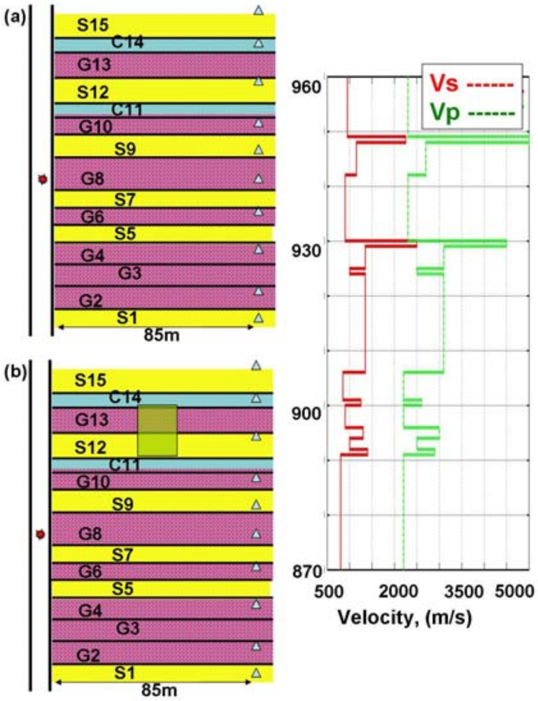

Figure 1: Computed models: a) baseline model; b) monitor model with time-lapse change in elastic properties. Reservoir change (green) is located 35 m away from the source borehole and has 10 m width. *P* and *S* velocities are reduced by 15% compared to baseline model (layers S12 and G13).

but discovered that later tube-wave-related arrivals exhibit strong time-shifts and amplitude changes.

Model

We start with a simple layered model for the produced interval of 870-960 m. Velocity and densities are taken from acoustic well logs (Bauer et al., 2005) and blocked as shown on Figure 1a. Aiming to reproduce tube-wave arrivals we utilize 2D radially symmetric code developed by Keldysh Institute of Applied Mathematics and Shell International E & P. This code allows to reproduce tube waves in the source well and model their conversion into various other waves propagating towards the receivers. However it does not allow modeling of the receiver well and thus we embed receiver arrays into the layered media without receiver borehole. Source well is modeled as a water-filled cased borehole with steel casing of inner radius 8 cm and thickness 1 cm. Perfect bonding is assumed between casing and formation. A point pressure source excites Ricker wavelet with a central frequency of 200 Hz. We focus on analyzing a shot gather with source at 910 m. Receivers cover depth interval from 870 to 960 m with 2 m spacing along a vertical profile 85 m away from the source well. We compute a trace of stress tensor response that approximates pressure recording done in the field with hydrophone array. Baseline model assumes homogeneous flat layers (Figure 1a), while for a monitor model we introduce an anomaly in the middle that roughly corresponds to gas-hydrate-bearing layers at 930-948 m (Figure 1b). The anomaly has 10 m extent in horizontal direction and is represented by a low-velocity zone with 15 % decrease in longitudinal and shear-wave velocities (Figure 1b).

Results of finite-difference modeling

Figure 2 shows two superimposed sets of seismograms representing baseline (black) and monitor (red) responses. Figure 3 schematically shows the main arrivals observed in modeling. First arrivals are represented by the direct transmitted longitudinal waves with approximate moveout shown in green. Other phases include TP and TS arrivals that propagate as tube waves in the source well (T) and later convert into P or S waves at a certain depth. By TP we actually mark two waves TP and TPP (Figure 3, blue): TP is a wave that first propagates as a tube wave to the interface at 930 m and then converts into the layer as a P-wave, while TPP is a multiple wave that follow the same path as TP and later reflects from the interface at 942 m.

Figure 2 clearly shows that those waves dominate the records between 930 m and 948 m. Later part of the record also contains TS waves (Figure 3, brown), which is a combination of converted shear wave and its multiple reflections between two boundaries at 930 m and 942 m. Note that amplitude of TP and TS arrivals are substantially larger than amplitudes of the first arrivals.

In the monitor model with a low-velocity anomaly between source and receiver wells, TP and TS waves arrive at later times. Although the delay is relatively small it can be clearly observed on the seismograms (Figure 2) having a value of about 1 ms. In contrast, no time shifts are observed in first arrivals. The difference data (monitor minus baseline) reveals the strong time-lapse effect in TP and TS arrivals and no change in first arrivals (Figure 4). Therefore the modeling results suggest higher sensitivity of TP and TS waves to production-related reservoir changes compared to those of direct P-waves.

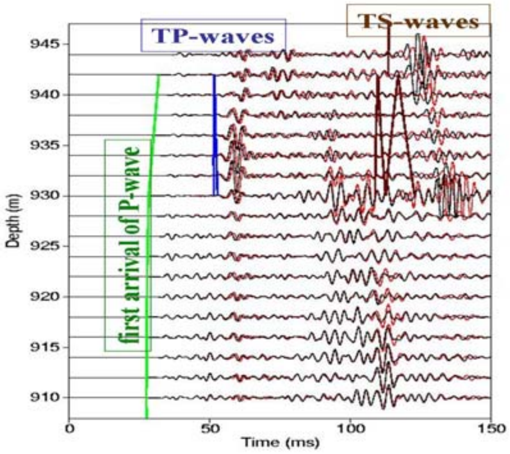

Figure 2: Modeled shot gather with a pressure response (trace of stress tensor) for the source at 910 m: black (baseline, Figure 1a) and red (monitor, Figure 1b). While the first P-wave arrivals show no time-lapse changes, the tube-wave-related arrivals reveal distinctive changes.

Comparison of the modeled and observed arrivals

Cross-well data obtained from Mallik experiment form quite a large dataset. In this study we focus on analysis of only one common-shot gather with source located at 910 m and receivers covering 860 m to 1000 m depth interval.

Common-shot gather from repeat surveys #1and #3 (Figure 5) reveals dominant TP and TS arrivals predicted by synthetic modeling (Figure 2). Same moveout curves as on Figure 2 are applied to Figure 5 and display remarkable similarity in arrival times and even amplitudes between real and synthetic data. TP arrivals display better match, whereas TS arrivals on real data are contaminated by tube waves in a receiver well that are not modeled in our synthetics.

Excellent similarity between TP and TS arrivals also unambiguously verifies that tube-wave conversion in the source well occurs at a geologic interface with highest acoustic contrast. This occurs at 930 m interface between low-velocity shales (S12) and high-velocity carbonate-rich inclusion (C11) right below the upper gas-hydrate-bearing layer (G10). Therefore we confirm that even in the absence of casing diameter changes and perforations, tube waves can generate converted waves with amplitudes larger than direct arrivals from the source. Such high-contrast interfaces in cased boreholes can enable application of tube-wave monitoring method (Korneev at el, 2005, 2006) even in the absence of perforations, casing diameter changes or other features enhancing the tube-wave conversion.

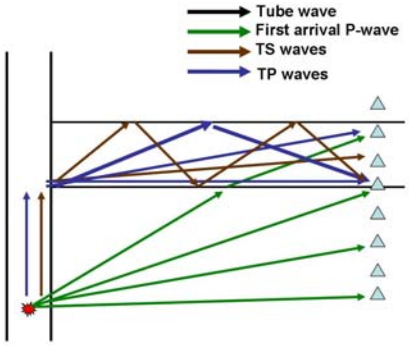

Figure 3. Schematic representation of different arrivals observed and modeled in cross-well data. Tube wave in the borehole is a black arrow, first arrivals are P-waves (green), TP and TS waves represent tube waves converted at the layer boundary into the P (blue) and S (brown) waves respectively.

Figure 5 shows time-lapse data from repeats #1 (black) and #3 (red). As it was observed by Watanabe et al (2005) and Bakulin et al (2006) there is no detectable change in first arrivals. On one side, it implies excellent repeatability of the time-lapse data. On the other side, it means that production-related reservoir changes are small and have limited spatial extent. Nevertheless, as pointed by Bakulin et al (2006), the changes in later arrivals are easily detectable. In particular we see clear time-shift of ~ 1 ms in TP and even larger time-shift in TS arrivals (Figure 5). This delay is better seen on TPT arrivals that represent TP wave further converting into tube wave in the receiver well (Figure 6). This wave propagates first as tube wave in the source borehole, then converts into P-wave at the 930 m interface, propagates horizontally in a cross-well space and converts into tube wave in the receiver well at the same 930 m interface as predicted by Bakulin et al (2006). Since the velocity of the tube waves didn't change in both wells, the only reason for the time-shift is the delay related to the horizontal path crossing the expected low-velocity anomaly near production well.

Multiple gas-hydrate bearing layers are present from ~ 800 m to 1050 m depth but thermal stimulation took place through perforated interval between 906 and 925 m. Time-lapse variations of temperature were recorded in this interval by distributed temperature array behind casing. However these temperature anomalies have largely dissipated already before repeat #1 was acquired. Therefore more complex distribution of heat and produced methane is anticipated.

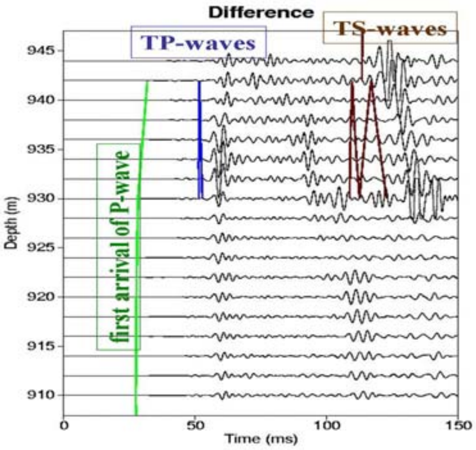

Figure 4. Modeled difference between monitor and baseline responses. Monitor model has low-velocity anomaly in two layers (S12 and G13), whereas baseline model has homogeneous layers. Significant time-lapse difference is seen in TP and TS waves.

If we place low-velocity anomaly near the perforated interval (906-925m) then no time-lapse changes are observed in all arrivals including TP and TS (not shown). The only way to explain the experimentally observed time-lapse effect is by placing production-related anomaly into 930-948 m interval (S12, G13) that included lower gas-hydrate-bearing layer located below the perforated interval. Such reservoir change is shown on Figure 1b and modeled on Figure 2 and 4. This reservoir change is consistent with the data on Figures 5 and 6 since it introduces clear delay of ~ 1ms into TP and TS arrivals for monitor survey while still does not lead to any change in the first arrivals observed in the same depth interval. One possible explanation may include channels in cement behind casing that may transfer stimulating agent into the lower hydrate layers. Another alternative may assume some vertical hydraulic communication between upper and lower hydrate-bearing layers away from the borehole. More work is needed to unravel an exact production pattern which is consistent with all available data.

Conclusions

We perform time-lapse analysis and modeling of full waveforms recorded in cross-well Mallik experiment. Using realistic finite-difference modeling which includes source (steel-cased) borehole we confirm that the most prominent arrivals are the TP and TS waves waves that start propagation as tube waves in the source well and later convert into the *P* or *S* wave propagating in the cross-well space. Data clearly show that those waves also convert into tube waves in the receiver well giving rise to the strong TPT arrivals thus justifying tube-wave monitoring method which utilises such arivals. We found that strongest conversion occurs at the geologic interface with the highest acoustic impedance at 930 m despite the presence of steel casing and in absence of either casing diameter changes or perforations. Excellent agreement between modeled and observed TP and TS arrivals is observed.

Data shows no time-lapse change in the first arrivals thus confirming excellent repeatability. However, identified late tube-wave related arrivals show clear time-lapse change. Modeling of the time-lapse changes we conclude that reservoir changes around perforated interval (906-925 m) cannot explain the anomalies observed in the data. Good agreement between the modeled and experimental data can be only obtained if reservoir change occurs in deeper layers (930-948 m) below the perforated interval. Our results suggest more complex distribution of heat and produced methane in the reservoir package than it was originally anticipated and as it follows from the near-well temperature measurements. New results from tube-wave monitoring revealed in this study need to be combined with other data in order to reach more integrated conslusion that is consistent with all the data.

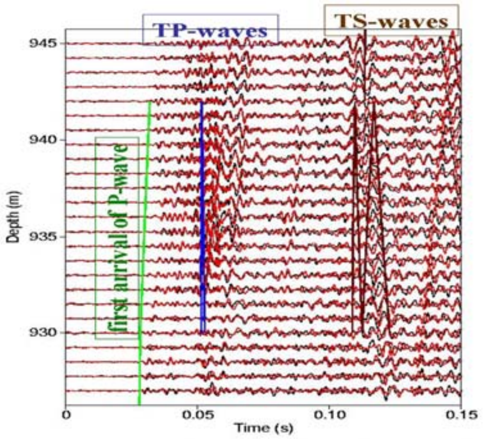

Figure 5. Hydrophone records with experimental common-shot gather at 910 m: black (repeat #1) and red (repeat #3).

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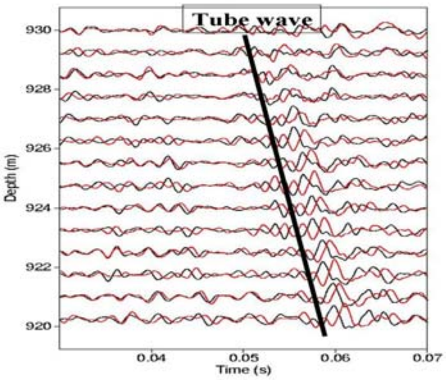

Figure 6. Hydrophone recording of experimental common-shot gather at 910 m: black (repeat #1) and red (repeat #3). We see clear delay in TPT converted arrival of about 1 ms.

Acknowledgments

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