RESERVOIR ROCK FLUID IMBIBITION EXPERIMENT: COMPLEX STUDY USING X-RAY COMPUTER TOMOGRAPHY AND ACTIVE ULTRASONIC TECHNIQUES

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ABSTRACT Forced imbibition was performed in a reservoir sandstone by injecting water into a dry sample. The injection was monitored with X-ray Computed Tomography (CT) and active ultrasonic measurements so that the time-space distribution of the invading fluid could be simultaneously observed in CT images and quantified through measuring saturation and P-wave velocities.

The CT scans allowed us to clearly observe a water front advancing away from the area of injection. Through the evolution of the P-wave velocities, we observed a strong influence on the acoustic response when we changed injection rates. Upon decreasing the injection rate from 5 mL/h to 0.1 mL/h, P-wave velocities decreased sharply: 100 m/s in 1 hour. This behaviour is related to the partially saturated condition of the sample (76 % of saturation) before decreasing the injection rate. The air that was still trapped in the pores is free to move due to decrease of the pore pressure that is no longer forced by the higher injection rate. After this sharp decrease, the P-wave velocities started increasing with small variations in saturation. Stopping the injection for 16 hours decreased saturation by 10 % and P-wave velocities by 100 m/s. Restarting injection at 5 mL/h increased saturation to 76 % while P-wave velocities fluctuated considerably for 2 hours until they stabilized at the final value of 2253 m/s.

Our experimental data confirms how sensitive acoustic waves are to the presence of water and that changing injection rates promote considerable fluid distribution that is drastically reflected in the acoustic velocities.

I. MOTIVATION

Quantification of fluid flow through porous media is an essential part of hydrocarbon recovery and reservoir characterization. In particular, the controlled replacement of one fluid by another is a common procedure in order to stimulate reservoir performance, for example, recovering oil by means of water flooding (Craft, Hawkins and Terry 1991). When injecting fluids in a rock, acoustic *data* can indicate the presence of fluids (as shown by our own data, Figure 1).

The presence of fluids results in a change of the elastic properties of a rock, reflecting the magnitude of solid/fluid interaction (Guéguen and Palciauskas, 1994). More particularly, seismic wave velocities and attenuation are affected by the degree of saturation and spatial distribution of fluids (Müller, Gurevich and Lebedev, 2010). Several laboratorial experiments dealing with fluid injection to study acoustic response by active monitoring (e. g., Monsen and Johnstad, 2005) and the time-space fluid distribution with X-ray CT (e. g., Akin *et al.*, 2000) have been performed extensively. But so far, very few used the simultaneous application of an ultrasonic measuring technique and an image processing technique (e. g., Lebedev *et al.* 2009).

It is our purpose to quantify fluid displacement through measuring saturation and acoustic wave velocities while providing an image representative of the fluid distribution during injection and present a more complete and comprehensive analysis of solid/fluid interaction when the injection rate (at which the wetting fluid is introduced) changes during the forced imbibition.

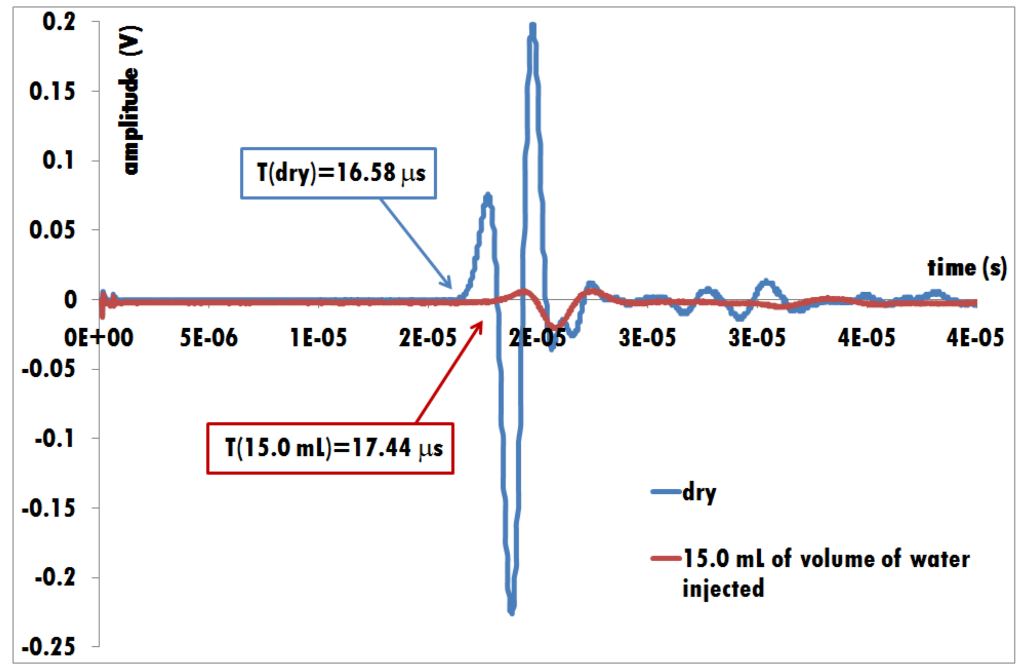
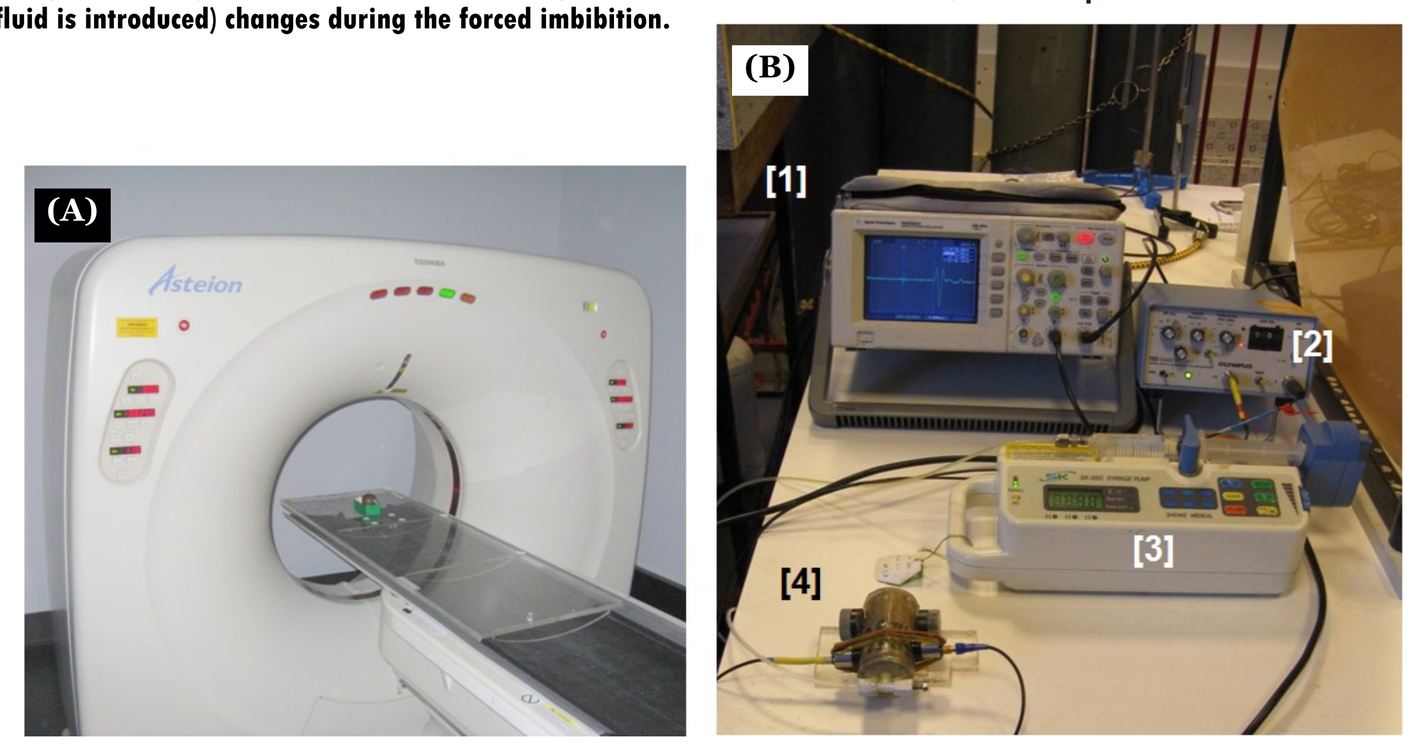
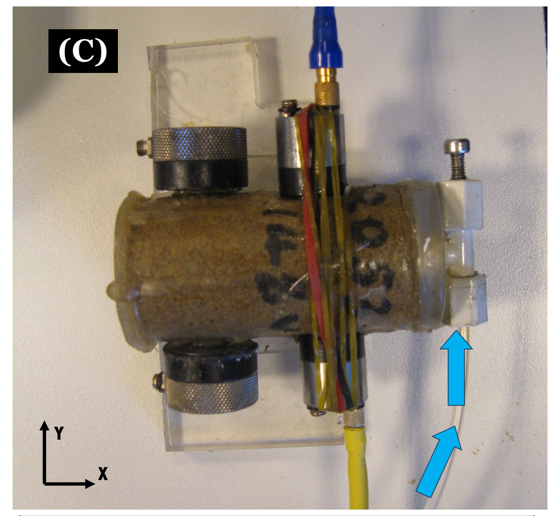


Figure 1. Waveforms for the P-waves picked during our experiment: before injection (blue line) and after injecting 15.0 mL of volume of water (red line). Note the decrease on wave-amplitude and an increase on the P-wave arrival time with the presence of water.





Length (cm)	7.43
Diameter (cm)	3.80
Porosity (%)	16.72
Permeability (mD)	66.67

Figure 2. (A) Medical CT scanner, Asteion Toshiba (resolution: 1 mm x 1 mm x 1 mm). (B) Experimental setup: oscilloscope [1], pulser/receiver [2], injection pump [3] and sample [4]. (C) Sample with connected transducers (central frequency: 1 MHz) and main petrophysical characteristics of the reservoir sandstone (90% sandstone and 10% of interbedded claystone and coal). Injection through the right side of the sample (represented by blue arrows).

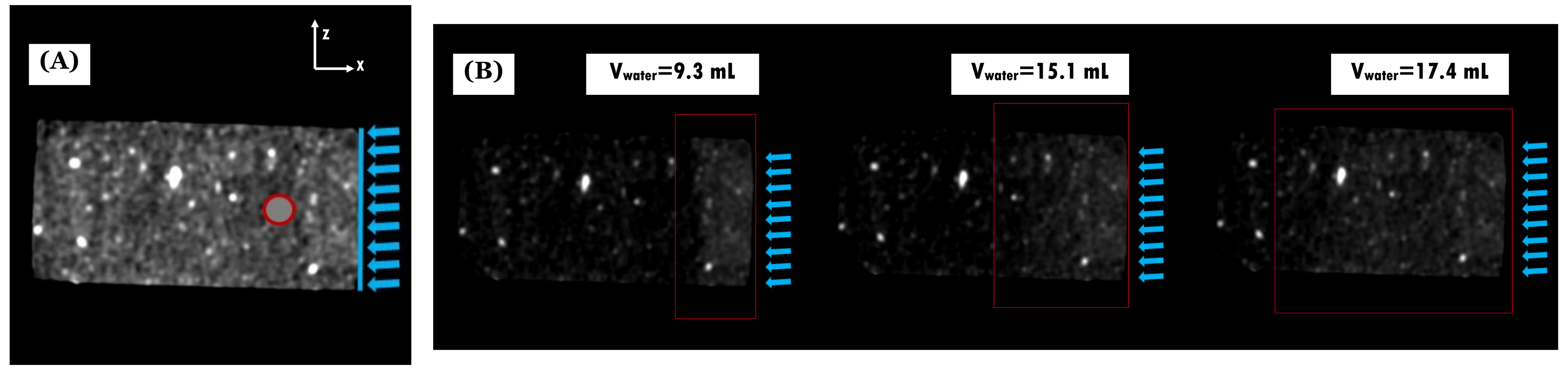


Figure 3. (A) Typical display of a CT image in gray-scale: shaded gray (or black) for low CT numbers and light gray (or white) for high CT numbers. The red circle marks the position of the transducers (in the x-z plane of scanning). (B) Through consecutive CT scanning during the injection, the CT images show a water front moving from right to left (we present the moments when 9.3 mL, 15.1 mL and 17.4 mL volume of water was injected). The areas filled with water become "whiter" and wider with the presence of water. Blue arrows indicate direction of injection.

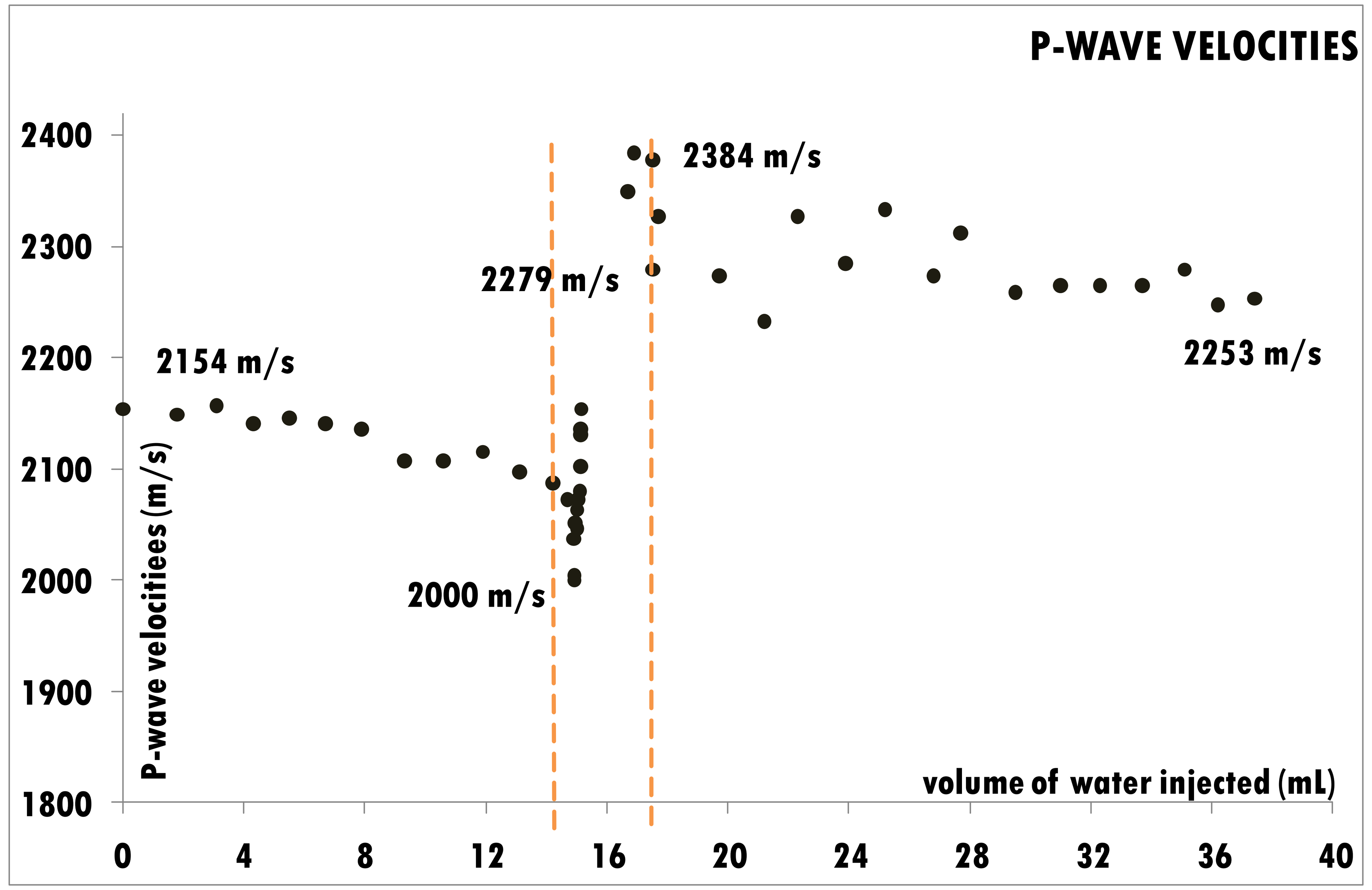


Figure 4. P-wave velocities with volume of water injected. Dashed lines represent the moments when we decreased injection rate, at 14.6 mL of volume of water injected, and when we stopped injection and restarted, at 17.5 mL. Note the sharp decrease followed by an increase of 384 m/s after decreasing the injection rate from 5 mL/h to 0.1 mL/h and a striking oscillation effect after we restarted injection at 5 mL/h.

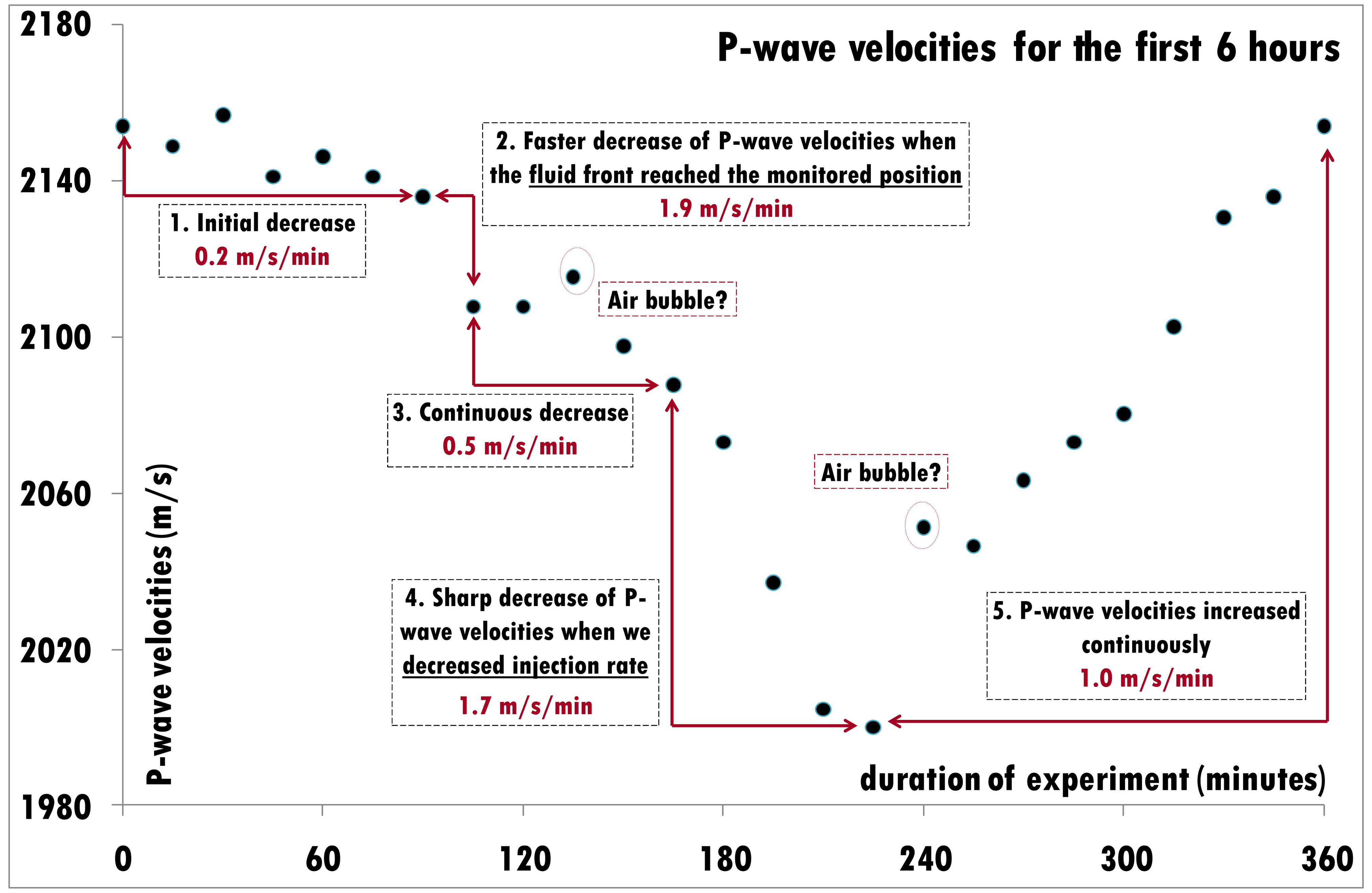


Figure 5. Detail of the evolution of P-wave velocities for the first 6 hours of experiment. Note the faster decrease of P-wave velocities *per* time due to the presence of water and due to the decrease of injection rate followed by a continuous increase of P-wave velocities.

II. EXPERIMENTAL SETUP AND METHOD

Water was forced with an injection pump to displace air in a reservoir sandstone. The experimental setup consisted of a signal source, an oscilloscope and an injection pump (Fig. 2-B). The sample was horizontal and water injection was directed from right to left (represented by blue arrows in Figure 2-C and Figure 3). The sample was laterally covered by epoxy and the opposite side to the area of injection was open. The experiment was performed at room temperature and atmospheric pressure. The experiment consisted of the following steps:

- Initial injection at 5 mL/h during approximately 3 hours (up to 14.7 mL of volume of water injected);
- The injection rate was decreased to 0.1 mL/h and was kept constant for the next 26 hours (no measurements or scans between 15.2 mL and 16.7 mL of volume of water injected);
- When we reached 17.5 mL of volume of water injected, we stopped injection for 16 hours (no measurements or scans during this period);
- We restarted injection at 5 mL/h and kept it for 4 hours up to the end of the experiment.

P-waves were picked by piezoelectric transducers placed on a position close to area of injection (Fig. 3-A) while the sample was scanned (always along the same axial plane) so that to a value of P-wave velocities we could match a value of water saturation. P-wave velocities were calculated through the first-break picking of the output signal given by the oscilloscope and the CT images provided us a visual display of the fluid distribution with injection (Fig. 3-B).

Also through the CT images, we were able to calculate water saturation. Each pixel of the CT images has a "CT number" associated that is directly related to the density of the scanned sample. The consecutive scanned images reflect the presence of water in the sample by an increase of the CT number. For each pixel, the water saturation, Sw, for a specific moment of the experiment is given by $Sw=[CT(w)-CT(dry)]/[P*1000]$, where P is the porosity of the sample (Toms-Stewart *et al.*, 2010).

III. RESULTS AND DISCUSSION

The evolution of P-wave velocities with volume of water injected is shown in Figure 4 and the first 6 hours in more detail in Figure 5. When the water front reached the monitored position, at 9.3 mL, P-wave velocities decayed by 2.2 % from the value when the sample was dry (2154 m/s). We can see the influence of changing injection rates in the acoustic response:

(1) Faster decrease of P-wave velocities when we decreased injection rate (100 m/s in 1 hour);
(2) Decrease of P-wave velocities from 2384 m/s to 2279 m/s when we stopped injection for 16 hours.
(3) A considerable oscillation effect on the P-wave velocities when we restarted injection.

Figure 6 shows the evolution of saturation with volume of water injected. The saturation increased continuously up to 76 % in the first 3 hours. After decreasing the injection rate, the saturation fluctuated between 70 % and 76 %. Stopping injection, decreased the saturation by 7 % and after restarting injection, the saturation increased continuously for 2 hours and stabilized at the final value of 76 %.

The faster decrease of P-wave velocities when we decreased injection rate seems to be connected to the partially saturated conditions of the sample (76 %). This means that locally there was still 24 % of pores filled with air that was "free" to expand and move due to decrease of the pore pressure that was no longer forced by the higher injection rate. This redistribution of fluid induced by changing the injection rate prompted higher values for the P-wave velocities (for example, at 76 % of saturation we have 2087 m/s for 14.2 mL of water injected and 2384 m/s for 17.0 mL).

It is clear from our experiment that acoustic wave velocities are very sensitive to the change of injection rates. This change implies a reorganization of fluid that may not be reflected in the final value of the saturation but it is drastically reflected in the acoustic response. The influence of fluid distribution in acoustic velocities has been observed experimentally (e. g., Cadoret, Marion and Zinszner, 1995) but this is the first time it is experimentally related to changing the injection rate of the invading fluid.

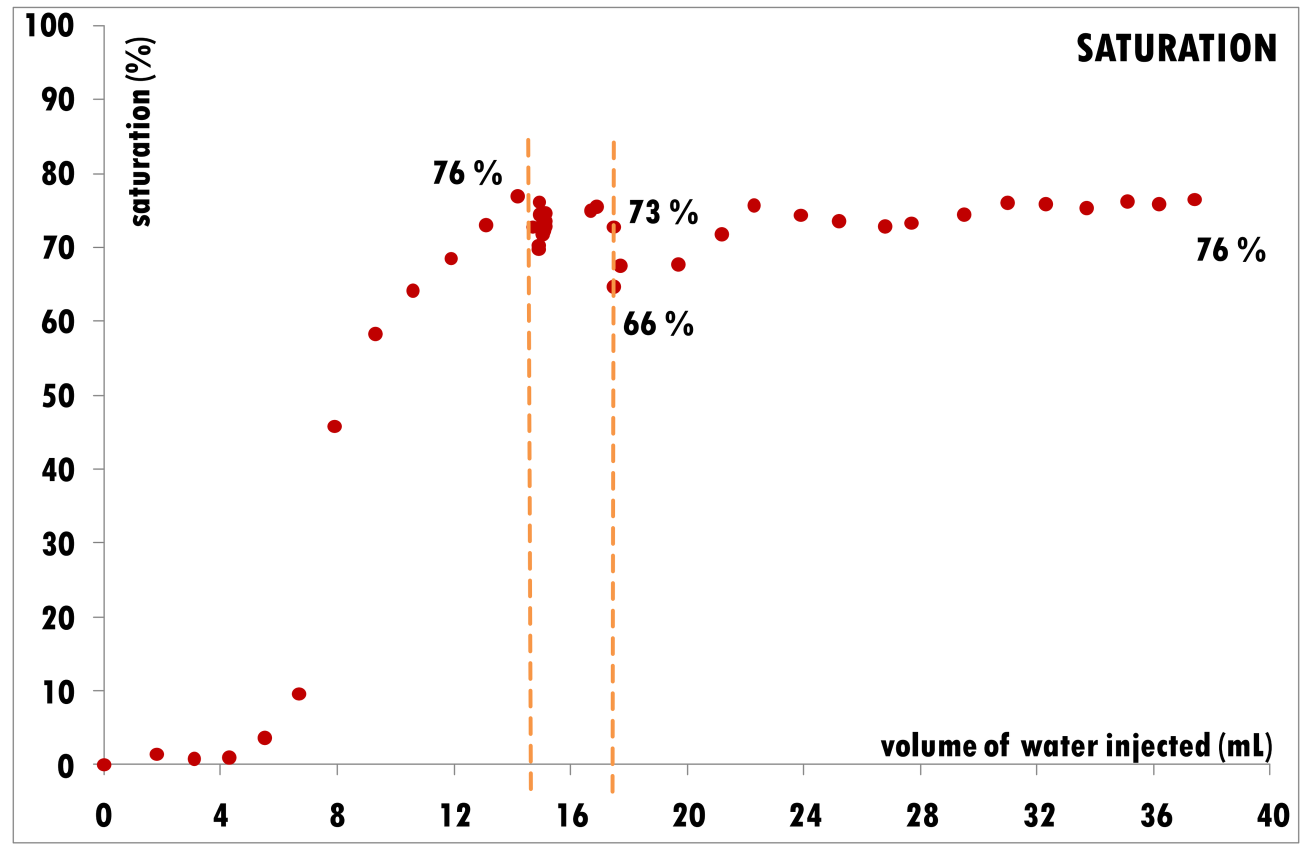


Figure 6. Saturation with volume of water injected. Dashed lines represent the moments when we decreased injection rate, at 14.6 mL of volume of water injected, and when we stopped and restarted injection, at 17.5 mL.

SUMMARY

The presented method enables us to relate simultaneously acoustic velocities, saturation and localization of fluid front during laboratory experiments dealing with fluid injection. We conclude with this experiment that:

- Changing the injection rate has a significant impact in the acoustic response, more particularly: (1) a faster decrease of P-wave velocities with decreasing injection rate, (2) a decrease of P-wave velocities after the injection is stopped and (3) an oscillating effect followed by stabilization upon restarting at a high injection rate when the sample is already considerably saturated;
- Though the resolution of our CT scans does not allow a microscopic analysis of the fluid distribution the fact that at the same level of saturation we present distinct values of P-wave velocities reinforces the idea that acoustic waves are extremely sensitive to fluid distribution.

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