Tube-wave monitoring of oil fields

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Summary

Tube-wave monitoring is a fit-for-purpose downhole imaging and monitoring technique. It aims to detect and characterize time-lapse changes in a cross-well space. In contrast to conventional cross-well seismic it does not require production interruption or reduces it to a minimum. Monitoring relies on tube waves in a well fluid column to carry the seismic signals to and from the reservoir. We present a simple modeling to support the concept and validate experimental data acquired at Stratton and Mallik fields.

Introduction

Various methods are used for time-lapse reservoir monitoring. Surface seismic is the most popular approach that delivers areal coverage. However this approach suffers from non-repeatable acquisition and changing near-surface conditions. Surface 4D may not have enough resolution for stacked reservoirs and has a threshold on the amount of change it can detect. Repeated VSP has better resolution, repeatability and sensitivity but has limited areal coverage and requires frequent well interventions or installation of permanent sensors with substantial shooting effort. Conventional cross-well seismic has even better characteristics but it requires intervention in two wells or drilling of dedicated observation wells and thus is rarely used in practice. Time-lapse logging can characterize detailed changes in the immediate near-wellbore, but also requires well intervention. A common weaknesses of all these methods are large time-lapse observation intervals and insufficient sensitivity to small changes.

We outline a real-time method for permanent cross-well monitoring that does not require well intervention and utilizes existing production and injection wells.

Method

Conventional cross-well seismic requires the source and receiver wells with many source/receiver locations spanning overburden and reservoir interval. This cannot be achieved without interrupting the production or drilling dedicated observation wells thus making it very expensive proposition. Also conventional cross-well utilizes direct *P*- or *S*-waves as the main signal carriers. The high-frequency content of those waves is preserved at rather short distances (on the order of ~ 100 m) which is much smaller then realistic cross-well distances on most of the producing oil fields. We propose to place sources and receivers in the idle space above the completed intervals or even at the wellhead (Figure 1). Tube waves are used as a couriers to deliver the energy to and from the reservoirs thus giving the name “tube-wave monitoring” to this approach.

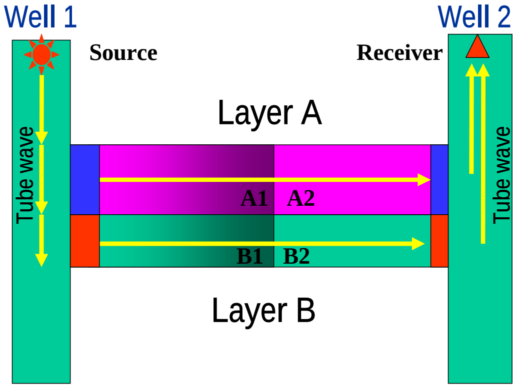

Figure 1: Tube-wave monitoring scheme.

A tube wave is the strongest wave excited by borehole sources and is by nature a trapped mode in a fluid column which propagates without attenuation. In producing wells both tubing and annulus fluid can support their own tube wave (Ziatdinov et al., 2005). Therefore we avoid interference with any downhole completion equipment, and every production or injection well can be used provided the well(heads) can be permanently instrumented. Multiple stacking is supposed to provide high signal-to-noise ratios for the recorded data.

Schematic wave propagation for tube-wave monitoring is shown on Figure 1. Downgoing tube wave propagating in a source well interacts with the reservoir and excites horizontally propagating waves along the layers. When this horizontal energy reaches other well, it converts back to the tube wave at the receiver well and transports the reservoir signal to the shallow sensors. Data with such arrivals have been shown on cross-well modeling (Kurkjian et al, 1994), in closely spaced coal wells (Allbright and Johnson, 1990) and in widely spaced gas-bearing wells (Korneev et al, 2005, Korneev, 2006). Time-lapse changes in tube and guides waves are reported by Bakulin et al. (2006) for cross-well Mallik data.

2D model with time-lapse changes

The wave propagation concept of tube-wave monitoring can be illustrated using the 2D example on Figure 2 that

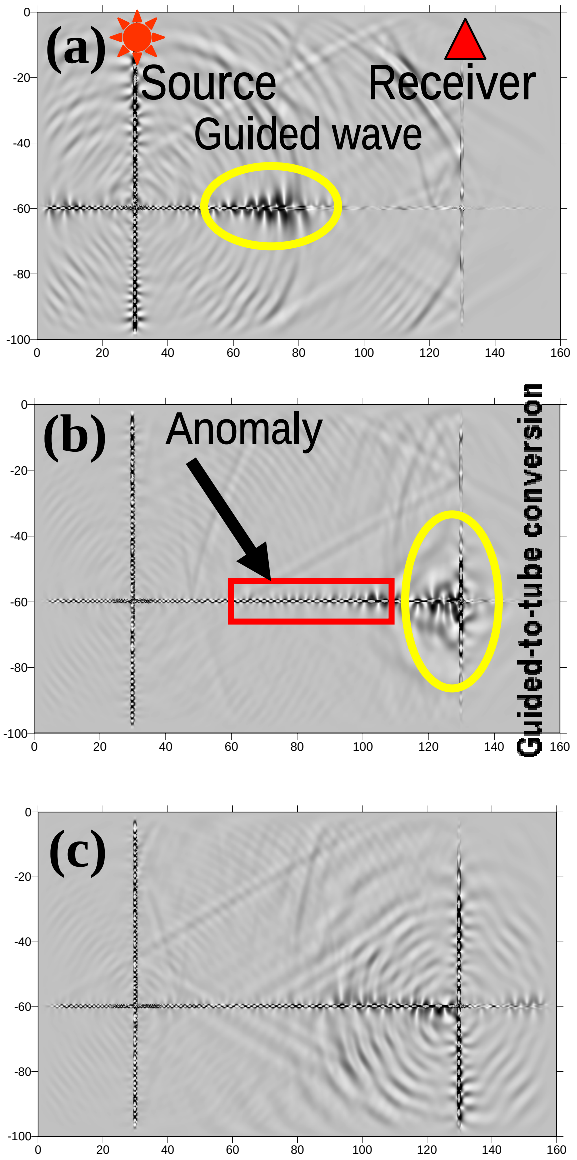

Figure 2: 2D wave propagation model illustrating tube-wave monitoring.

contains source and receiver boreholes intersecting a low-velocity reservoir layer. The borehole was modeled as a thin fluid layer. Wu and Harris (2003) have shown that 2D modeling can represent the main features of the cross-well wave propagation including tube-wave-related arrivals. The tube wave propagates down the source hole, then converts into guided wave in a reservoir layer, guided wave propagates horizontally (Figure 2a), converts into tube wave in receiver well (Figure 2b) and, finally, propagates as upgoing tube wave (Figure 2c). When a 10 % velocity increase is introduced in a part of the reservoir between wells (Figure 2b), it results in a strong time-lapse change of the guided-wave coda (Figure 3). Note that early arrivals before guided wave are almost unchanged. The challenge of such time-lapse signature is difficult interpretation, while clear advantage is better sensitivity to small changes. Guided wave is quite sensitive to any production-related changes since it remains trapped in the reservoir throughout its whole propagation path. Tube wave merely serves as a convenient courier that delivers the signal to and from the reservoir.

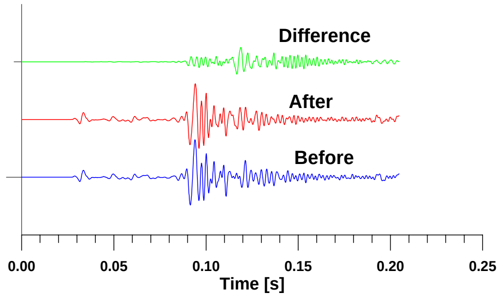

Figure 3: Time-lapse signatures in tube-wave monitoring.

3D model with reservoir as a fluid layer

To verify wave-propagation concept in 3D we use 3D finite-difference code (Falk, 1993) to model survey with two uncased boreholes intersecting thin reservoir represented by a fluid layer (Figure 4).

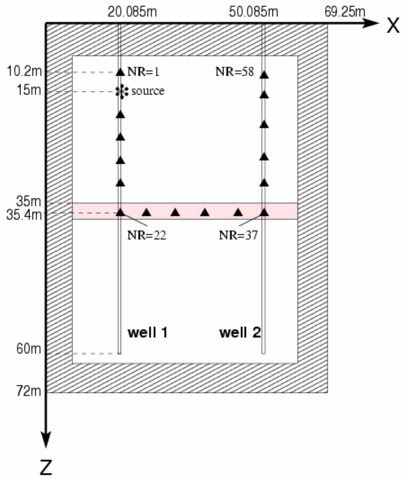

Figure 4: Cross-well 3D model.

The wavefield in the source borehole consists of downgoing tube wave (Figure 5) with constant amplitude of ~ 1000 units. Upon hitting the reservoir it excites two guided waves propagating in a fluid layer with amplitudes of ~ 1. Therefore conversion coefficient of tube-to-guided wave is of the order ~ 1/1000. While it may sound small, in the fluid layer this conversion generates waves with much larger amplitudes than any direct arrival coming from the source. Finally, guided waves convert to tube waves at receiver borehole with conversion coefficient of ~ 1 (Figure 5). Thus, the tube wave in a receiver well has amplitude that far exceeds any amplitude of direct arrivals. While direct conversion at 1/1000 and reverse transformation of ~1 may seemingly contradict reciprocity, such violation is only apparent and results from the 3D nature of the wave propagation.

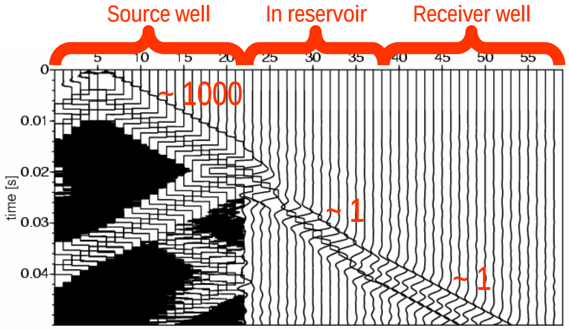

Figure 5: Pressure in a source well, fluid layer and receiver well.

Guided waves in a fluid layer consist of slow Stoneley-type and faster Rayleigh-type modes (Figure 6). At a realistically large cross-well distances the amplitude ratio of guided to direct waves will only improve since guided modes experience 2D geometrical spreading, while body waves and reflections have 3D spreading. In addition, waves of interest would arrive very late when other signals have already passed (Korneev et al., 2005). All these advantages suggest that tube-wave monitoring is feasible for realistic cross-well distances.

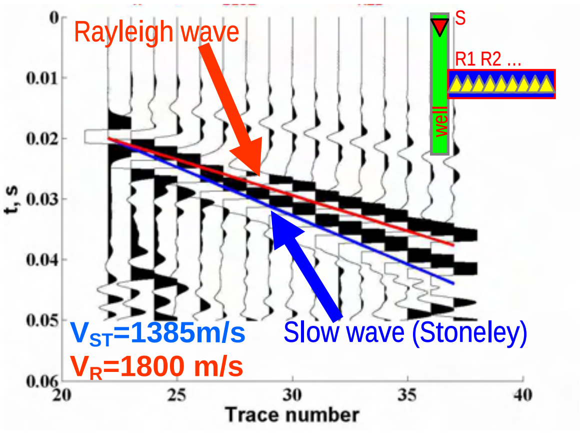

Figure 6: Wavefield (pressure) recorded inside fluid layer consists of propagating horizontally Rayleigh and Stoneley waves.

Conversion into reservoir and non-reservoir layers

In layered formations tube waves may in principle convert into any layer. However in Stratton field experiment (Korneev et al., 2005) these waves preferentially convert into reservoir intervals. We may speculate on a possible reasons for such preference. First, interaction with perforations may enhance the conversion as reported in West Texas cross-well experiment (Wu and Harris, 2003).

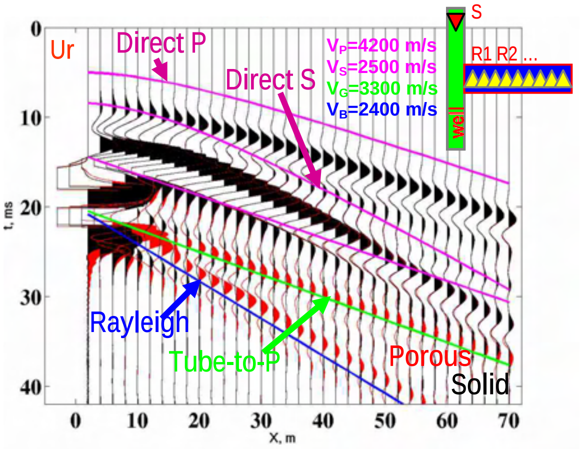

Figure 7: Conversion of tube wave into formation waves is better in poroelastic (red) than in elastic (black) impermeable layer.

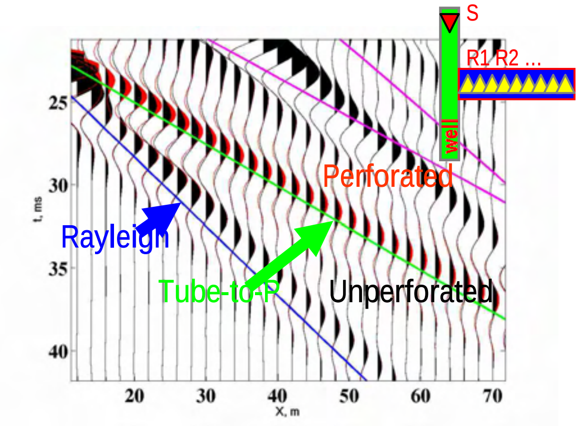

Figure 8: Comparison of tube-wave conversion in a poroelastic reservoir with (red) and without (black) perforation.

Perforations act as secondary sources located at the reservoir face. Another reason may be because of poroelastic nature of the reservoirs. Finite-difference modeling that includes cased borehole with cylindrical perforation of 16 cm intersecting 2.4 m thick layer (Figure 7), shows that conversion is larger into the poroelastic reservoir (modeled as Biot layer) than in non-porous layer. Strong tube wave arrives at ~ 20 ms and converts to formation *P*-wave and Rayleigh-type waves. Note that low-frequency velocities and density are identical for both type of layers which explains identical amplitudes of direct *P*- and *S*-wave arrivals. Nevertheless tube-to-*P* and tube-to-Rayleigh conversion is clearly better in the poroelastic reservoir layer (Figure 7). While it may be tempting to attribute this effect to fluid interaction at the perforation, this is only partly true. Conversion to unperforated reservoir, albeit smaller than in perforated, is still substantially larger than in non-porous layer (Figure 8 and 7). Mallik experiment suggests that conversion may also happen at the layer boundaries with sharp acoustic contrast (Bakulin et al., 2006). Further studies are needed to obtain more analytical insight.

Conclusions and discussion

Fluid-saturated reservoirs can be monitored with help of tube waves using the scheme shown on Figure 9. Wellheads of producing and pumping wells are equipped with low-power repeatable sources which excite tube waves propagating downwards reaching reservoir depths. At those depths tube waves convert into waves propagating along the reservoir as surface (Rayleigh and/or Stoneley) waves, forming guided waves at appropriate frequencies. Part of the converted energy might also propagate as body (*P*- or *S*-) waves. After reaching other wells, all these waves can be converted into tube waves and recorded by the sensors in the wells or at the wellheads. Repeatability of the sources should allow in-situ stacking of the recorded traces significantly improving signal-to-noise ratios. Using telemetry, the stacked traces can be transferred to data processing centers providing real-time data for detection of production-induced changes in the reservoir. These changes can be caused by propagating fronts of water or CO_2 floods which are used to stimulate and enhance gas and oil production. Quantitative interpretation of changes depends on the reservoir structure and rock properties. Detection of changes can be also used for triggering of time-lapse repeat surveys ensuring their cost effectiveness and timely manner. The proposed technology will not interrupt production operations providing low-cost tool for real-time reservoir monitoring. Preliminary modeling provides encouraging results. More work is needed to understand the feasibility of tube-wave monitoring in realistic producing wells. In particular, it is critical to understand tube-wave conversion for different completions and robustness with respect to flow noise. Permanent instrumentation needs to be developed for excitation and recording of signals in real wells.

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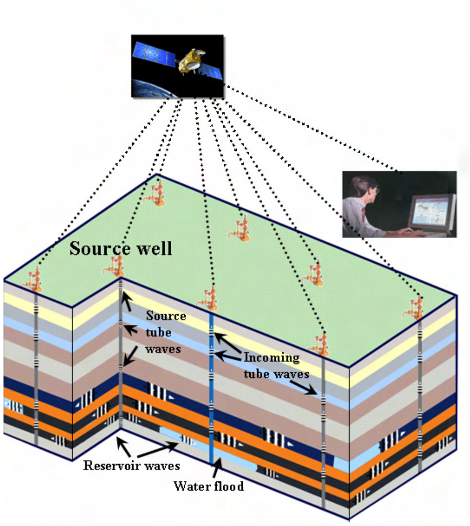

Figure 9: Tube-wave monitoring of producing gas/oil fields.

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