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# Direct correlations between volume injection rates and microseismic resonances

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## Summary

Microseismic experiments are commonly monitored by geophones deployed in observation wells. Rather than studying microseismic events, we employ time-frequency pictures of continuous recordings to delineate several resonances in a 2-stage microseismic experiment.

Variations in resonance frequencies are strongly correlated with variations in volume injection rates, especially the slurry flow and the nitrogen injection rate. This strong correlation suggest fluid flow-related mechanisms, like non-Darcian flow, at the perforation location or in the reservoir could be their source.

This example shows that resonances interpretation could lead to new ways for reservoir monitoring during hydraulic stimulations, such as for hydrocarbon and geothermal reservoirs, $CO_2$ sequestration or even volcano monitoring.

## Introduction

Hydraulic stimulations are increasingly used to fracture a reservoir in order to improve the drainage of hydrocarbons or fluid movements in geothermal operations. Numerous microseismic events are occurring during the fracturing, corresponding to brittle and tensile failures within the reservoir. As a consequence, microseismic monitoring primarily relies on brittle failure to evaluate the stimulation performance.

However, the energy coming from the recorded microseismicity is far smaller than that of the fluid injection (Maxwell et al. 2009). This suggests that other kinds of deformations are occurring inside the reservoir, like semi-ductile or slow deformations (Chorney et al. 2012). Some candidates are unconventional events, such as long-period long-duration events (Das and Zoback, 2013), and resonance frequencies (Pettitt et al. 2009). Time-frequency transforms, such as the short-time Fourier transform aka spectrogram, are well-suited for the analysis of resonances in continuous recordings (Tary and van der Baan, 2012).

We here present a microseismic experiment during which several resonances were observed. Variations in resonance frequencies are highly correlated to variations in treatment conditions.

## Observations

The microseismic experiment includes 2 stages recorded by 12 geophones deployed in a vertical borehole. They are regular 15-Hz geophones, sampled at 4000 Hz. Apart from approximately 100 microseismic events, several families of resonances are recorded during both stages (Figure 1 and 2).

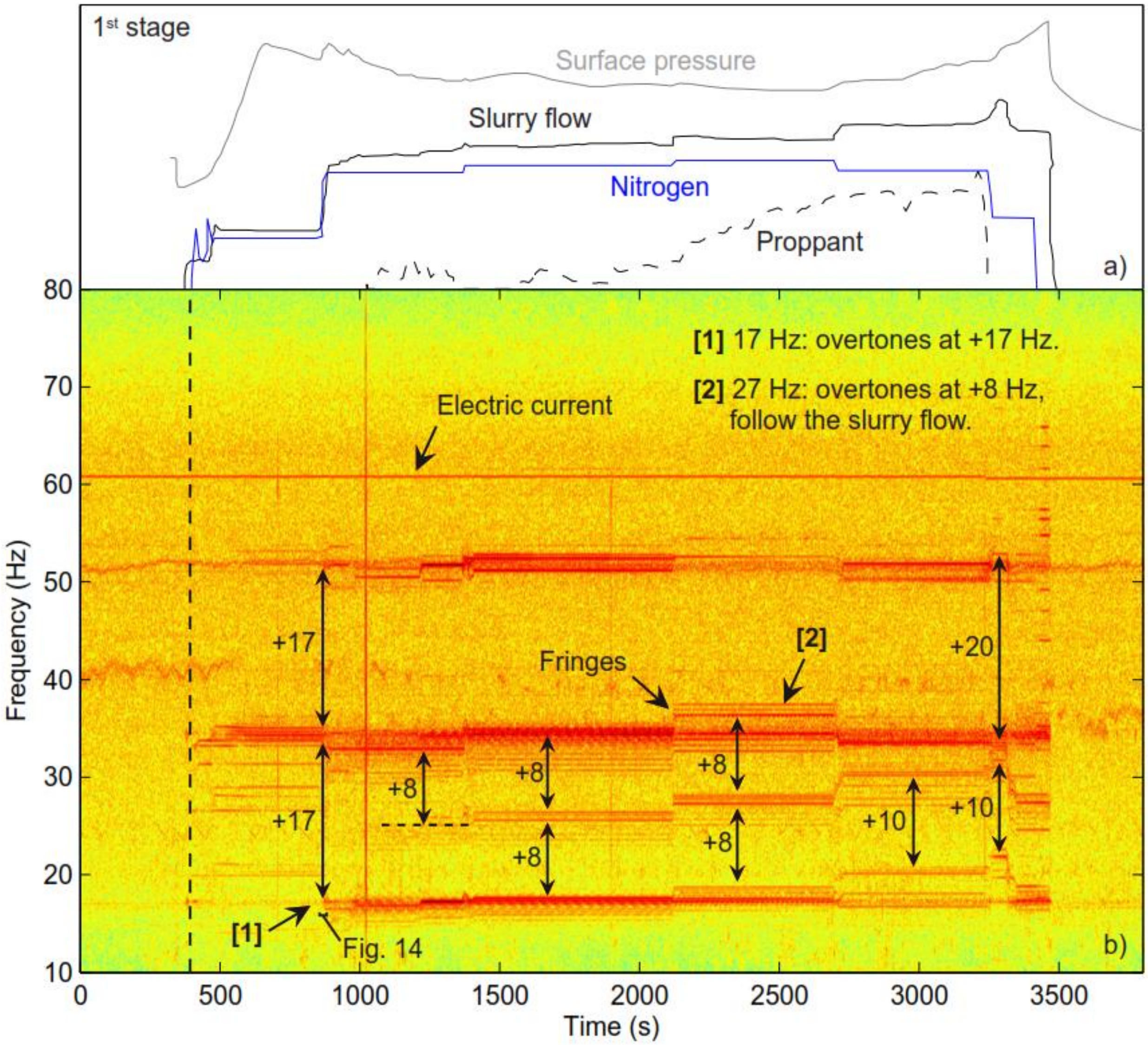

Figure 1. Treatment curves (a) and time-frequency representation (b) of the first stage of the microseismic experiment (geophone 12, vertical component). The data are downsampled from 4000 Hz to 160 Hz prior to the time-frequency analysis. Hot colors correspond to high amplitudes. A window of 8 s with 90 % overlap is used to compute the short-time Fourier transform. A time shift of +323 s is applied to the treatment curves to align them with the time-frequency representation. In the treatment plot, the gray line = surface pressure, the black line = slurry flow, the blue line = injection rate of nitrogen, and dashed line = proppant concentration.

One family of resonances has a frequency at 17 Hz and overtones at 35 and 51 Hz. The second family has a frequency at 27 Hz during the first stage and at 16 Hz during the second stage, and harmonics every 8 to 10 Hz. The third family is present only during the second stage, has a frequency at 29 Hz and an overtone at 58 Hz. Harmonics of the main resonances are usually easily identified as they have the same variations over time. For example, see the hat-like feature of the second family at 3400 s during the first stage (Figure 1).

The electric current is also visible with the spectral line around 60 Hz. The three families of resonance show a spatial amplitude pattern, having higher amplitude on the deeper geophones. The signal amplitude for both stages follows the variations in slurry flow. The main source of these resonances is then connected to the fluid injection. Variations in injection rates correlated with variations in resonances are also reported in Pettitt et al. 2009.

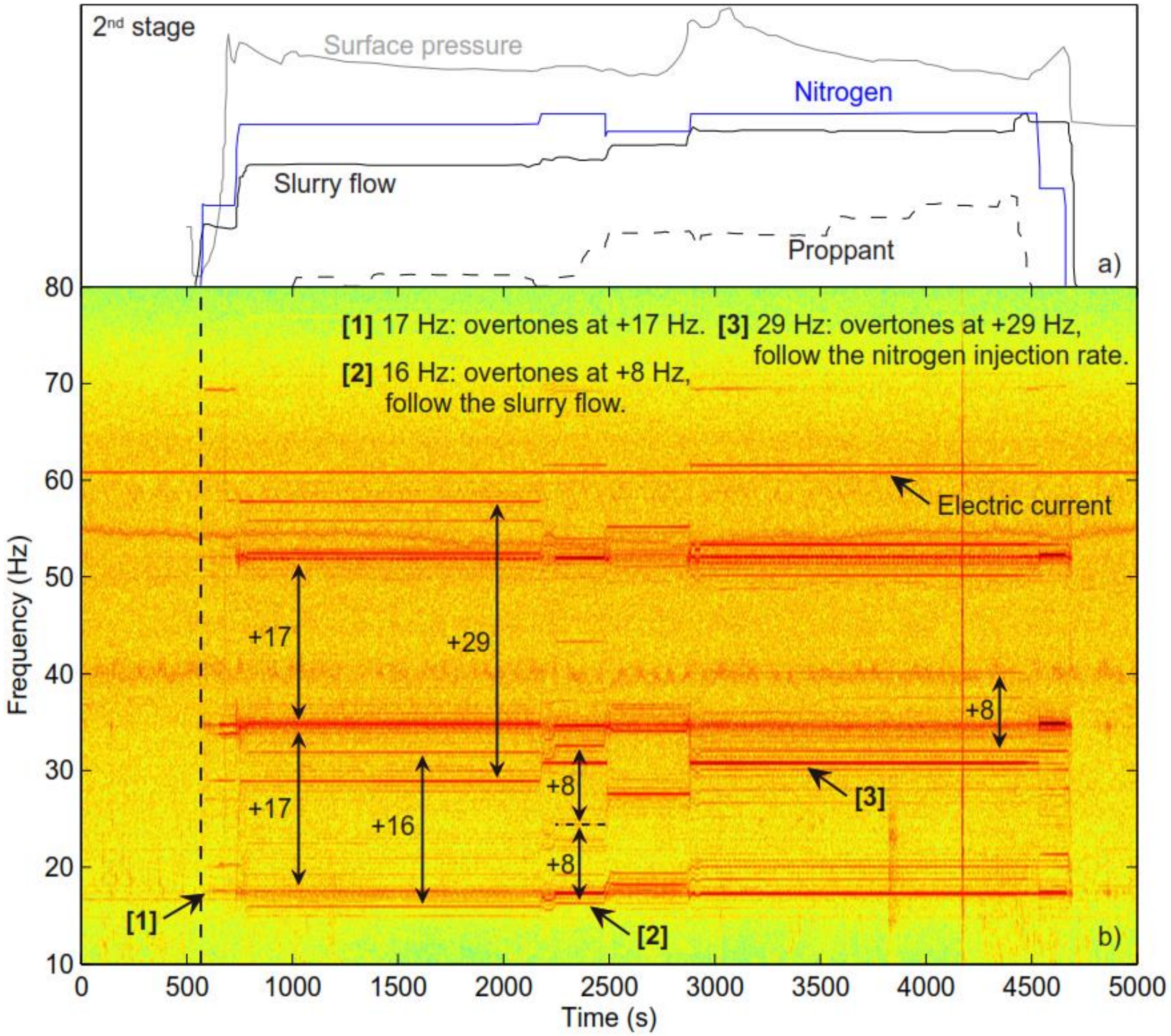

Figure 2. Same as Figure 1 for the second stage of the microseismic experiment (geophone 12, vertical component). The time shift applied to the treatment curves is +227 s.

## Correlations frequency content with treatment curves

Step-like variations in either slurry flow or nitrogen injection rate are reflected in step-like variations in frequency, for each family, but after a time delay of 323 and 227 s for the first and second stage, respectively. The second (16 and 27 Hz) and third families (29 Hz) are clearly correlated with the slurry flow and the nitrogen injection rate, respectively. The first family (17 Hz) seems more correlated to the nitrogen curve than the slurry flow. No clear correlations with the treatment pressure or the proppant concentration are observed.

Multiple correlations between resonances with fluid-flow indicate that complex interactions could occur between different physical processes, especially due to the multiphase character of treatment fluids (nitrogen gas, solid particles, water with surfactant…). Nitrogen is in a gas state on top of the well and becomes a supercritical fluid at the reservoir depth. Fluid properties are then expected to change over time, such as the viscosity and the density. Still, a clear correlation between fluid-flow and frequency content is observed.

Fluid-flow can introduce resonances due to non-Darcian fluid flow in irregular channels (Julian 1994), or from fluid-flow instabilities at the perforation location for example. These instabilities can be related to differences in flow rates or fluid properties between two fluids (Orr-Sommerfeld instabilities).

These resonances would be unrelated to the growing fracture network but dependent on the fluid properties and injection rate at the source location. Resonances would then also vary over time depending on fluid-flow regimes (Tary et al. 2014).

## Conclusions

Although correlations between fluid injection rates and resonances could be explained by fluid-flow models, some questions remain. For example, why are some resonances correlated to the slurry flow (27 Hz) and others with the nitrogen rate (29 Hz)? Thickening agents and supercritical fluids are used to change the fluid viscosity in order to efficiently distribute the proppant into the reservoir. What is then the influence of multiphase flow and viscosity on the fluid flow regimes and on resonance frequencies? Finally, complex interactions are expected between the fracture network in expansion and flow patterns during fluid injection.

These questions are of importance for enhanced hydraulic stimulation monitoring for hydraulic fracturing, geothermal operations, $CO_2$ sequestration and storage, and volcano monitoring.

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