Time-lapse changes in tube and guided waves in cross-well Mallik experiment

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Summary

We analyze cross-well seismic data from the Mallik experiment and demonstrate time-lapse changes in tube and guided waves. Although such changes are challenging to interpret, they are generally of a larger magnitude compared to any time-lapse signatures of the first *P*-wave arrivals reported elsewhere. This suggests better sensitivity of tube and guided waves to small production-related changes and their feasibility for reservoir monitoring.

Introduction

Tube and guided waves are usually considered as a noise on cross-borehole surveys. They usually dominate in seismic records and substantial efforts are needed to suppress those waves. However, many of these later arrivals propagate through the reservoir in cross-well space and therefore contain valuable information about reservoir properties. Korneev et al. (2005) have shown and interpreted such arrivals at Stratton gas field. Wu and Harris (2003) modeled similar arrivals at a West Texas field. The tube-wave monitoring method (Korneev et al., 2005, 2006) has claimed that such converted tube waves can be used for sensitive cross-well reservoir monitoring. In this study we analyze time-lapse changes in tube and guided waves in the cross-well Mallik experiment (Bauer et al., 2005, Watanabe et al., 2004, 2005). We demonstrate traveltime shifts and amplitude changes that are substantially larger than similar time-lapse signatures of direct *P*-wave arrivals reported in previous studies (Bauer et al., 2005, Watanabe et al., 2004). This validates the idea of sensitive cross-well monitoring with tube and guided waves.

Experiment

Time-lapse cross-well seismic dataset 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). Several repeated surveys have been acquired during the production test that produced methane from gas-hydrate-bearing layers at depth of 900-1100 m. Time-lapse surveys were conducted from two dedicated boreholes located 42.5 m away from the central producing well (Figure 1). Bauer et al. (2005) provide details of the data acquisition as well as refer to many modeling and inversion studies utilizing the data. In essence, a very dense recording was done with a shot and receiver spacing of at least 2.5 ft (0.76m) at a depth range 800-1050 m providing angular coverage of $\pm 50^0$ (Bauer et al., 2005). Piezoelectric sources and hydrophone receivers were used. Watanabe et al (2004, 2005) applied differential waveform tomography using first arrivals from time-lapse data, and concluded that no clear velocity change in the production zone (890 – 930 m) was observed.

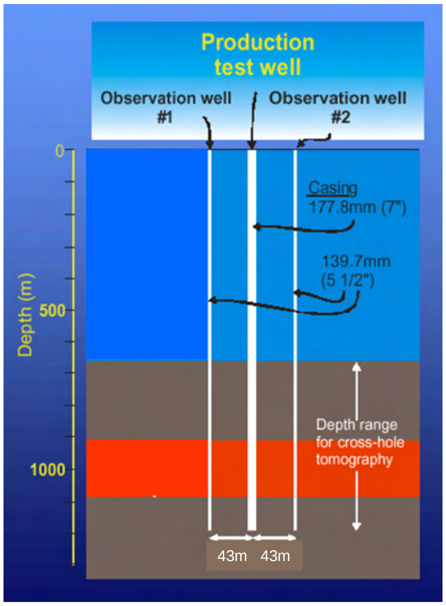

Figure 1: Mallik cross-well experiment setup.

Challenges of seismic monitoring

We believe that the time-lapse detectability problem in Mallik experiment is caused by at least two major problems. First, all three repeat surveys (#1-3) were conducted during the condensed time period of March 6-8, 2002 shortly after production test commenced. This implies only small changes around producing well which are difficult to detect using direct arrivals. Such sensitivity problem is well-known in seismic monitoring and could be solved by either installing permanent sources and receivers or by using more sensitive later arrivals. Second, strong tube waves generated at some depths cover the whole gathers and mask the signals such as direct, reflected and scattered waves (Figure 2,4). Thus, a large part of the processing effort was focused on suppressing these tube-wave-related arrivals by multiple f-k filtering (Watanabe et al., 2004, 2005). Such pre-processing is always undesirable for 4D datasets because it mixes many traces and smears out true 4D response. In this study, we focus on analysis of full-waveform field data before any pre-processing.

Main arrivals on full-waveform data

Tube-wave-related arrivals are easily recognized on both source and receiver gathers based on its linear moveout and velocity of 1400 m/s. To establish exact character of these events it is instructive to re-sort the data into the different domains. Figure 2 shows common-shot gather at 914 m. Figure 3 shows moveouts of some cross-well arrivals assuming realistic geometry but a homogeneous velocity model with source at 950 m. Direct *P*- and *S*-wave arrivals are recognized by symmetric hyperbolic moveouts. All other arrivals are related to tube-waves: PT (ST) represents direct P(S)-wave from the source that converts to a tube wave in receiver borehole, TPT (TST) starts as a tube wave excited in source borehole, converts to *P*(*S*)-wave in the formation and re-converts to a tube wave in the receiver borehole (Figure 3). It was assumed that conversion occurs at the depth corresponding to sharp interface between two horizontal formation layers. Other arrivals (TP and TS) have curved moveouts. Likewise, in a receiver gather configuration TP and TS will have the triangular

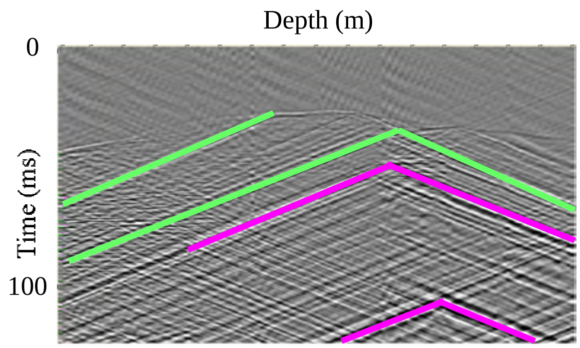

Figure 2: Common-shot gather at 914 m. Green lines highlight PT waves, while magenta TPT and possibly TST arrivals.

moveouts, while PT and ST would be curved. Comparing Figure 2 and 3 we clearly recognize strong PT, TPT and possibly TST arrivals on real data. In a layered medium with many sharp boundaries tube-wave arrivals can be generated at multiple depth location. In addition guided waves or other later arrivals can also convert into tube waves. In tube-wave monitoring scheme (Korneev et al., 2005, 2006), the arrivals of interest are TPT, TST or other arrivals that start and end as tube waves in both boreholes. In order to distinguish those arrivals from the others it is instructive to re-sort the data to zero-offset gathers with source and receiver moving in parallel (Figure 4). Figure 5 proves that in this configuration all arrivals that start and end with T (like, TPT or TST) have an apparent velocity of about 700 m/s or half of the tube-wave velocity. In the same time, the other arrivals like PT/TP, ST/TS still have a velocity of 1400 m/s. Comparing Figures 4 and 5 we clearly recognize TP, TPT and possibly TST arrivals on the real data. Analyzing many gathers we conclude that late arrivals with apparent velocity of 700 m/s dominate the records in both number of events and their amplitudes. Therefore, Mallik data confirms the tube-wave monitoring concept that assumes existence of arrivals that start and end as the tube waves in both boreholes. Data suggests that most of the conversions occur at the sharp boundaries between high-velocity gas-hydrate-bearing layers and low-velocity shales. This is also supported by the fact that both observation wells do not have any perforations or diameter changes, which could serve as energy-converting inhomogeneities. Modeling study is underway to confirm feasibility of this conclusion.

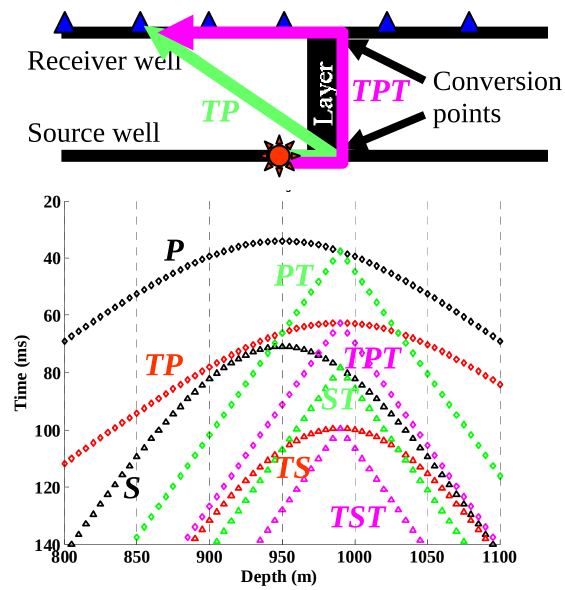

Figure 3: Moveouts of cross-well arrivals for common-shot gather configuration at 950 m. Tube waves are converted at fixed depth of 990m at both boreholes.

Time-lapse changes

Figure 6 shows comparison of time-lapse data. On the zero-offset data the first arrivals in the gas-hydrate-bearing layer (Figure 6b) are well-repeatable but display no time-lapse effect. Difference zero-offset data (Figure 6b-d) demonstrate measurable changes in various arrivals with apparent velocity of 700 m/s that travel as tube waves in both boreholes thus confirming tube-wave monitoring concept. Most likely tube-wave conversions occur at the layer boundaries.

Common-shot gather (Figure 6e-h) illustrates the same conclusion. First arrivals are very repeatable for all offsets and display no time-shift or amplitude changes while there are clear time-shifts in tube and guided waves (Figure 6f). Filtering allows highlighting of changes in different

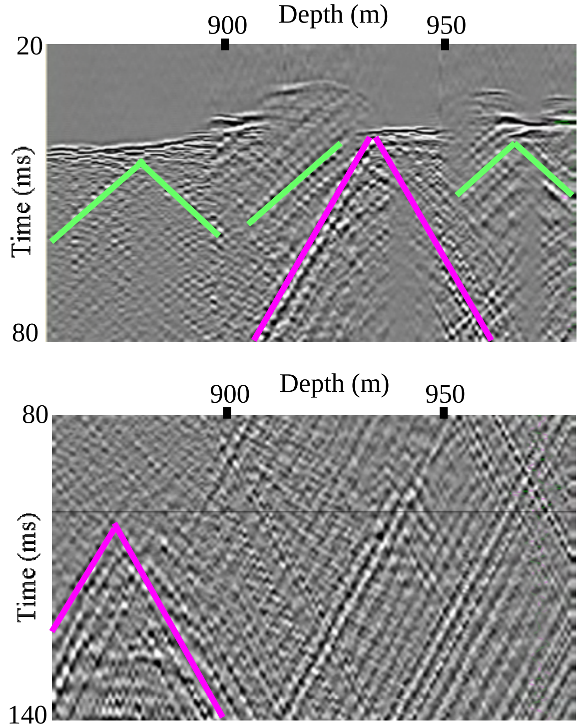

Figure 4: Zero-offset cross-well data from repeat survey #1 (same source and receiver depth).

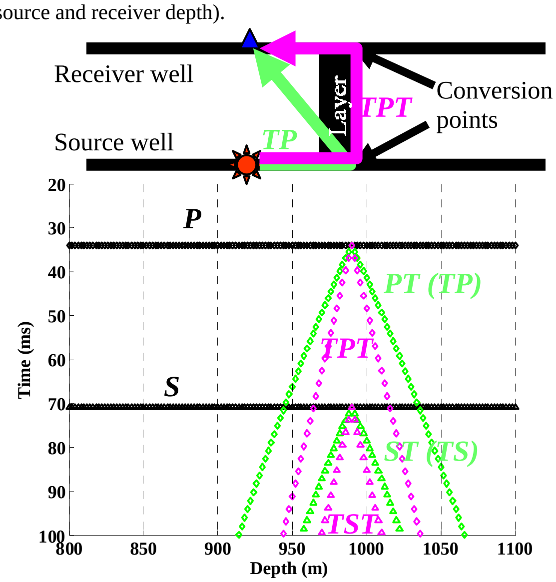

Figure 5: Moveouts of different waves for zero-offset acquisition (source and receiver at the same depth). Conversion points in source and receiver well are at the same depth.

arrivals (Figure 6h) whereas higher frequencies more clearly show changes in suspected guided waves (Figure 6g). More quantitative study is underway to identify exact nature of the most prominent arrivals and model their time-lapse signatures.

Conclusions

We analyze time-lapse changes in the full waveforms recorded during Mallik cross-well monitoring experiment. First arrivals show no time-shifts or amplitude changes confirming excellent repeatability of the data. This conclusion is consistent with previous studies. However, full waveforms show clear time-lapse changes in later arrivals. We analyze the data and confirm that most prominent late arrivals are tube-wave related which start and end their propagation as a tube waves in source and receiver boreholes respectively. These arrivals have apparent velocity equal to one-half of tube-wave velocity on a zero-offset gathers. Between the boreholes, those arrivals may travel as *P*-, *S*- or guided waves. Conversion of formation waves to and from tube waves most likely occurs at the layer boundaries with sharp impedance contrasts. We observe clear time-shifts and amplitude changes in these tube-wave-related arrivals as well as in suspected guided waves. Modeling study is underway to confirm the nature of prominent late arrivals and explain time-lapse variation in these signatures. Reported experimental observations verify tube-wave monitoring concept that suggests use of tube-wave related arrivals for sensitive fit-for-purpose cross-well monitoring from producing wells. These arrivals can be excited and detected well above the reservoir intervals and therefore sources and receivers can be deployed in a shallow idle space of producing wells without interference with completion equipment.

Acknowledgements

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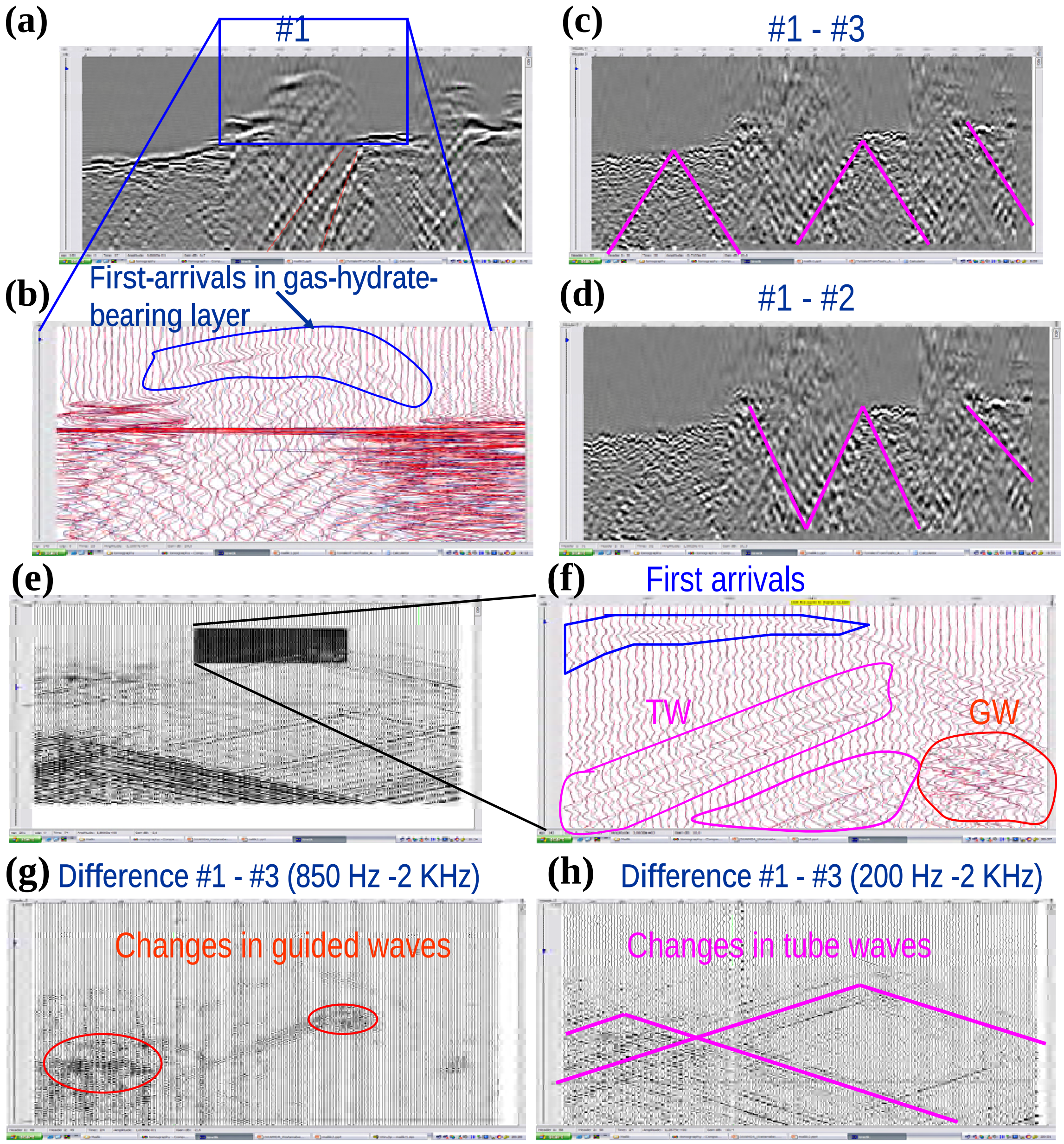

Figure 6: Time-lapse changes in tube and guided waves: (a)-(d) zero-offset data shows no change in first arrivals and substantial changes in tube waves; (e)-(h) common-shot gather at 914 m shows changes in tube waves at low frequencies and in guided waves at high frequencies.

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