SECOND MIDDLE EAST NONDESTRUCTIVE TESTING CONFERENCE AND EXHIBITION
Jubail, Saudi Arabia
December 8-10, 2003

CHARACTERIZATION OF FORMATION DAMAGE USING ULTRASONIC TECHNIQUES

M. A. Khan, Ph. D., Senior Research Scientist
Center for Applied Physical Sciences, The Research Institute
King Fahd University of Petroleum & Minerals
Dhahran 31261, Saudi Arabia

S. Z. Jilani, M.S., Engineer II
Center for Petroleum & Minerals, The Research Institute
King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

A. H. Mohammed, M. S.,
Dept. of Petroleum Engineering
King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

H. Menouar, Ph. D., Research Engineer
Center for Petroleum & Minerals, The Research Institute
King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

A. A. Al-Majed, Ph. D., Associate Professor and Director
Center for Petroleum & Minerals, The Research Institute
King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

Synopsis

We have recently demonstrated the applicability of ultrasonic techniques to the study of formation damage. The basic idea is that in porous media the velocity of ultrasonic waves (e.g., longitudinal waves) is significantly different when the pores are empty (air- or gas-filled) or filled with a fluid such as oil, and when these are filled or even partially filled with solid particles. In this study, oil-saturated, and particle-infested Berea rock samples were prepared in the laboratory using a leak-off apparatus. The depth of 'mud invasion' was monitored under varying conditions of overbalance pressure and contamination time. Furthermore, we have investigated the effect of 'mud' particle sizes on the depth of invasion. Particles of different sizes ranging from 5 μm to 75 μm diameter were added to the drilling fluid to monitor the corresponding invasion depth. An important correlation between the diameters of the 'mud' particles and the pore size distribution in the formation was observed consistent with Abram's rule. A review of the technique and some significant results are presented.

Introduction

The production rate of an oil well depends on several parameters including the oil viscosity, pressure gradient, and permeability of the geological formation. Permeability in this context 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. Formation damage is the name given to impairment of the permeability of the formation caused by various mechanical deformations, chemical interactions, biological incursions (through bacteria and other organisms), hydrodynamic and thermal interactions of the porous formation [1-3]. Permeability of the formation can also 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 the pores

and/or their interconnections/throats which leads to a decrease in the permeability of the formation [4,5]. This results in a decrease of the oil production rate.

Numerous studies have been undertaken thus far to find ways and means of minimizing the formation damage [1-5]. In any case, however, a reliable method has to be developed to monitor any damage to the formation. We have recently reported a non-destructive method for mapping formation damage [6]. This is based on ultrasonic techniques and builds on the difference in ultrasonic velocities through the formation or parts thereof when the pores are "empty" (air- or gas-filled), filled with a liquid (oil or water), or infested with solid particles [6-8].

Starting from dry rocks, oil-saturated and 'mud'-damaged Berea rock samples were prepared in the laboratory using a dynamic leak-off apparatus. The depth of 'mud invasion' was monitored under varying conditions of overbalanced pressure ΔP and contamination time ΔT. Furthermore, the effect of 'mud' particle sizes on the depth of invasion was also monitored. Particles of different sizes ranging from 5 μm to 75 μm diameter were added to the drilling fluid to monitor the corresponding invasion depth. An important correlation between the diameters of the 'mud' particles and the pore size distribution in the formation was observed. It was noted that within the investigated range of ΔP and ΔT, a substantial layer of cake is formed on the surface beyond a certain critical particle size and this subsequently acts as a filter allowing only some fine particles to continue penetrating into the formation.

Experimental Details

As reported earlier by Khan et al [6-8], 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 [9] that could accommodate cylindrical rock

samples up to 25 cm long and 5.08 cm in diameter (Fig. 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 1 cm 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.

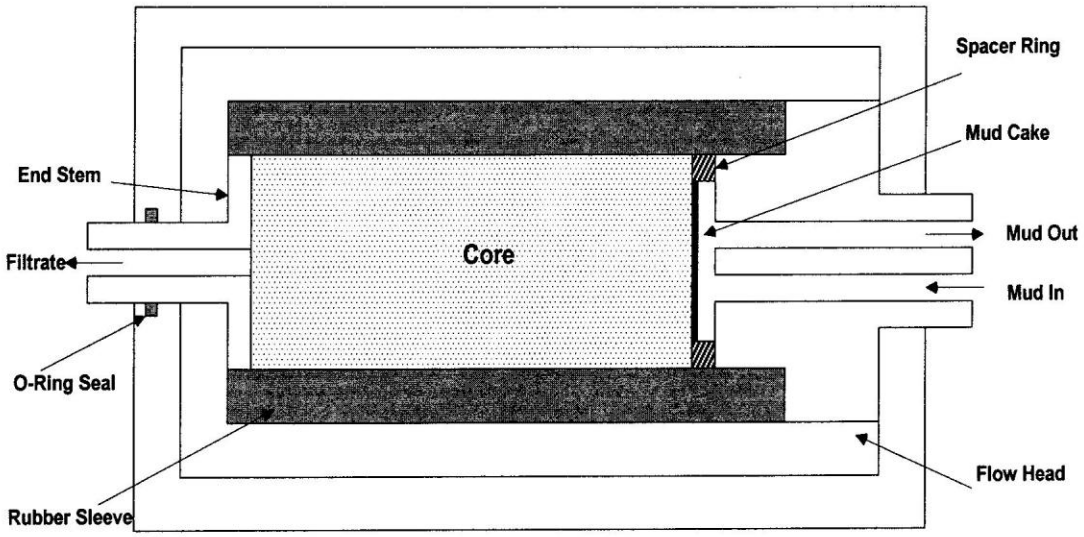


Figure 1: Hassler Type Core Holder

Leak-off Experimental Set-Up

Fig. 2 shows a schematic diagram of the leak-off experimental set. Two transfer cells were employed to deliver 'mud'/oil/brine to the core holder. A Beckmann piston pump was connected to the transfer cell to deliver the fluids ('mud'/oil/brine) at desired flow rate and pressure. A mixture of kerosene and silicon oil was used as transferring fluid in the pump. The pump could deliver the fluid at a maximum flow rate of 10

cc/min and a pressure of 10,000 psi. Back Pressure Regulators (BPR) were installed at each end to control and maintain the desired pressure in the system by means of pressurized nitrogen gas. A regulator at the injection end was used to maintain the overbalance pressure across the core while another one retained the pore pressure inside the core. A Validyne DP303 differential pressure transducer was mounted over the core holder for measurement of differential pressures across the core. These differential pressures were displayed on analogical digitor. The signals from the transducer were also recorded on a chart recorder. An ISCO fraction collector was used to collect the produced fluids in 10 cm^3 test tubes. The whole setup, except for the pump and backpressure regulators, was confined in an electric oven to operate at reservoir temperature up to 300°C.

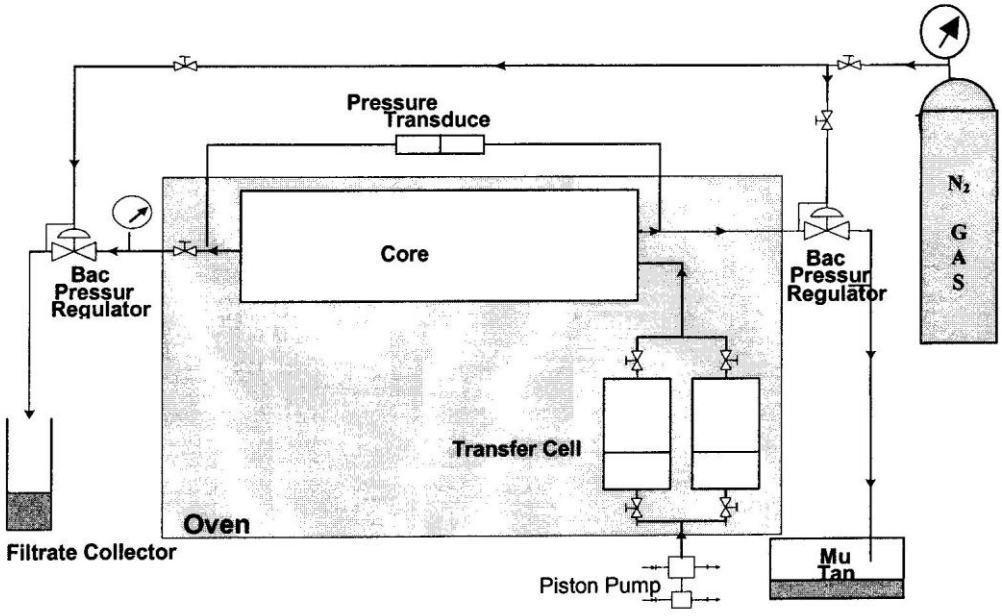


Figure 2: Schematic of a dynamic Leak-off apparatus

Drilling Fluids

A 33.5° API Arabian medium crude oil was used in the experiments. Paraffinic compounds were removed using a 1-micron oil filter. 3.5%

(35,000 ppm) KCl brine was prepared to saturate the cores. 35 gm KCl was dissolved in one liter of distilled water in a stirrer for up to 2 hours. Brine was then filtered by no. 50 filter paper and evacuated in a desiccator to remove air bubbles for nearly 2 hours. This brine was selected to avoid clay swelling and clay migration and to keep the salt concentration above the so-called 'Critical Salt Concentration'. A water-based polymeric drilling fluid was used during the experiments. An image analyzer was employed to measure the particle size distributions.

Subsequently, polymeric water-based 'muds' with four different-sized $CaCO_3$ particulates, namely 5, 10, 38.5, or 75 μm, were used. Different filters were employed to remove particles of diameters greater than a chosen size.

Core Preparation

Berea sandstone cores were reduced to the appropriate size and their dry weights and dimensions were determined. These cores were evacuated for 8 hours in a saturator before leaving them to soak in brine for 12 hours under 2,500 psi pressure. Gas porosity and permeability and pore size distribution of Berea sandstone were determined for each sample before running the Leak-off test. Sample cores of nearly the same effective permeability (450±120 md to crude oil) and pore size distribution were selected.

Measuring the Invasion Depth

The experimental set-up for ultrasonic mapping of the formation damage has been described previously [6-8]. Briefly, it consisted of two Panametric transducers to launch and receive longitudinal ultrasonic waves using a Pulser-Receiver unit. The transmitted signals were amplified and recorded on a digital oscilloscope and subsequently transferred to a personal computer for further processing and analysis (see Fig. 3). Refined petroleum jelly was used as couplant.

Cylinder-shaped rock samples were investigated by sending ultrasonic waves along the diameter at different positions scanning the entire length with a 0.5 cm resolution. 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 on transit times of the waves traveling from the source to the receiver at different positions along the length were stored in the PC. Velocities were determined simply by calculating the ratios of the 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.

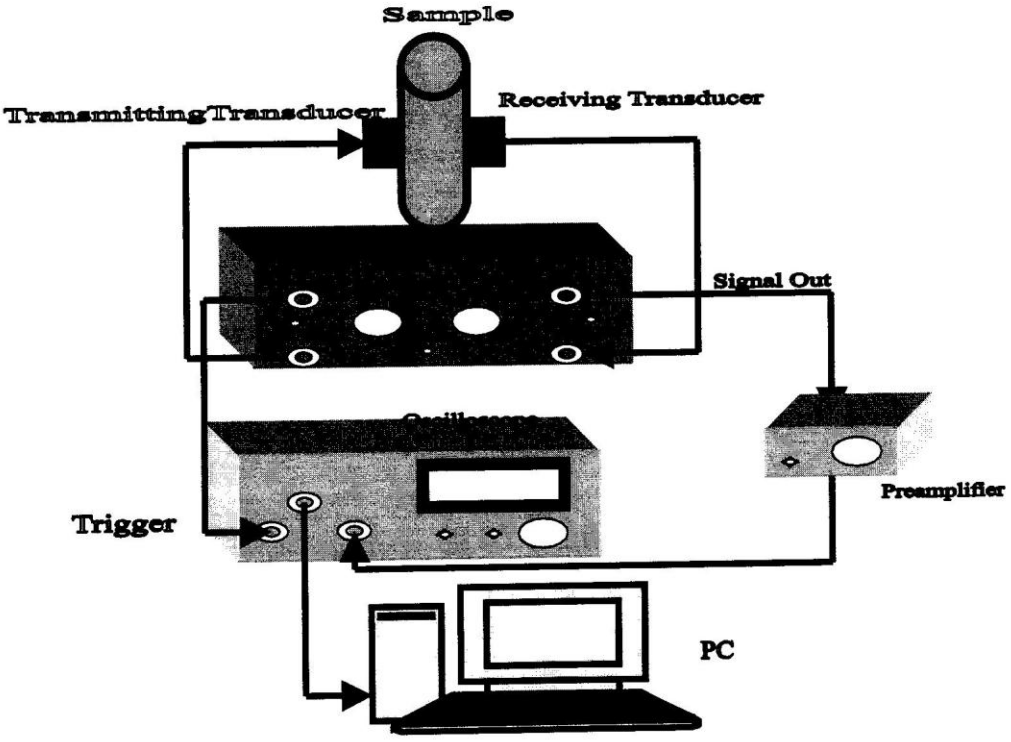


Fig. 3: Schematic diagram of the set up for ultrasonic mapping of formation damage.

Drilling fluid was circulated for different periods of time ΔT and under different overbalance pressures ΔP. A large number of samples with lengths varying from 10 cm to 25 cm were investigated.

For each sample, the wave velocities were determined under three different conditions. First, the completely dry samples where the pores have nothing other than the air or gas 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.

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 below.

The oil-saturated samples were subsequently exposed to the circulating drilling fluid for different times ΔT while keeping a constant overbalance pressure ΔP and vice versa. In the process, the sample core got 'mud'-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 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.

Results and Discussion

Typical oscilloscope traces showing the first arrival of the ultrasonic pulses at the receiving transducer are presented in Fig. 4: Dry sample

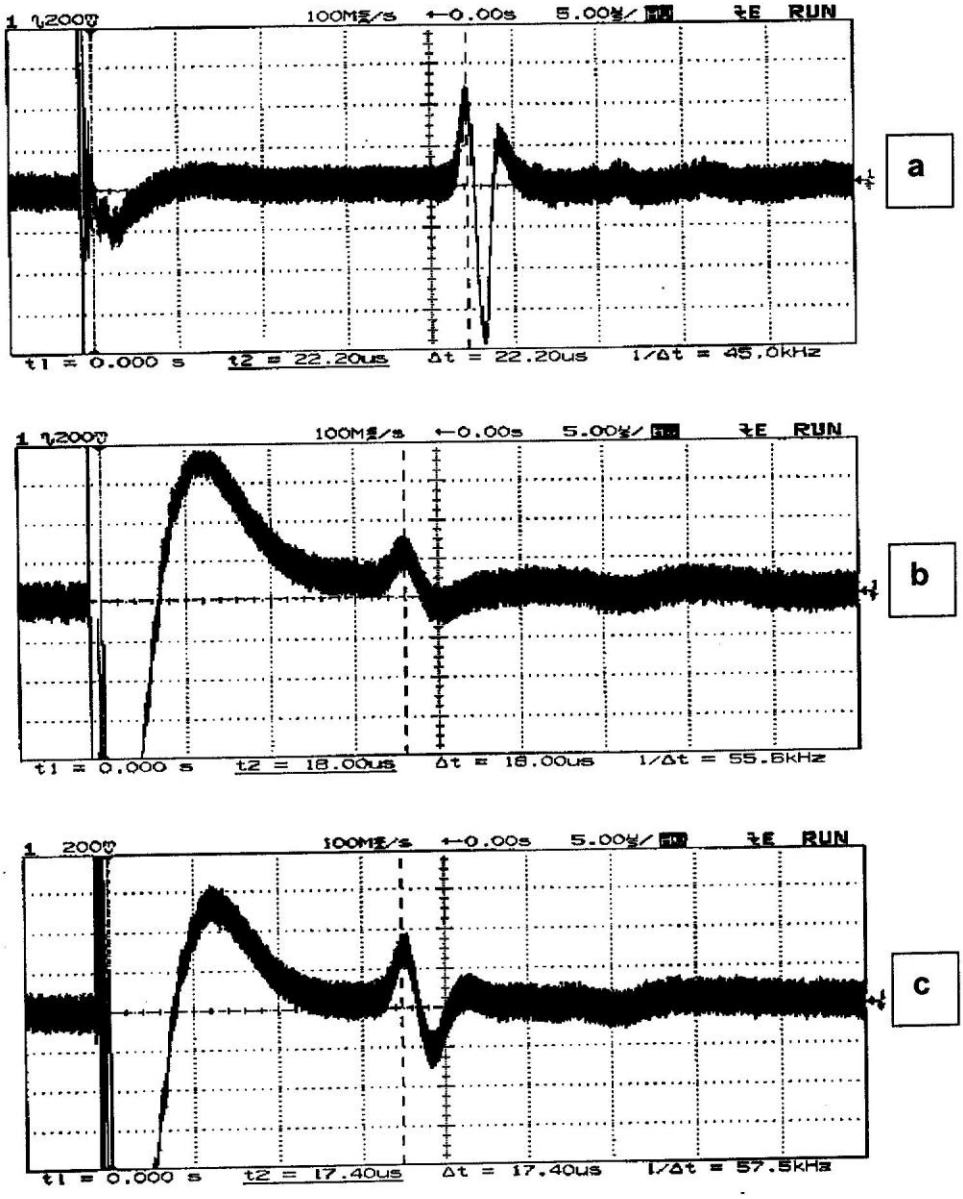
(Transit time 22.2 μs, Fig. 4a); Oil-saturated sample (Transit time 18.0 μs, Fig. 4b); and 'mud'-infested sample (Transit time 17.4 μs, Fig. 4c). The velocities were calculated for points with 0.5 cm resolution. Simple graphs were plotted to display velocity as a function of position along the length of the sample core in order to obtain unambiguous information about the 'mud'-invaded portion of the sample [6-8]. The depths of 'mud' invasion for different contamination times were measured from the constructed ultrasonic velocity profiles.

Fig. 5 displays a set of typical velocity profiles for a 10 cm long sample exposed for ΔT = 24 hours with ΔP= 300 psi. 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 this figure, 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 ΔP and ΔT. 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 decreasing velocity profile, on the other hand, indicates a partial filling of the pores by 'mud'.

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 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 $\pm$ 2.5 mm in our experiments as long as a clear discrimination can be made between the velocities in 'mud'-damaged region and the base line.

In our work, 10 cm long samples were used for ΔT = 4 or 12 hours, while 25 cm long samples were used for ΔT = 30 hours.

Fig 4 : Typical oscilloscope traces showing the first arrival of the ultrasonic pulse in (a): Dry Sample; (b): Oil-saturated Sample; (c): 'mud'-infested Sample



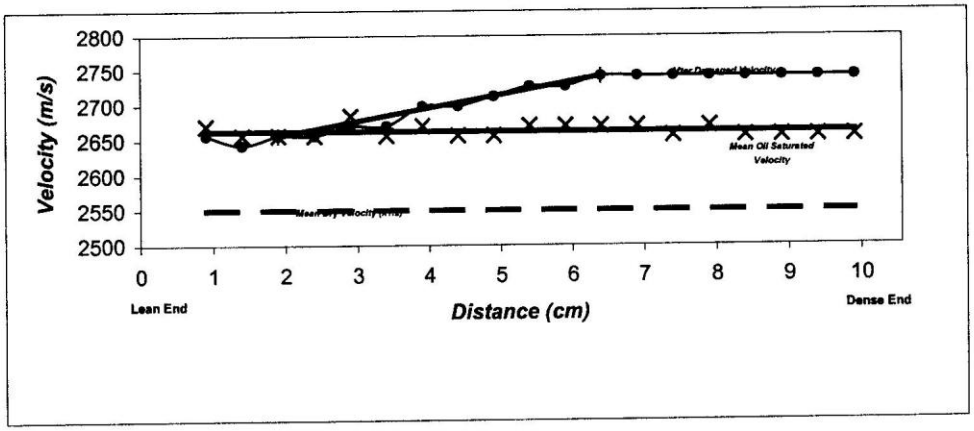


Fig. 5: Typical velocity profiles for a 10 cm long sample exposed for ΔT = 24 hours with ΔP = 300 psi

Invasion Depth as a function of Contamination Time

Fig. 6 shows the invasion depth as a function of ΔT under different ΔP of 100, 300 and 700 psi using the same drilling fluid (without any $CaCO_3$ bridging additives). The invasion depth increases essentially linearly till about 24 hours of contamination time in the case of ΔP =100 or 700 psi, while some saturation effects are visible beyond that point. However, the behavior at ΔP = 300 psi was somewhat different. In particular, the saturation point seems to have shifted towards 12 hours contamination time. As discussed by Jilani et al [7], ΔP around 300 psi is a critical region where strong bridging action occurs at the pore throats. Further increase in ΔP (e. g., 700 psi) apparently results in breaking these particle bridges.

Effect of Particle Size

The measured depths of 'mud' invasion as a function of varying ΔT from 4 to 30 hours at constant ΔP = 100 psi, and increasing particle size from 5 μm to 75 μm are summarized in Fig. 7. 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 particles sizes 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.

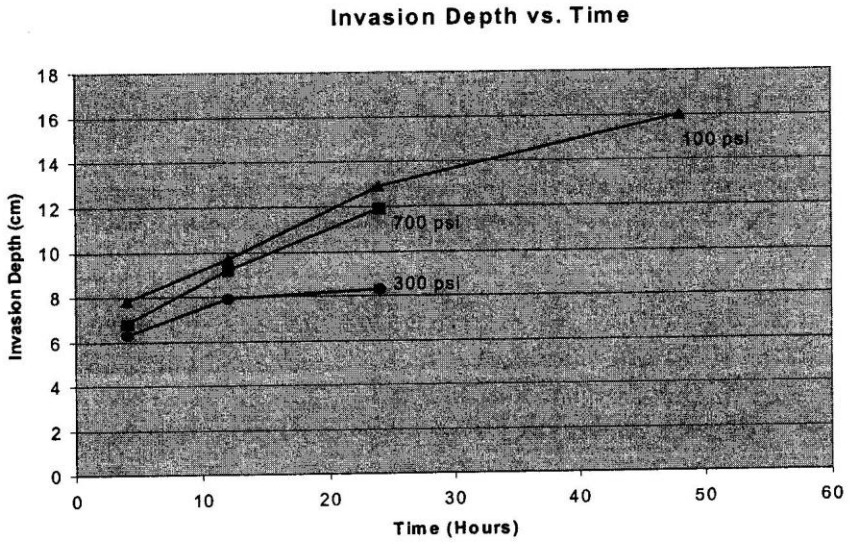
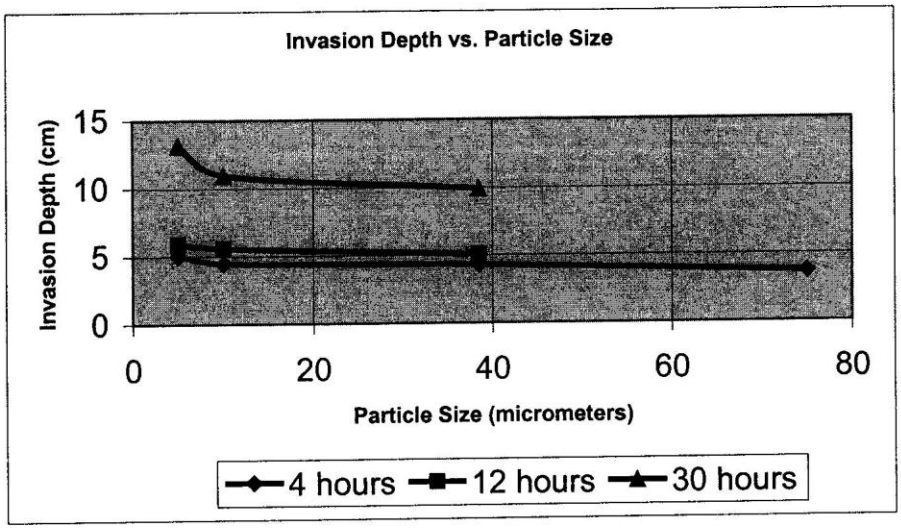


Fig. 6: Invasion depth as a function of contamination time.

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 and further into the formation.

Fig. 7: Invasion depth as a function of particle size for different contamination times, but constant ΔP = 100 psi.



The bridging action has been discussed in some detail by several authors previously [10, 11]. 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 the average pore size within the formation. This is known as Abrams' rule of thumb [10] suggesting that a significant level of bridging occurs when the 'mud' particle size reaches about one-third the median pore size. Analysis of the pore size distributions in our samples revealed that nearly 65 % of the pores are around 36 μm in size [8]. Indeed, initiation of virtual saturation around 12 μm (Fig. 7) 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 [6].

Conclusions

We have investigated the depth of 'mud' invasion as a function of contamination time, overbalance pressure, and particle sizes in the drilling fluid. For a given overbalance pressure, the invasion depth was found to increase with increasing contamination time before reaching a saturation region, as expected. However, a region of critical overbalance pressure was found around 300 psi where the invasion depth was minimum. The invasion depth also shows a rapid decrease with increasing particles sizes until the maximum particle size reaches about one-third 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 Abram's rule correlating the pore size and the particle size for significant bridging to occur.

Acknowledgements

The support provided by KFUPM and the Research Institute is gratefully acknowledged.

References

1. Civan, F., "*Reservoir Formation Damage*", Gulf Publishing Co., Houston, Texas, 2000).

2. Kruger, R. F., "An Overview of Formation Damage and Well Productivity in Oilfield Operations." *SPE-10029, J. Pet. Tech.*, 38 (1986) 131.

3. Beatty, T., Hebner, B. and Benion, D. B., "Minimizing Formation Damage in Horizontal Wells, Laboratory and Field Case studies", *J. Can. Pet. Tech.*, 34 (1995) 57.

4. Glenn, E.E. and Slusser. M.L., "Factors affecting well productivity II: Drilling particle invasion into porous media", *Pet. Trans. AIME,* 210 (1957) 132.

5. Yan, J., Jiang, G. and Wu X., "Evaluation of formation damage caused by drilling and completion fluids in horizontal wells", *J. Can. Pet. Tech.*, 36 (1997) 36.

6. Khan, M. A., Jilani, S. Z., Menouar, H. and Al-Majed, A. A., "A non-destructive method for mapping formation damage", *Ultrasonics* 39 (2001) 321.

7. Jilani, S. Z., Menouar, H. Al-Majed, A. A. and Khan M. A. "Effect of overbalance pressure on formation damage", *Journal of Petroleum Science and Engineering,* 36 (2002) 97.

8. Khan, M. A., Mohammed A. H., Jilani, S. Z., Menouar, H. and Al-Majed, A. A., "Ultrasonic characterization of formation damage: effect of particle sizes", *Measurement Science and Technology,* 14 (2003) 59.

9. Gruber, N.G. and Adair, K.L., "New Laboratory Procedures for Evaluation of Drilling Induced Formation Damage and Horizontal Well Performance", *J. Can. Pet. Tech.*, 34 (1995) 27.

10. Abrams, A., "Mud Design to Minimize Rock Impairment due to Particle Invasion", *SPE-5713, J. Pet. Tech.,* (1977).

11. Longeron, D. G., Jlfenore, J. and Poux-Guillaume, G., "Drilling Fluids Filteration and Permeability Impairment: Performance Evaluation of Various Mud Formulations", *1998 SPE Annual Tech. Conf., New Orleans, Louisiana, USA.*