Influence Of Changing the Flow Rate In The Acoustic Response And Saturation During Forced Imbibition In A Limestone (#1438094)

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ABSTRACT

Forced imbibition was performed in a limestone 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 monitoring water saturation and P-wave velocities. Through the evolution of the P-wave velocities, we observed a strong influence on the acoustic response with the presence of water and with the changing of the injection rate. The approaching of the water front to the monitored position decreased P-wave velocities while the saturation increased continuously. The P-wave velocities decreased occurred for a short period of time and was followed by a sharp increase which happened when the fluid front crossed the monitored position. Decreasing injection rate decreased P-wave velocities and saturation. Increasing injection rate, increased P-wave velocities and saturation.

I. MOTIVATION

Quantification of fluid flow through porous media is an aspect 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. The presence of fluids results in a change of the elastic properties of a rock and therefore seismic wave velocities and attenuation are affected by the degree of saturation and spatial distribution of fluids. Acoustic data can indicate the presence of fluids: waveforms change amplitude and wavelength with increasing saturation (Fig. 1). It is our purpose to quantify fluid displacement through simultaneous acquisition of CT scan (fluid distribution and estimation of saturation) and P-waves (estimation of P-wave velocities) and study the influence of changing the flow rate in the acoustic response and evolution of saturation.

II. RESULTS

The evolution of P-wave velocities and the water saturation with volume of water injected is shown in Figure 3. We observe four characteristic stages in the evolution of $V_p$ and $S_w$:

- The approaching of the saturation front decreases $V_p$ for a short but measurable period of time. We believe this is a grain-contact weakening effect. Above the saturation front, we have a moisture front due to water evaporation. This moisture front induces softening of the grains’ cement and the bulk density decreases, decreasing the P-wave velocity.
- When the saturation front crosses the monitored position, $V_p$ increases sharply. This is interpreted as a water saturation effect promoted by the increase in $S_w$.
- Decreasing the injection rate, decreases $V_p$ and $S_w$. This is interpreted as a capillary pressure effect. When we decrease the injection rate, we decrease the capillary pressure gradient and the gas trapped in the pores during the initial imbibition is free to move and expand. Redistribution of fluids is reflected in the decrease in $S_w$.
- Increasing the injection rate increases $V_p$ and $S_w$. This is again a water saturation effect where the increase in $V_p$ is influenced by the increase in $S_w$.

III. SETUP and METHODOLOGY

Water was forced with an injection pump to displace air in a limestone (porosity 26.5%, permeability 91.5 mD). The experimental setup was placed in the X-ray CT scanner room (Fig. 2-a) and consisted of an injection pump, a signal source and an oscilloscope (Fig. 2-b). The sample was laterally covered by epoxy, to force an unidirectional flow of the fluid. The experiment was performed at room temperature and atmospheric pressure and consisted of the following steps:

- Initial injection at 2 mL/h ($\Delta t \approx 3h$) — decreases to 0.2 mL/h ($\Delta t \approx 15h$) — increases back to 2 mL/h ($\Delta t \approx 3h$).
- P-waves were picked by piezoelectric transducers placed on a position close to the area of injection while the wavefront and pick the P-wave output signal given by the oscilloscope and the CT images provided us a visual display of the advancement of the fluid front and data to estimate saturation (Fig. 4).

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Figure 1. Waveforms for the P-waves picked during this experiment: before injection (blue line) and after injection of 6.8 ml of volume of water (orange line). Note the decrease of wave-amplitude and increase of wavelength.

Figure 2. (a) Medical X-ray CT scanner, Axiom Tis40b (resolution: 0.2x0.2x0.2 mm³). (b) Experimental setup: [1] sample set for vertical injection, connected to the piezoelectric transducers (central frequency: 1 MHz); [2] injection pump (control the injection rate); [3] pulse/receiver (trigger the acoustic impulse) and [4] oscilloscope (visualize the waveform and pick the P-wave arrival time).

Figure 3. Evolution of P-wave velocities and water saturation. Note that if we did not change the injection rate, the P-wave velocities and water saturation would continue to increase up to a level of stabilization and remain constant at their maximum values.

Figure 4. Sequence of CT scans showing the advancement of the fluid front in height, from dry sample to 3.8 mL of volume of water injected. Blue arrows indicate the direction of injection. Through the CT images, we can estimate water saturation. Each pixel of the CT scan has a “CT value” that is directly related to the density of the scanned sample. The consecutive scanned image reflects the presence of water in the sample by an increase of the CT value, i.e. the area filled with water becomes “whiter.”

SUMMARY

The presented method enables us to relate simultaneously acoustic velocities, saturation and localization of fluid front during laboratory experiments dealing with fluid injection. The presence of water and the change of injection rates have a significant impact in the acoustic response. More particularly, changing injection rates implies a reorganization of fluid that is reflected in both the evolution of water saturation and acoustic response. Our previous work on sandstones (Lopes, S. and Lebedev, M., 2012) research noted: laboratory study of the influence of changing the injection rate on the geometry of the fluid front and on P-wave ultrasonic velocities in sandstones. Geophysical Prospecting 60, 572–580 shows also a clear dependence of the acoustic response and water saturation evolution with the injection rate, though in sandstone the decrease and increase of P-wave velocities was higher in absolute value and the response was more immediate which is consistent with a less stiff matrix.