Acoustic signatures of cross-flow behind casing: downhole monitoring experiment at Teapot Dome

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Summary

We present measurements of acoustic signatures of cross-flow behind a pipe in time and frequency domain. We show that despite being called “noise” these signatures represent superposition of tube waves with impulsive waveforms. We further present observation of change in those signatures during injection and release of air, and suggest that these changes can be used for real-time acoustic characterization of depletion in stacked commingled reservoirs.

Introduction

Cross-flow behind the pipe (casing) generates distinct acoustic response that was named "noise" in the past. Noise logging utilized single-sensor passive listening and was used to detect flow through uncemented channels behind casing (McKinley, 1973). Actual signature measured downhole was peak-to-peak or averaged amplitude over a long observation time. The higher the "noise" level the closer sensor is to the "leak" location. In addition, distribution of acoustic energy within the spectrum was used as a diagnostic of one- and two-phase flow. Since acoustic signature was considered "noise", no attempt to record seismograms in time domain was made.

Field experiment

Passive downhole listening have been performed in a dedicated small-diameter well (microhole) at Teapot Dome oil field, Natrona County, Wyoming. This field represents Naval Petroleum Reserve # 3 operated by Rocky Mountain Oilfield Testing Center of U.S. Department of Energy. This microhole is located 50 ft (15 m) away from the actual producing well NPR # 3 67 SX 34 (Figure 1). Production occurs from two Upper Cretacesous reservoirs represented by Upper and Lower Shannon bio-turbated shelf sandstones (Tomutsa et al., 1986). Upper Shannon has better porosity and permeability and is separated from Lower Shannon by well logs (Figure 2). Producing well has perforations in a low-permeability bioturbated shelf siltstone as seen on the

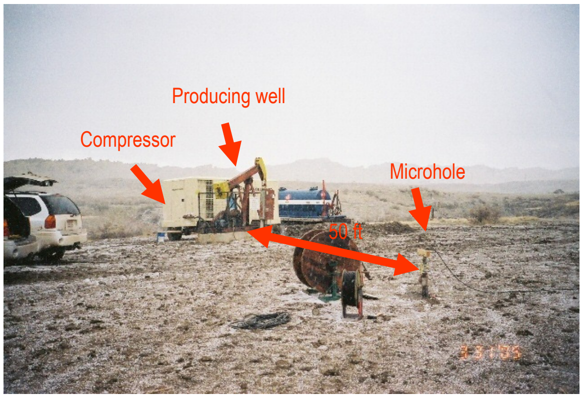

Figure 1: Field experiment layout with producing well and microhole.

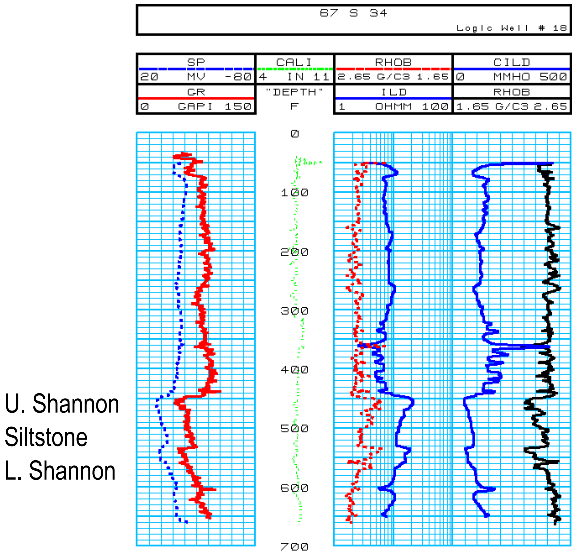

Figure 2: Well logs from NPR # 3 67 SX 34 showing location of Upper and Lower Shannon sansdtone reservoirs.

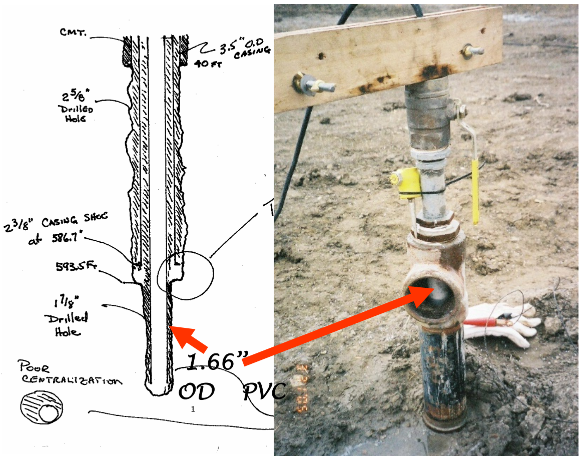

Figure 3: Sketch (left) and photo (right) of the microhole.

both Upper and Lower Shannon and production is commingled. Figure 3 shows wellhead of the microhole drilled by Los Alamos National Laboratory (LANL) under Department of Energy initiative. It has three casing strings all cemented to surface: internal plastic string to 800 ft (244 m) with diameter of 1 1/16", steel casing 2 3/8" to 586.7 ft (179 m), and 3 ½" steel conductor to 40 ft (12 m). Twenty-level hydrophone array with spacing of 5 m (16.4 ft) was used for recording.

Persistent signals

Seismic recording in the absence of any active source has revealed very coherent events shown on Figure 4. For short recording time (2 s) these events were not always present and mysteriously appeared and disappeared on repeated seismograms.

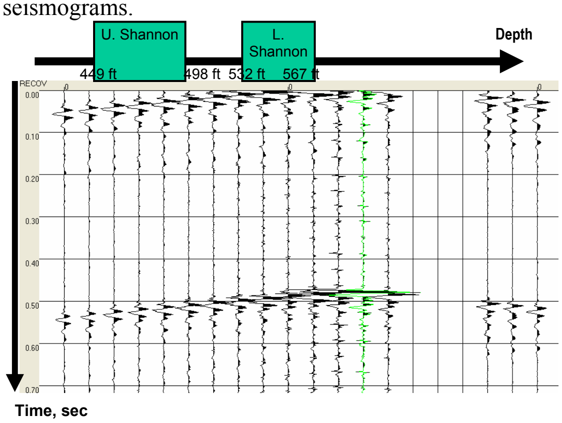

Figure 4: Events recorded without any obvious seismic source.

Low frequency (<1000 Hz), linear moveout and velocity of ~ 960 m/s suggest that these are tube waves. Triangular-shaped travel-time "curves" consist of upgoing and downgoing tube waves with the apex in Lower Shannon that represents an apparent source location (Figure 4). Other similar events originated mostly in or around both reservoirs but some were also present in the overburden. These events have clear impulsive waveforms as if airguns had excited them. Analysis of longer records revealed that the waveforms of the events from the same depth are very repeatable (Figure 5).

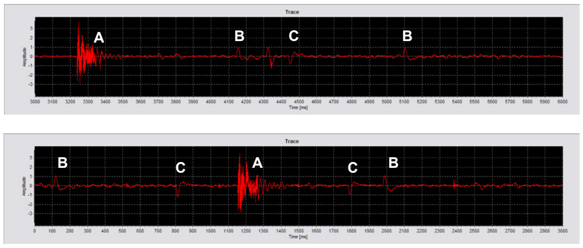

Figure 5: Parts of a longer records illustrating repeatable character of events from the the same depth.

Where is the source?

To understand the nature of the recorded signals, three hypotheses were considered initially: mechanical noise from the surface, signals from neighboring pump jacks propagating horizontally along the reservoir, gas bubbles bursting in the vicinity of closest producing well. All of these hypotheses were tested and none of them has been confirmed. Almost all beam pumps have been switched off one by one in a 1000 m radius; other distant mechanical facilities on the surface were shut down. Repeated measurements in the borehole and with surface geophones with and without operating beam pumps and with and without those mechanical noises have showed that signals of interest remain abundant. Third hypothesis was tested at a later stage when closest producing well was subjected to three weeks of air injection. Although the conditions for bubble bursting were eliminated, the observed signals clearly remained.

Cross-flow

Final hypothesis was that such signals are due to a flow behind the pipe caused by a poor cementation (McKinley et al., 1973). As suggested by Figure 3 microhole design may be susceptible to poor centralization that may cause channels in cement. The production logging technique called "noise" logging listens to passive acoustic response along the borehole and identifies location and characteristics of such leaks behind casing (McKinley, 1973). However those wireline measurements are performed with a single channel and thus only analyze amplitude spectrum averaged over a long recording time (~60 s).

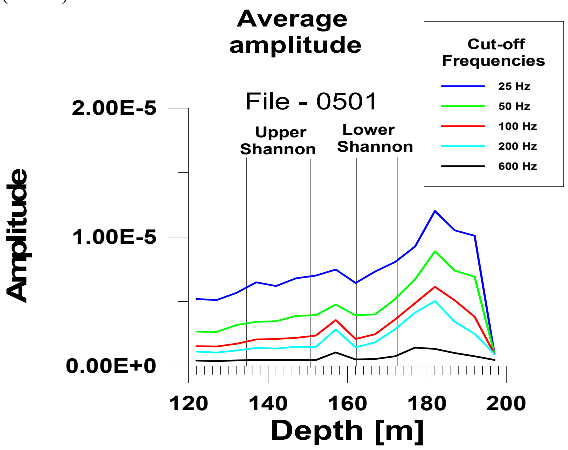

Figure 6: Average amplitude spectrum of acoustic response of cross-flow as a function depth.

No time-domain data have been reported in the literature. If we present our data in a similar format (Figure 6) than it reveals structure resembling that of a typical "noise" logging response (McKinley, 1973): peak of the amplitude corresponds to the location of the flow, lower frequencies have higher amplitudes.

To simulate the artificial leak we measured response excited by squeezing water from a plastic bottle at the wellhead (Figure 7).

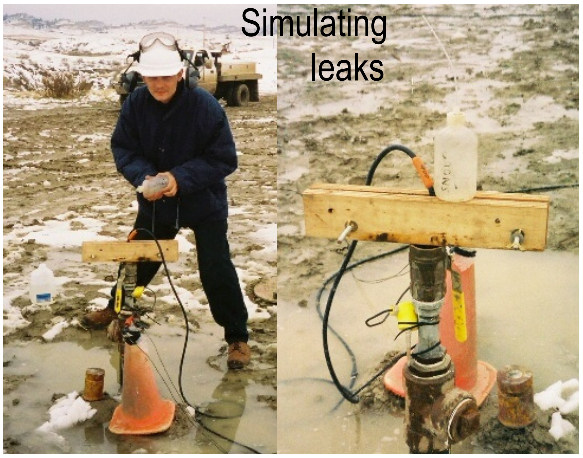

Figure 7: Squeezing plastic bottle filled with water as a source.

Slight squeeze by fingers has generated a downgoing response that is similar to cross-flow signatures both in magnitude and frequency content (Figure 8).

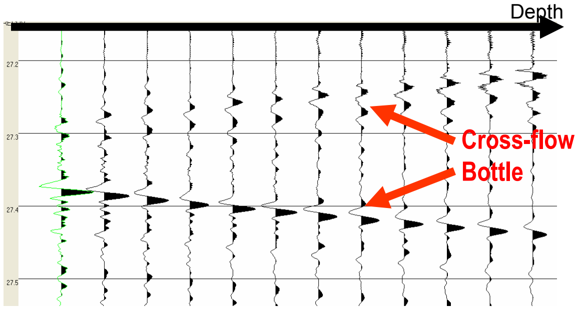

Figure 8: Record with downgoing tube wave excited with a bottle at the wellhead and upgoing tube wave caused by cross-flow deep at reservoir level.

Finally, recorded traces have been converted to an audio file and played. Most of the people, including several noise logging experts, associate these records with a noise of stream flowing through the throttle.

Time-lapse changes in acoustic signatures of cross-flow

The cross-flow signatures were also recorded after three weeks of air injection performed in the producing well. After pressurizing reservoir to about 300 psi, we started to release the air during part of the day and shut-in period during the night. We observed characteristic changes in the acoustic signatures: after extensive shut-in periods the average amplitude response was always similar to Figure 9a with a most energetic feature right below Lower Shannon. When air was released for several hours, the response changed to that of Figure 9b when the most energetic feature moved to right below Upper Shannon. This pattern repeated on the next day, after another extended shut-in period (Figure 9c-f). We interpreted this pattern as a change of cross-flow direction between Upper and Lower Shannons. To verify this hypothesis, a simple radially symmetric reservoir model was built and history-matched to existing pressure measurements done with Echometer. Even for identical initial reservoir pressures, the model predicted that pressures in Upper Shannon become higher during injection. However, during air release, the pressure in Upper Shannon drops faster and during observation period becomes lower than in Lower Shannon (Figure 9g). Such pressure behavior is common for commingled stacked reservoirs that have different permeability and porosity. This model included only large perforated wellbore. Microhole was not modeled since it serves as an infinitely small gauge that does not affect the volumetric flow. Rather it measures the cross-flow that occurs mainly through the large perforated wellbore. As expected crude radial model does not predict multiple crossovers between two pressure curves. Nevertheless, it confirms that characteristic 4D changes in cross-flow signatures are likely explained by change in sign of the pressure gradient caused by cross-flow that occurs between two reservoirs via the large perforated borehole.

Conclusions

For the first time we report time-domain acoustic array measurements of flow behind the casing. This flow is likely caused by cross-flow between two commingled reservoirs with different pressures. Conventionally reported as "noise" and only measured in spectral domain, these acoustic signatures turn out to be a superposition of separated in time tube-waves arrivals with impulsive waveforms similar to those excited by airguns. Waveforms excited by cross-flow at the same depth are well repeatable. Time-domain observation with the array allows using powerful time-processing techniques. Recordings can be made above or below completed intervals; arrivals from several sources of flow at different depths can be separated.

We have shown that acoustic signatures experience characteristic changes during repeated periods of air release and shut-in conditions. These changes seem to follow the repeated pattern and indicate change in the sign of a pressure gradient between two commingled reservoirs.

Reservoir modeling confirms possibility of such pressure changes. Results suggests that real-time acoustic monitoring may allow better characterization of depletion in a commingled stacked reservoirs using permanent sensors in production and injection wells.

These findings may also have an implication for permanent downhole seismic monitoring. There are many evidences that large percentage of wells are subject to various integrity issues and thus are conducive to cross-flow. If cross-flow is an abundant phenomenon for commingled reservoirs then the whole concept of placing permanent seismic sensors in production/injection wells may be jeopardized. In this case dedicated observation wells may be an attractive solution for permanent monitoring.

Acknowledgments

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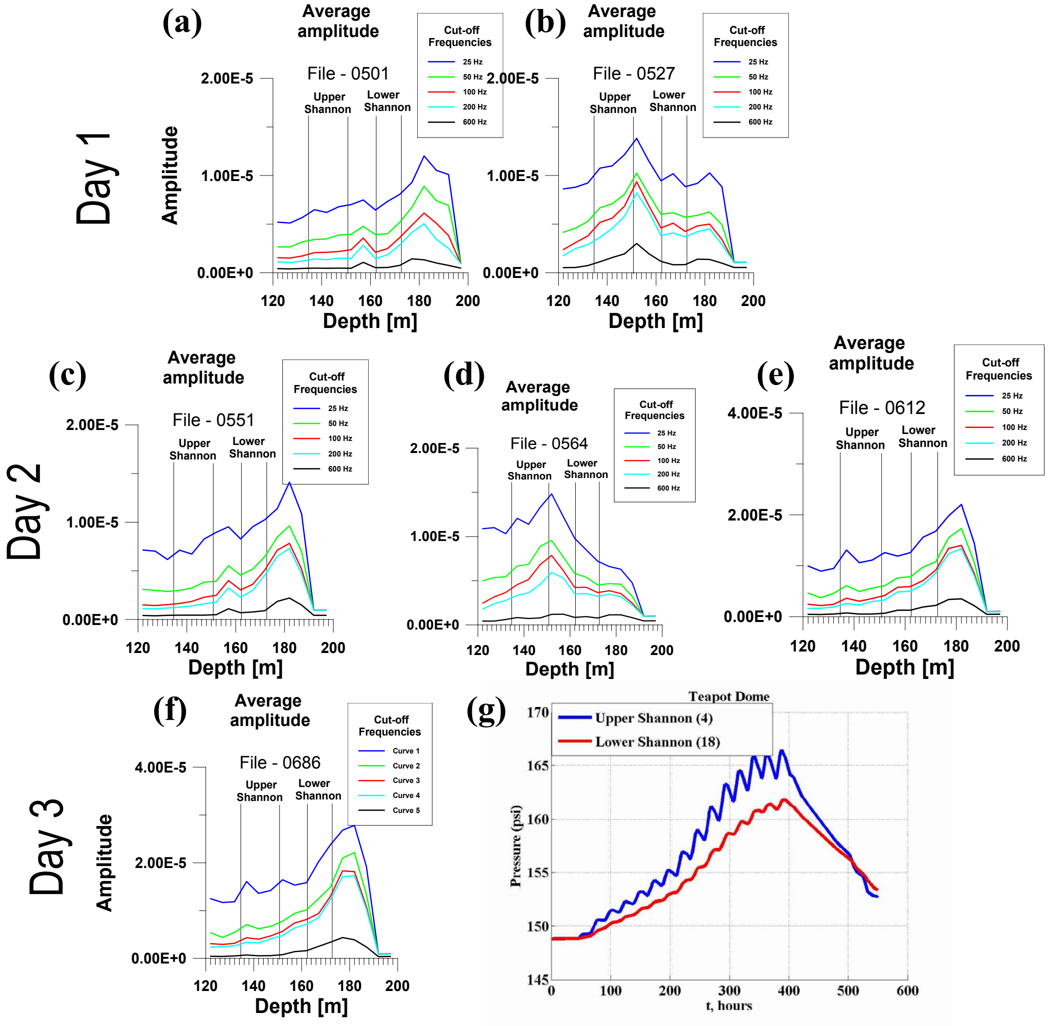

Figure 9: Acoustic response of cross-flow at the beginning (a) and end (b) of first day and beginning (c), middle (d) and end (e) of second day and morning of third day (f). (g) Pressure in two reservoirs as predicted by reservoir model showing cross-over at observation time.

EDITED REFERENCES

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