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Ultrasonic characterization of formation damage: effect of particle sizes

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Abstract
Permeability of a geological formation such as an oil field can be altered locally during drilling operations through penetration of particulates from the drilling fluid into the formation pores. This can adversely affect the overall production rate by constricting the pores. The composition of these fluids, particularly the sizes of the particulates therein, can be critical from the point of view of controlling the extent of 'damage' to the formation. Using our recently reported ultrasonic mapping technique, we have investigated the depth of particle penetration as a function of particle size and contamination time. An important correlation is observed between the diameters of the 'mud' particles and the pore size distribution in the formation. It is further noted that a substantial layer of 'mud cake' is formed on the surface beyond a certain critical particle size and this subsequently acts as a filter allowing only some finer particles to continue penetrating into the formation. The results are discussed in the context of bridging action at the pores.

Keywords: formation damage, ultrasonic characterization, mud particle size effects

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Permeability in the context of any petroleum-bearing geological formation is an index of the ease with which oil flows through the pores of the formation and is a function of the porosity of the formation and the degree of interconnection between the pores. The permeability at different places in the same formation may vary considerably due to local variations in the shape, size and nature of interconnections between pores. Assuming a formation of constant permeability k, the well known Darcy equation [1, 2] relates the rate of flow per unit cross-sectional area (Q/A) to the rate of pressure drop ($\mathrm{d}P/\mathrm{d}l$) in the overall direction of flow and the viscosity μ of the fluid, as given below.

$$Q/A = -(k/\mu)\,\mathrm{d}P/\mathrm{d}l. \qquad (1)$$

Thus, the production rate of an oil well depends, among other parameters, on the oil viscosity, the pressure gradient and the permeability of the formation. However, the permeability can be considerably altered locally during drilling operations. In particular, invasion of some particles of the drilling fluid, or the so called 'mud', into the formation constricts or clogs

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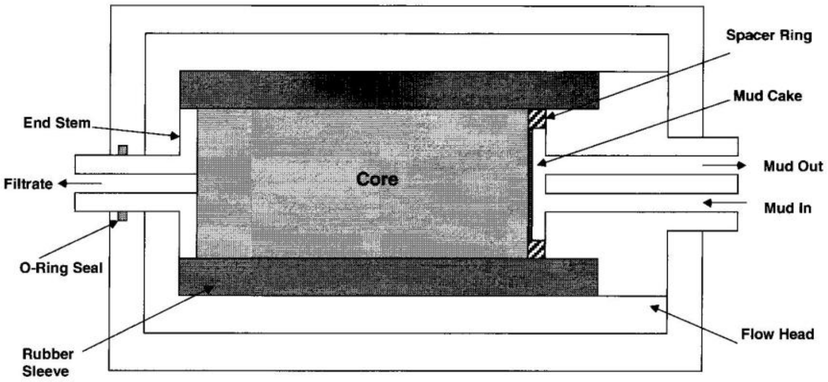

Figure 1. Schematic diagram showing Hassler type core holder.

the pores and/or their interconnections/throats, which leads to a decrease in the permeability of the formation. A decrease in permeability, also called 'formation damage', results in a decrease of the oil production rate. It should also be noted that formation damage could also occur through several other processes such as chemical interactions, biological incursions (through bacteria and other organisms etc) and thermal and mechanical deformations of the formation under stress and fluid shear [1–4]. However, in the present paper, we will restrict ourselves to the formation damage caused by the 'mud' invasion, even though the ultrasonic characterization technique could in principle be applied equally successfully to map all types of formation damage.

Numerous studies have been undertaken thus far to find ways and means of minimizing the formation damage [1–8]. In this context, the composition of drilling fluids can be quite critical. One possible way is to add some polymeric particles of particular sizes to the drilling fluids to enhance the growth of a 'soft mud cake' on the surface to restrict the flow of particles into the formation.

We have recently reported the applicability of ultrasonic techniques in mapping the formation damage [9]. As an extension of that work, we report here the effect of particle sizes in the drilling fluid on the invasion depth. The results confirm an important correlation between the diameter of the 'mud' particles and the average pore size in the formation.

2. Sample preparation

As reported in Khan *et al* [9], a leak-off experimental set-up was used in the laboratory to simulate the drilling fluid circulation process at the formation face in the well bore under bottom hole conditions. This consisted of a Hassler type core holder [10] that could accommodate cylindrical rock samples up to 25 cm long and 5.08 cm diameter (figure 1). The rock sample was mounted inside a rubber sleeve and subjected to an overburden (confining) pressure. The injection end of the core holder had two ports (inlet and outlet) to circulate the drilling fluids across the face of the core, or to inject oil and brine. The other end had only one port to collect the filtrate, and/or oil, and/or brine, pumped from the injection end. A 10 mm thick ring-shaped stainless steel spacer was placed between the core face and the injection end to allow the 'mud' to circulate and form 'cake' on the core face.

Polymeric water-based 'muds' with four different-sized $CaCO_3$ particulates, namely 5, 10, 38.5 or 75 μm, were used in these studies. Different filters were used to remove particles of diameters greater than a chosen size. Pore- and particle-size distributions in the dry samples were determined using the centrifugal method and image analyser respectively. The initial oil permeability of the core was also measured by flowing filtered crude oil through the core and then measuring the flow rates and differential pressures, under steady state conditions.

In the experiments reported here, drilling fluid was circulated for different periods of time ΔT but under constant overbalanced pressures $\Delta P = 6.90 \times 10^2$ kPa. Ten different samples of 10 or 25 cm length were investigated. Return oil permeability of the damaged core was also determined by flowing the oil in the opposite direction at a constant flow rate.

3. Experimental details for ultrasonic mapping

The experimental set-up for ultrasonic mapping of the formation damage has been described previously in Khan *et al* [9]. Briefly, it consisted of two Panametric transducers (model V403) to launch and receive longitudinal ultrasonic waves using a pulser–receiver unit (Panametric model 5072). The transmitted signals were amplified and recorded on a digital oscilloscope (HP 54615B) and subsequently transferred to a personal computer for further processing and analysis (see figure 2). Refined petroleum jelly was used as couplant.

In order to eliminate any stress-induced velocity variation, we carried out *ex situ* ultrasonic measurements on each sample mounting it on a separate platform for mapping the 'mud' invasion profiles while it was held upright without any pressure or stress [9].

The question of two unknowns, i.e., wave velocity and invasion depth, was resolved by measuring the wave velocity along the diameter (thin cross-sectional element) and not along the length. Accordingly, measurements of the wave velocity were made at different equally spaced points along the entire length of the sample with a resolution of 0.5 cm. The transmitting and receiving transducers were always kept coaxial with the help of a contoured aligning support-plate fixed to an optical table with adjustable height. The data

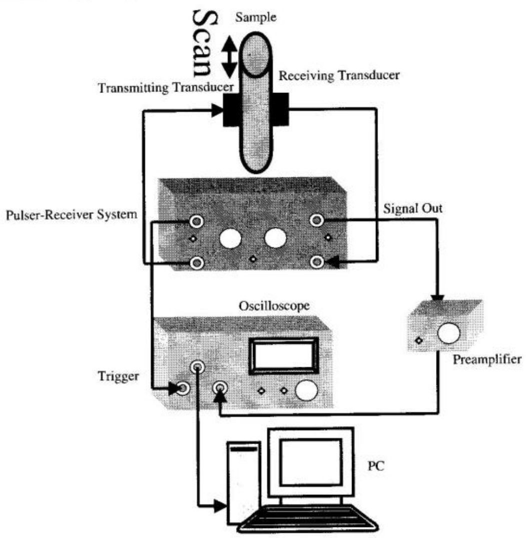

Figure 2. Schematic diagram of the experimental set-up for ultrasonic mapping of formation damage.

on transit times of the waves travelling from the source to the receiver at different positions (0.5 cm resolution) along the length were stored in the computer. Velocities were determined simply by calculating the ratios of diameter and the transit times. Velocity profiles were subsequently constructed for each sample under different experimental conditions by plotting velocity as a function of position along the length.

For each sample, the wave velocities were determined under three different conditions. First, the completely dry samples where the pores contain nothing other than the air were investigated. This was to check for any possible inhomogeneities or voids inside the sample. However, no real inhomogeneities were detected in the samples investigated.

In the second step, the dry samples were completely saturated with brine, that was subsequently displaced by crude oil to get irreducible water S_{wi} and then the oil S_{oi} in place, using the leak-off apparatus. Ultrasonic scans were performed again to determine a velocity profile under these conditions. This provided a reference profile for comparisons with a 'mud-infested' sample discussed in the third step below.

The oil-saturated samples were exposed to the circulating drilling fluid in a third step for different times ΔT while keeping a constant overbalance pressure ΔP. In the process, the particles of the drilling fluid penetrated the core at least partly, thereby clogging the pores or constricting pore throats. Accordingly, the sample core got damaged. An ultrasonic scan was again carried out to determine the velocity profile as discussed earlier.

It should further be noted that each sample was always kept in a particular orientation with the help of a reference line marked on the sample and another line on the platform. These two lines were carefully aligned visually before starting the experimental measurements. This was to ensure that the pore orientations do not change for one particular specimen during the course of measurements under dry, oil-saturated and mud-damaged conditions. Furthermore, when the oil-saturated cores were exposed to different circulating drilling fluids, the particulates penetrated the sample cores to different lengths. However, for a given set of pore size distributions, the invasion depth also varied with the particle sizes.

After measuring the velocities in the three steps noted above, simple graphs were plotted to display velocity as a function of position along the length of the sample core in order to obtain unambiguous information about the mud-invaded portion of the sample [9]. The depths of mud invasion for different contamination times were measured from the constructed ultrasonic velocity profiles.

4. Results and discussion

It is noted that the structure of rocks can be quite complex and there may be some inhomogeneities in the material composition, grain sizes and their shapes and pore sizes and their orientations as well as their distributions within the rock volume. However, all ten samples used in this work were taken from the same 'mother core' from the same particular region. Therefore, the pore size distributions are generally expected to be quite similar although local variations in pore sizes as well as their orientations may be expected. But the overall behaviour was not significantly different as confirmed by our measurements on dry samples.

The average velocity v_{av} in the oil-saturated or 'mud'-damaged samples at a particular point can be calculated from the measured total transit time t and the total length L of the sample,

$$v_{av} = L/t$$

where

$$t = \sum_i (L_i/v_i). \tag{2}$$

Here, L_i is the part length occupied by the material i (rock grain, mud, oil etc) and v_i is the ultrasonic velocity through the part length occupied by the material i.

As noted earlier, for each sample, velocities were measured under three different conditions: dry, oil-saturated and mud-damaged. The velocities in the oil-saturated case were observed to be considerably higher than the case of dry samples. This can be understood from the fact that ultrasonic velocities through a medium are related to the density ρ and the elastic constants of the medium. More specifically, for the longitudinal waves, the wave velocity v in a particular medium is best given in terms of the Young modulus E and the Poisson ratio σ [11] by

$$v = \{E(1-\sigma)/[\rho(1+\sigma)(1-2\sigma)]\}^{0.5}. \tag{3a}$$

For fluids, however, the wave velocity can be written in terms of the bulk modulus K or compressibility $\kappa = K^{-1}$

$$v = \{K/\rho\}^{0.5} = \{\rho\kappa\}^{-0.5}. \tag{3b}$$

The difference in the bulk modulus for a sample containing oil-filled pores and one containing air-filled pores is mainly responsible for different wave velocities. Since gases are more compressible than liquids, velocity v for a sample containing liquid-filled pores is expected to be higher. Likewise, since

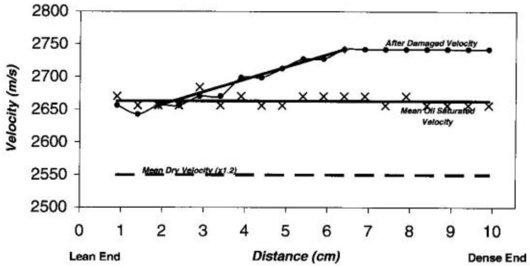

Figure 3. Typical velocity profiles for a 10 cm long sample exposed to 24 h contamination time under a 2.07×10^3 kPa overbalance pressure. The velocity in the dry sample has been multiplied by a factor of 1.2 to highlight comparisons between the mud-damaged and oil-saturated samples.

solids generally exhibit higher wave velocities than liquids, ultrasonic waves will travel faster through the pores plugged by the solid particulates.

Figure 3 displays a set of typical velocity profiles for a 10 cm long sample exposed to 24 h contamination time under a 2.07×10^3 kPa overbalance pressure. The velocity in the dry sample has been multiplied by a factor of 1.2 to highlight the comparison between the mud-damaged and oil-saturated sample. In figure 3, the dense end is actually the 'injection end' where the drilling fluid was circulated during the sample preparation and is generally saturated with the mud in our experiments. The lean end, on the other hand, may remain unaffected or at least less affected by the 'mud', depending on the overbalance pressure and the contamination time. The flat portion of the velocity profile in the mud-damaged sample on the dense end side shows a virtually complete saturation of pores. The linearly increasing/decreasing velocity profile, on the other hand, indicates a partial filling of the pores by 'mud'.

The invasion depth was measured from the constructed velocity profiles similar to figure 3 as a function of position along the length of the sample. The distance of the point from the injection end (dense end) where the velocity in the mud-damaged sample becomes equal to the velocity in the oil-saturated sample is taken as the invasion depth for the particular sample under the specific experimental conditions. The uncertainty in measuring the invasion depth is within ±2.5 mm in our experiments as long as a clear discrimination can be made between the velocities in the mud-damaged region and the base line.

This experimental approach was first reported by Khan *et al* [9] and validated by a systematic study of invasion depth as a function of time under constant overbalance pressure using the same drilling fluid in this set of experiments [12]. Figure 4 shows the invasion depth as a function of contamination time under constant overbalance pressure of 6.90×10^2 kPa using the same drilling fluid (without any $CaCO_3$ bridging additives). The invasion depth increases linearly until about 24 h of contamination time in this case while some saturation effects are visible beyond that point. A similar behaviour was recorded for other overbalance pressures confirming the intuitively expected results [12]. However, the saturation point is expected to be different for different experimental conditions.

Another experimental test was also carried out for validating this method. The core sample in this case was cut into two halves, and the two halves were subsequently put together again next to each other to be exposed to the mud circulation as one sample for 30 h with an overbalance pressure of 2760 kPa. However, due to the boundary separating the two halves, the pressure distribution in this case was different along the length. Consequently, the back half essentially remained virgin while the front half (facing the mud circulation at the input end) was totally saturated along its length by mud invasion. The velocity profiles along the length of the core clearly displayed two distinct regions separated by a virtual step function (figure 5), the virgin half displaying the base velocity and the contaminated region showing higher velocity [13]. Some boundary effects resulting in accumulation of mud and fluids near the edge (and hence somewhat higher velocity) are visible in this figure. This is because of the long exposure time and high overbalance pressure in this case. However, the step-like profile separating the two halves clearly demonstrates the effectiveness of the method.

After a few preliminary trials, it was indeed possible for us to make a reasonable estimate of the expected invasion depth [9]. For example, long contamination times (ΔT) and large overbalance pressures (ΔP) should generally result in deeper invasion of particles. In the present work, 10 cm long samples were used for $\Delta T = 4$ or 12 h, while 25 cm long samples were used for $\Delta T = 30$ h.

The measured depths of mud invasion as a function of varying contamination time from 4 to 30 h and increasing particle size from 5 to 75 μm are summarized in figure 6. We note that the invasion depth increases with contamination time, as expected. However, the invasion depth does not decrease linearly with increasing particle size. It rather shows a rapid initial decrease with increasing particle size until the maximum particle size in the mud reaches a critical value that can be correlated to the average pore size in the formation. Beyond this point, the invasion depth displays a much slower drop representing a virtual saturation around a particle size of about 12 μm.

As a cross check, the permeability of the damaged cores was also measured. The ratio of the permeability before and after damage is taken as the return permeability. This is an index of the total damage where no damage should correspond to a return permeability of 100%. Figure 7 summarizes our results on return permeability as a function of particle size. These results are consistent with the invasion depth results (figure 6) knowing that increased damage means reduced permeability although it may not be a simple relationship in the sense that other parameters such as 'skin' are also involved.

The reason for decreasing mud invasion with increasing particle size can be understood in terms of 'bridging' at the pores by the particles of the mud. Basically, a coarse bridge may be initiated when two large (but still smaller than the pore size) particles start to move into an opening at the same time and lodge themselves against each other. However, since these particles have irregular shapes, further bridging of the pores around this 'coarse' bridge might occur later on through other smaller particles. This narrows down the pore throats, and eventually a layer of mud, the so-called 'cake', begins to form on the surface of the specimen. This acts as a filter that stops the larger particles from penetrating the formation although the smaller and finer particles continue to move through the cake

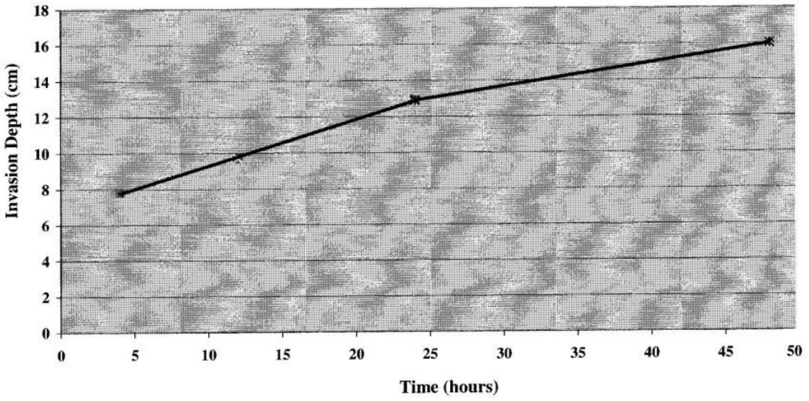

Figure 4. Invasion depth as a function of contamination time under constant overbalance pressure of 695 kPa using the same drilling fluid.

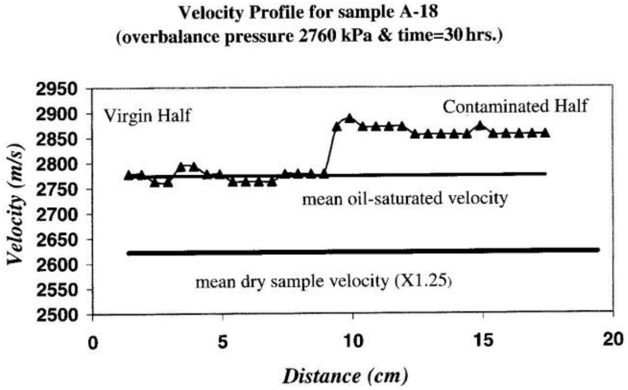

Figure 5. Velocity profile for a core sample cut into two halves where one half was completely saturated with mud while the other half remained virgin. The steplike change in the velocity profile in the middle shows the boundary. See text for further details.

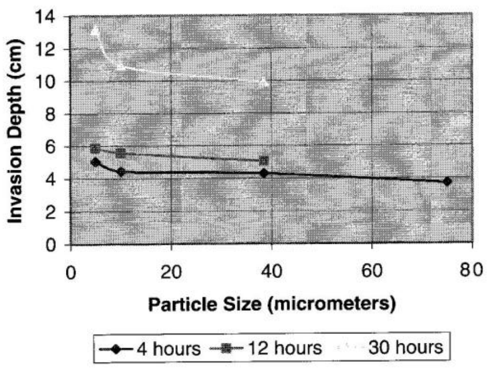

Figure 6. Measured invasion depths as a function of particle size for different contamination times.

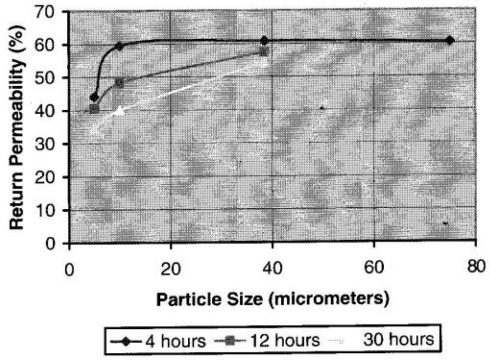

Figure 7. Return permeability as a function of particle size for different contamination times.

and further into the formation. This could continue until even the smaller secondary pores existing between the larger mud particles are fully blocked by the finer particles. This extreme situation, if created, would correspond to zero permeability. In addition to the particle sizes, an important parameter for rate of cake formation is the concentration of particles of appropriate size in the drilling fluid.

The bridging action has been discussed in some detail by several authors previously [14, 15]. Apparently, at high flow rates of the drilling fluid, randomly dispersed particles tend to interfere with each other as they approach the pore constrictions and finally cause some bridging action. Previous work on enhanced cake formation through a choice of mud particles indicates a critical particle size about one-third of

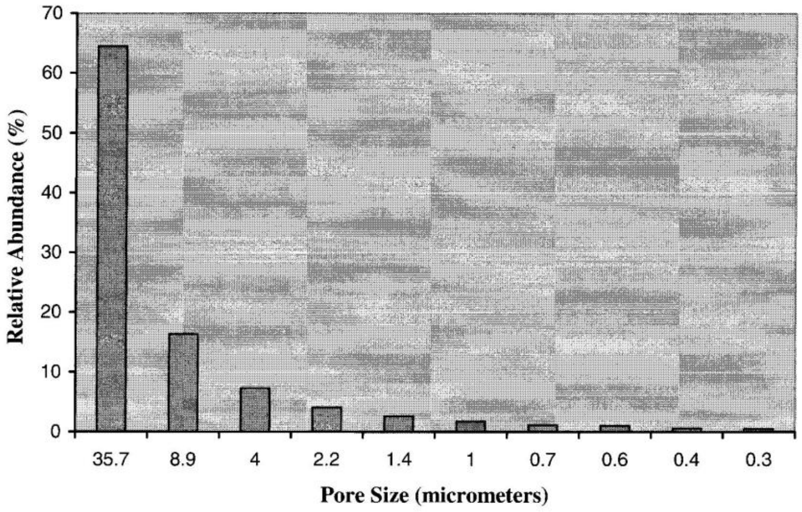

Figure 8. Typical pore size distribution in the cores used.

the average pore size within the formation. This is known as Abrams' rule of thumb [14] suggesting that a significant level of bridging occurs when the mud particle size reaches about one-third the median pore size. If we look at the pore size distributions in our samples (figure 8), about 65% of the pores are around 36 μm in size. Indeed, initiation of virtual saturation around 12 μm (figure 6) is consistent with Abram's bridging rule for pore size versus particle size.

It may be noted that previous experiments generally utilized the analysis of external 'mud cake', filtrate and return permeability to estimate the extent of damage to the formation. Our results on the other hand are based on a direct non-destructive measurement using ultrasonic mapping introduced only recently [9].

5. Conclusions

We have investigated the depth of mud invasion as a function of particle size in the drilling fluid and the contamination time. For a given overbalance pressure, the invasion depth was found to increase with increasing contamination time, as expected. However, invasion depth shows a rapid decrease with increasing particle size until the maximum particle size reaches about one-third of the average pore size within the formation. Beyond that point the invasion depth decreases rather slowly reaching a virtual saturation. These results are based on a direct ultrasonic mapping technique not used hitherto, and are consistent with Abrams' rule correlating the pore size and the particle size for significant bridging to occur.

Acknowledgments

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