

Optimization of core restoration procedure based on adsorption of polar crude oil components onto sandstone and carbonate rocks

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Abstract. Capillary forces, dictated by rock wettability, are important for fluid flow in porous media. For obtaining representative wettability in cores used for laboratory tests, core cleaning and restoration processes are of utmost importance. Increased crude oil volume exposure used in and between core restoration procedures leads to lower water wetness in both the outcrop chalk and reservoir sandstone rocks tested in this study. Reproducible capillary forces and initial core wettability in both chalk and sandstone was obtained by desiccation to establish S_{wi} and controlling the volume of crude oil exposure. Oil recovery results in both chalk and sandstone were successfully reproduced in a second restoration after mild core cleaning and exposing the cores to a volume of $(1-S_{wi})PV$ of crude oil. The results highlight the importance of controlling the crude oil amount during core restoration if reproducible core wettability is required or desired to be achieved.

1 Introduction

1.1 Significance of capillary forces in oil recovery

The flow of fluids in reservoirs is controlled by viscous, gravity, and capillary forces. The importance of capillary forces in oil recovery processes has become more apparent with increased focus on Smart Water EOR processes in both sandstone and carbonate formations. In the mid-1990s, Morrow and co-workers confirmed that low salinity brines can significantly affect the ultimate oil recovery from restored Berea core material [1-3]. Later, Austad and co-workers confirmed that seawater (SW) and modified SW can also significantly increase ultimate oil recovery over formation water (FW) in both spontaneous imbibition (SI) and viscous flooding experiments (VF) [4-6] of Stevns Klint (SK) outcrop chalk, shown in Fig. 1.

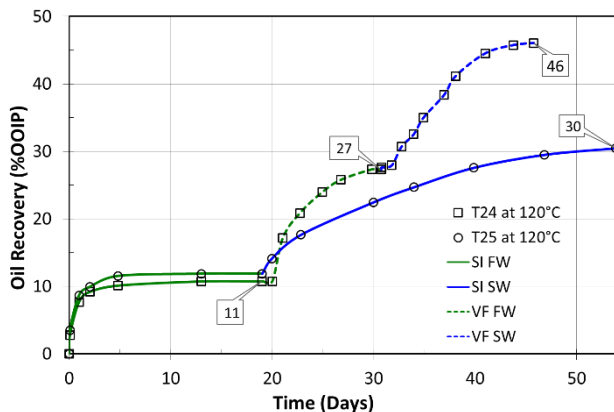


Fig. 1. Comparison of FW and SW efficiencies in spontaneous imbibition (SI) and viscous flooding (VF) of two equally restored outcrop chalk cores [5].

The change in wettability towards more water-wet conditions creates increased positive capillary forces, which can be observed for the T25 core when the SI brine changed from FW to SW and the recovery increased from 11 to 30 %OOIP.

The equally restored T24 core was initially also spontaneously imbibed with FW, reaching an oil recovery of 11 %OOIP after 5 days. During the subsequent VF of FW, only oil was produced the first days, with increasing amount of FW producing in the following days, until the ultimate oil recovery plateau of 27 %OOIP was reached. After 32 days, the injected brine was changed to SW and a sharp change in oil recovery was observed, reaching a new recovery plateau of 46 %OOIP. The physical explanation for the observed EOR-effect is the increase in positive capillary forces due to wettability alteration, observed for the T25 core, as there are only small differences in brine density and viscosity, which could contribute to significant viscous and gravity forces.

When the ionic composition of the injected brine is different from that of the FW present, a significant increase in oil mobilization from heterogeneous pore systems has been reported both on laboratory and field scales. Thus, increased positive capillary forces can promote increased brine imbibition into non-swept pores on core-scale or into matrix blocks on reservoir-scale, mobilizing more oil and improving sweep efficiency.

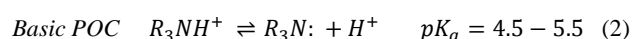
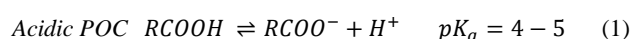
1.2 Establishment of reservoir wettability

Initially, the porous rock in the reservoir traps is saturated with aquifer brine, and the pore surfaces are mostly considered strongly water-wet, except where organic material or naturally non-water wet minerals may be present. Crude oil migrating from mature source rocks will gradually flow in and fill the reservoir trap due to buoyancy forces, and then, over geological time, an equilibrium is established within the

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crude oil, brine, rock (COBR) system. The type of pore surface minerals, the properties of the FW and the amount of surface-active components in the migrating oil, reservoir conditions as well as geological time determine the established reservoir wettability.

The oil phase contributes with polar organic compounds (POC), which can interact with charged mineral surfaces and change the reservoir wettability towards less water-wet conditions [7, 8]. Crude oils have two main types of POC, acidic and basic POC. These are quantified by acid number (AN) and base number (BN) using potentiometric titration. The charges of the POC are controlled by the pKa-value of the individual species and the pH of COBR-system, described by equations (1) and (2).



At higher H^+ concentrations (lower pH), basic POC become positively charged, while acidic POC become more negatively charged at lower H^+ concentrations (higher pH).

Previously published work has shown that POC interact with mineral surfaces in both carbonate and sandstone rocks [9-11]. Fig. 2 shows an example of POC interaction with strongly water-wet SK outcrop chalk.

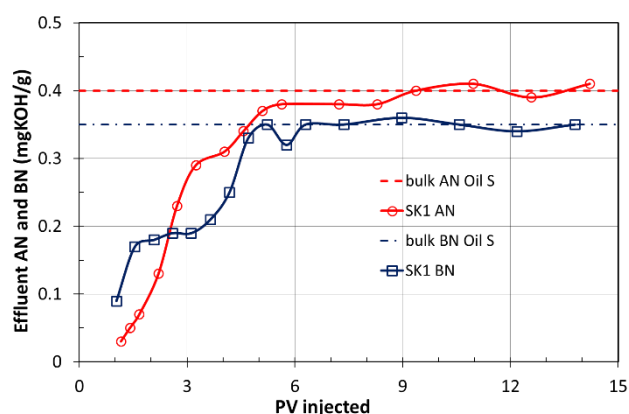


Fig. 2. Adsorption of acidic and basic POC onto SK chalk as determined by AN and BN measurements of the effluent crude oil during core restoration. Core SK1 with $S_{wi} = 10\%$ FW was flooded with Oil S (AN = 0.40 and BN = 0.35 mg KOH/g) at 50 °C at a rate of 4 pore volumes a day (PV/D) [12].

Cuiec [13] pointed out that different oil components should be expected to adsorb onto surfaces of opposite charges, such as carbonate and silicate surfaces. Thomas et al. [14] found that organic acids tended to adsorb onto calcite. Dubey and Doe [15] also noticed that wetting behaviour in crude oil/silica systems correlated with the crude oil base to acid ratio. The results in Fig. 2 show that when flooding a chalk core with crude oil, acidic POC have strong affinity for the positively charged calcite surface. The first oil produced was nearly stripped of POC and adsorption equilibrium was not reached until 9 PV of crude oil had been injected.

On the other hand, basic POC are more intensively adsorbed onto silicate minerals [10, 16]. Fig. 3 shows that the adsorption behaviour of POC with respect to silicate minerals differed from that of calcite when an outcrop sandstone core was flooded with a crude oil with AN = BN = 0.23 mgKOH/g.

Approximately 30 % of the basic POC were adsorbed during the test and adsorption equilibrium for basic POC was not reached after 10 PV of crude oil injection. The acidic POC showed weak surface affinity and low adsorption as the adsorption equilibrium was reached within 4 PV injected.

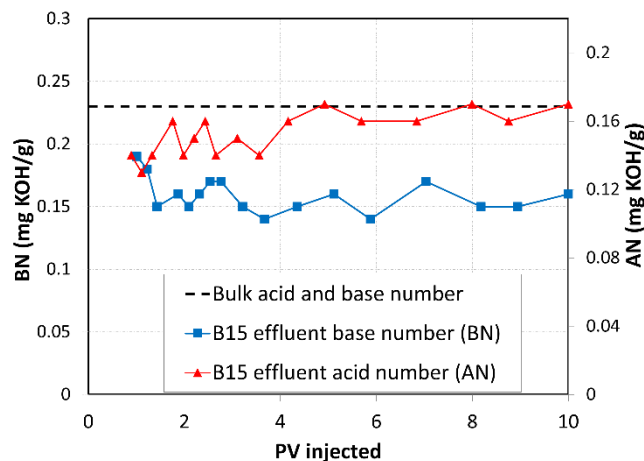


Fig. 3. Adsorption of acidic and basic POC onto an outcrop sandstone core determined by AN and BN measurements of the effluent during crude oil flooding. Core B15 with $S_{wi} = 20\%$ FW was flooded with crude oil (AN = BN = 0.23 mg KOH/g) at 60 °C at a rate of 4 PV/D [10].

The amount of adsorbed or retained POC by chalk and sandstone cores was previously quantified by calculating the area between the bulk (influent) AN/BN line and the effluent AN/BN curves [11, 17], Table 1.

Table 1. Quantitative assessment of POC adsorption onto various carbonate and sandstone material.

	Outcrop chalk		Outcrop sandstone	Reservoir sandstone
Main surface minerals	Calcite 99 %	Calcite 94 %, silica 6 %	Quartz 57 %, albite 32 %, illite 8 %	Quartz 62 %, albite 8 %, illite 15 %
BET, m ² /g	2.2	4	1.8	3
AN _{ads}	1.33	0.83	0.1	0.04
BN _{ads} /AN _{ads}	0.7	1.22	6.5	10.3
Modified oil used	AN≈BN≈0.35 mgKOH/g		AN≈BN≈0.2 mgKOH/g	

The results presented in Table 1 show that the amount of adsorbed acidic POC (AN_{ads}) is the highest in the pure calcite sample, more than 10 times higher than that in the sandstone samples. However, the ratio of adsorbed basic to acidic POC (BN_{ads}/AN_{ads}) increases in proportion to the increase in the amount and type of silicate material present in the rock. The more pronounced adsorption of basic POC in the reservoir sandstone compared to that in the outcrop can be explained by the increased amount of illite clay present, reflected by a surface area of the reservoir sandstone almost twice as large as that of the outcrop sandstone.

All the above adsorption tests were performed by injecting approximately 10 PV of crude oil through the core, and subsequent SI oil recovery tests showed a significant reduction in water wetness in the crude oil flooded cores compared to the initial core wettability.

POC present in the crude oil interacts with charged mineral surfaces [8]. As observed in Fig. 3, positively charged basic POC have the highest affinity toward negatively charged silicate surfaces. For calcite surfaces the opposite is observed, positively charged surfaces have higher affinity for negatively charged acidic POC, as seen in Fig. 2.

The crude oil cannot be described as a homogeneous phase. It contains a variety of POC with different molecular weights and chemical structures, resulting in charged organic species with different affinity towards oppositely charged mineral surfaces. Buckley [18] summarized that the most plausible wettability concept in reservoirs is that proposed by Salathiel [19], that some parts of the surface areas contacted by crude oil would become oil-wet due to adsorption by oil components, while other parts remained water-wet. She also highlighted that even though Kaminsky and Radke [20] found that strongly adsorbing crude oil species turned all surfaces into oil-wet, there should be different components in the crude oil with varying tendency to adsorb onto the rock surface influencing its wettability [18].

For calcite it was found that the smaller water-soluble carboxylic acids were the most easily adsorbed POC, and these were also the ones most difficult to desorb [21, 22].

Regarding sandstones, it was observed in Fig. 3 that only approximately 30 % of the basic POC adsorbed to the sandstone surface, and it is reasonable to believe that it is the most reactive species that will adsorb first. Thus, by time and increased volumes of crude oil flooded, it can be assumed that more of the reactive species will adsorb, possibly displacing the less reactive species from the surface in a process similar to that illustrated for calcite in Fig. 4.

1.3 Core restoration

When drilling a reservoir, sections of the reservoir zones are extracted and brought to the surface to further characterize the rock properties. These whole cores are accordingly exposed to drilling fluids and reduced temperature/pressure conditions. On the surface, the individual whole cores are commonly sealed in wax before storage or further laboratory analyses. Prior to special core analysis (SCAL), reservoir core plugs (also referred to as reservoir cores) drilled from the whole cores undergo a restoration process. Several methods and procedures are available, and the best practice guide for core analysis has been provided by McPhee et al. [23]. The main outcome of the core restoration should be a restored core with FW/crude oil saturations and wettability conditions resembling those of the reservoir. In addition, the core sample should possess representative capillary forces to perform reliable laboratory experiments and correctly interpret the results to be used in further simulations and upscaling. Generally, the core restoration process can be divided into two main parts: (1) core cleaning and the subsequent (2) fluid restoration.

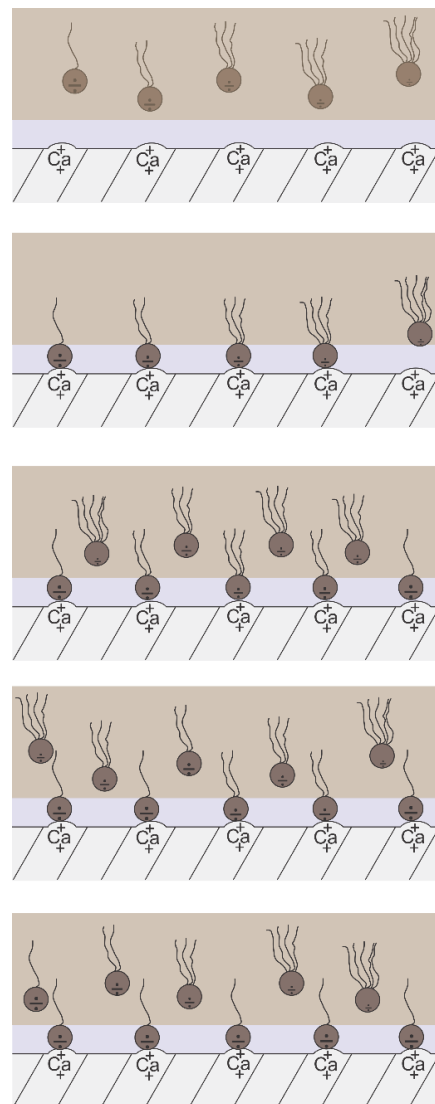


Fig. 4. Increased adsorption of more reactive negatively charged acidic POC onto a positively charged calcite surface with time by increased volume of fresh crude oil flooded.

1.3.1 Core cleaning

The choice of core cleaning method generally depends on the state of wettability desired or required. There are two main approaches to cleaning reservoir cores. The standard approach for the oil industry is to use strong solvents to obtain a strongly water-wet core prior to fluid restoration. This is normally performed by toluene-methanol Soxhlet extraction, aimed at removing most of the adsorbed POC. In this rather harsh cleaning method, the rock surface wettability, which was established over millions of years, is erased, and if the properties of the produced reservoir crude oil are not representative of the migration oil filling the reservoir trap, it will most likely not be possible to reproduce the original wettability and capillary forces during core restoration.

On the other hand, in a mild core cleaning method, the reservoir core is cleaned using weak solvents with reduced solubility of POC. In a typical mild core cleaning process performed by core flooding, low aromatic kerosene first displaces residual crude oil, and then heptane displaces kerosene. These organic liquids are weak POC solvents, and

as a result, a significant amount of oil components, which determine the wettability of the core, remains adsorbed on mineral surfaces. Thus, weak solvents have a significantly lower impact on surface wettability and capillary forces compared to the toluene/methanol harsh cleaning [24].

1.3.2 Fluid restoration

After cleaning the reservoir core, the pore space should be filled with representative formation brine and crude oil. To compare results from different SCAL processes, the restored cores should have comparable water and oil saturations. Typically, the fluid restoration process starts at 100 % FW saturation, which can be reduced to the desired saturation value by evaporation, porous plate, centrifugation, or oil displacement. Displacement of water by continuous crude oil flooding easily leads to a large variation in S_{wi} -values, depending on the properties and heterogeneity of the core plug material. The crude oil volume needed to reach the same S_{wi} -values in different core plugs will therefore vary, and thus, the resulting wettability of the core plugs will not be similar nor comparable. Establishing a constant S_{wi} while not extensively exposing the core to crude oil with surface-active POC can be a challenging process. Porous plate and centrifugation are methods that do not require extensive crude oil volumes in the restoration process. By centrifugation of soft, or somewhat unconsolidated core plugs, there is risk of disintegration, hence it is not a preferred method in e.g., chalk. Desaturation by porous plate of low permeable material represents can be a challenge because of the pressure needed to displace the water from the smallest pores, and the time it will take to reach low and consistent S_{wi} -values [25]. Springer et al. [26] proposed a desiccator method that allows the establishment of a constant S_{wi} before introducing the oil phase, a method especially beneficial for low permeable core plugs.

1.4 Objective of study

Realistic reproduction of core wettability in the laboratory is an important step prior to SCAL procedures. Core restoration procedures are many, but they have different effect on the initial core wetting and should therefore be chosen with care depending on purpose.

In this study the aim was to reproduce wettability between restorations, as observed by similar capillary forces causing spontaneous imbibition of water and corresponding oil production. An optimal core restoration procedure for obtaining wettability reproduction was proposed for low permeable chalk and sandstone core plugs consisting of: a mild core cleaning procedure to preserve wettability from the previous restoration, followed by establishment of reproducible S_{wi} -values by desiccation, which allowed complete fluid restoration with only a limited crude oil volume exposure of $(1-S_{wi})PV$ to obtain representative initial wetting conditions.

2 Materials and methods

2.1. Core material

Low permeable carbonate and sandstone material were used in this study. The carbonate material was outcrop chalk, obtained from the Stevns Klint quarry in Denmark. This carbonate rock is 99 % calcite and a good model rock for carbonate reservoirs on the Norwegian Continental Shelf (NCS). The sandstone material was reservoir cores obtained from the Varg oilfield on the NCS. "Sister" sandstones cores V6 and V7 obtained from the same sealed whole core and carbonate cores SK27 and SK29 obtained from the same chalk block therefore are assumed to have similar mineralogical composition and properties. Mineralogical composition and average properties of the core material used are presented in Table 2.

Table 2. Mineralogy and average properties of carbonate and sandstone core material.

	Carbonate core material, SK27, SK29	Sandstone core material, V6, V7
Main surface minerals, wt%	Calcite – 99 %	Quartz – 62 %, Albite – 8 %, Illite clay – 15 %, Carbonate – 5 %
Core length, cm	7.0	
Diameter, cm	3.8	
Pore volume, cm ³	38	18
Porosity, %	48	22
Absolute permeability by water, mD	1.4	7.0

2.2 Saturation fluids

Two synthetic brines and two crude oils were used to establish the initial fluid saturation of carbonate and sandstone cores. The formation waters, FW SK and FW V, were used for establishing S_{wi} and as imbibition brines in SI oil recovery tests in carbonate and sandstone cores, respectively. The brines were prepared in the laboratory by dissolving various salts in deionized water (DI) followed by filtration and degassing.

The crude oils used were 1) reservoir oil from the Varg formation (Oil V) and 2) modified crude oil (Oil SK) prepared by diluting reservoir oil from the NCS Heidrun oilfield with n-heptane. Before use, the oils were stabilized at atmospheric conditions and filtered. Composition and properties of the formation brines and crude oils used in this study are presented in Table 3 and Table 4, respectively.

Table 3. Composition and properties of brines.

	Formation water used in carbonate cores, FW SK	Formation water used in sandstone cores, FW V
	Ionic composition, mM	
Na ⁺	997	2086
K ⁺	5	51
Ca ²⁺	29	536
Mg ²⁺	8	144
Ba ²⁺	-	7
Sr ²⁺	-	8
Cl ⁻	1066	3526
HCO ₃ ⁻	9	-
TDS, g/l	62.8	201.6
Viscosity at 23 °C, cP	1.06	1.45
Density at 23 °C, g/cm ³	1.041	1.139

Table 4. Composition and properties of crude oils.

	Crude oil used in carbonate cores, Oil SK	Crude oil used in sandstone cores, Oil V
AN, mgKOH/g	~0.4	0.13
BN, mgKOH/g	~0.3	1.25
Viscosity at 23 °C, cP	2.4	11.3
Density at 23 °C, cP	0.81	0.85

2.3 Core restoration procedure

2.3.1 Core cleaning

The outcrop chalk carbonate core was initially cleaned by injecting 5 PV DI to dissolve precipitated salts possibly present in the porous structure [27].

The reservoir sandstone core was mildly cleaned at ambient temperature using 10 PV low-aromatic kerosene followed by 5 PV n-heptane. The purpose of using these solvents for core cleaning is to remove the oil phase in the pore space of the rock without significantly changing the wettability, i.e., preserving the adsorbed POC [24]. The aromatic content of kerosene is low, hence kerosene is a much weaker solvent for large organic components, such as asphaltenes, than the strong solvent toluene. To displace heptane, 10 PV of 1000 ppm NaCl was injected at the end. The same mild cleaning procedure was also applied between core restorations for both rock types.

2.3.2 Initial water saturation

After cleaning, the cores were dried until constant weight in an oven at 90 °C, followed by the establishment of S_{wi} using the desiccation method [26]. Upon reaching the desired core weight corresponding to $S_{wi} \approx 10\%$ for carbonate cores and $S_{wi} \approx 20\%$ for sandstone cores, the samples were equilibrated

for 3 days to achieve uniform FW distribution within the porous structure of the rock.

2.3.3 Oil exposure and aging

Core samples with established S_{wi} were exposed to various amounts of their respective crude oil to study the effect of crude oil volume on rock wettability. The carbonate core SK29 was exposed to 5 PV of Oil SK, while the sandstone core V6 was exposed to 11 PV of Oil V in both the first restoration (R1) and second restoration (R2) processes. In contrast, the cores SK27 and V7 were exposed to a crude oil volume of only $(1-S_{wi})$ PV of Oil SK and Oil V, respectively, in both R1 and R2. The oil exposure process was carried out by an initial vacuum saturation followed by either 1) flooding oil (4 or 10 PV) through the cores in both directions at a rate of 0.1 ml/min and a temperature of 50 °C for carbonates and 60 °C for sandstones, or 2) flooding oil from both sides until the cores had been exposed to a volume of $(1-S_{wi})$ PV.

After crude oil exposure, the oil-saturated cores were wrapped in Teflon tape to avoid unrepresentative adsorption of POC at the outer surface of the cores, and then placed, surrounded by the same crude oil, for aging in closed steel cells. The aging process continued for 2 weeks at 50 °C and 60 °C for carbonate and sandstone cores, respectively.

2.3.3 Spontaneous imbibition oil recovery test

SI oil recovery tests were performed to determine the effect of oil exposure on wettability. The restored cores were placed in glass Amott cells surrounded by their corresponding FW as imbibing fluid. Since the formation brine is in chemical equilibrium with the core minerals, the wettability of the rock does not change during FW imbibition, and thus the amount of oil produced can serve as an indicator of core wetting state. The SI tests were performed at 50 °C and 60 °C for carbonate and sandstone cores, respectively.

3 Results and discussions

Control of the core restoration process is key to achieving the required rock wettability, representative of real reservoir conditions. Oil exposure studies were performed on various carbonate and sandstone cores. The volume of crude oil exposure during core restoration varied from several PVs (5 to 11) to only $(1-S_{wi})$ PV. The effect of oil exposure and mild core cleaning on rock wettability and capillary forces was assessed by performing SI recovery test on oil-saturated and aged cores.

3.1 Effect of crude oil exposure on wettability

Preserved sandstone cores from the NCS Varg oil reservoir were used in this study. The reservoir rock material is part of an established equilibrium state in the COBR reservoir system prior to coring operations. During the extraction of core material from the formation to the surface, pressure and temperature are reduced to surface conditions, which leads to expansion of fluids and their loss before preservation. Therefore, prior to oil exposure tests, the preserved reservoir

sandstone core V6 was restored in R1 according to the procedures described above.

The outcrop SK chalk cores used have never been exposed to crude oil and, thus, initially behave strongly water-wet. To establish an initial COBR equilibrium comparable to a reservoir core, the core SK29 was restored in R1 according to the procedures described above.

The presence of initial capillary forces after R1 was investigated by performing SI experiments. Fig. 5 shows the results of SI oil recovery tests on the restored sandstone core V6 and carbonate core SK29 using their respective FWs as the imbibing brines.

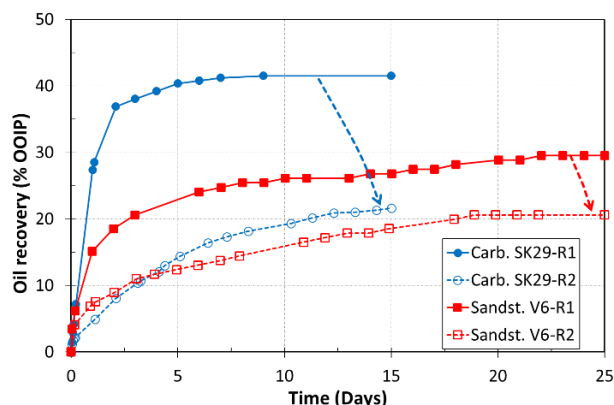


Fig. 5. Comparing the effect of restorations and crude oil volume exposure on oil recovery by SI in carbonate (at 50 °C) and sandstone (at 60 °C) cores. The carbonate core SK29 was exposed to 5PV of Oil SK in both R1 and R2, while the sandstone core V6 was exposed to 11PV of Oil V in both R1 and R2.

A significant amount of oil was produced from both the carbonate and sandstone cores after the first restoration process; core SK29-R1 reached 41 %OOIP in 9 days, and core V6-R1 reached 30 %OOIP after 22 days. The results confirm the presence of positive capillary forces in both cores after R1.

When production plateau had been reached, the cores underwent core cleaning and restoration in R2, as described above, to further investigate the impact of core restoration and crude oil exposure. Note that in R2 core SK29 was again exposed to 5 PV of Oil SK, while core V6 was again exposed to 11 PV of Oil V. The SI oil recovery results after R2 for the cores V6-R2 and SK29-R2 are also presented in the same Fig. 5. The ultimate oil recovery of 22 %OOIP from core SK29-R2 was reached after 15 days, which is significantly lower than that obtained in R1: 41 %OOIP after only 9 days.

For the sandstone core V6-R2, a recovery plateau at only 21 %OOIP was obtained after 22 days, which is also significantly lower than the 30 %OOIP ultimate oil recovery plateau obtained after 22 days in R1.

As the available surfaces are exposed to more oil during fluid restoration, increased amount of POC will interact and reduce the amount of positive capillary forces as seen in Fig. 5. Injection of larger volumes of fresh crude oil would increase the interactions between reactive mineral surfaces and the more reactive crude oil species, which could result in an up-concentration of the highly reactive species at the mineral surface, enhancing the oil-wet areas, as suggested by the calcite example in Fig. 4.

Thus, the general trend is the same for both sandstone and carbonate cores, that a significant reduction in both speed of imbibition and ultimate oil recovery was observed at increased crude oil exposure. When the cores were exposed to a large volume of crude oil (5 PV/11 PV) during restorations, a dramatic change in capillary forces was observed, highlighting the importance of developing improved fluid saturation protocols before reliable SCAL can be performed in the laboratory. Note that the aging time after each oil saturation cycle was limited to 2 weeks. Increasing the aging time together with the use of crude oils with higher asphaltene content can lead to an additional decrease in water wetness, resulting in less changes in capillary forces in between restorations.

3.2 Reproducing wettability with limited oil exposure

The second set of outcrop chalk and reservoir sandstone cores, SK27 and V7, was restored in R1 with only $(1-S_{wi})PV$ of the respective crude oils. The presence of initial capillary forces after R1 was investigated by performing SI experiments. The SI oil recovery tests results from V7-R1 and SK27-R1 using the representative FWs as the imbibing brines are presented in Fig. 6.

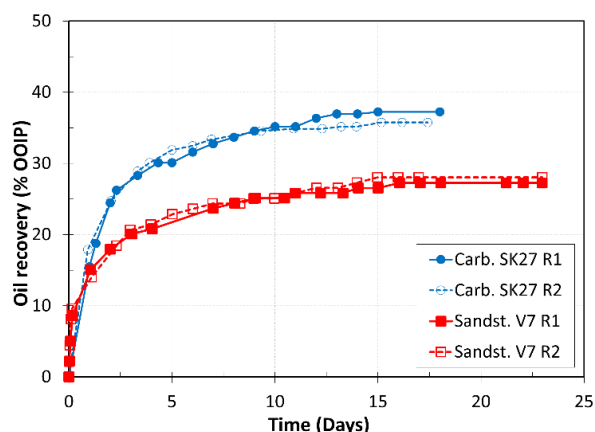


Fig. 6. Reproduced wettability obtained between restorations R1 and R2 in carbonate (at 50 °C) and sandstone (at 60 °C) cores. Carbonate core SK27 and sandstone core V7 were exposed to crude oil volumes of $(1-S_{wi})PV$ of Oil SK and Oil V, respectively, in both R1 and R2.

The presence of positive capillary forces was confirmed and an ultimate oil recovery of 37 %OOIP was reached in 13 days for core SK27-R1, while for core V7-R1 the recovery plateau of 25 %OOIP was achieved in 15 days.

Thereafter, both cores were again restored and exposed to only $(1-S_{wi})PV$ of crude oil in R2, resulting in cores SK27-R2 and V7-R2. SI oil recovery tests were again performed, and the results are presented and compared with the results from R1 in Fig. 6. After mild cleaning and limited crude oil exposure the capillary forces were reproduced in both the chalk and reservoir sandstone cores. After R1, mild cleaning was performed prior to R2. Hopkins et al. [19] found that approximately 75 % of the initially adsorbed POC remained adsorbed at the surface of chalk after mild cleaning. By introducing a crude oil volume of only $(1-S_{wi})PV$, it is expected that this limited volume is sufficient to re-adsorb the 25 % of POC removed by the mild cleaning procedure. The

reproduced oil recovery curves in both sandstone and chalk suggest that this is the case. The results also suggest that what was quantified and deduced from the chalk experiments by Hopkins et al. [24] is somewhat similar for the reservoir sandstone.

As expected, a lower total volume of crude oil interacting with the mineral surfaces during fluid saturation resulted in restored core samples with more positive capillary forces. For both chalk and sandstone material, capillary forces were reproduced in the second restoration, both in terms of imbibition rate and the ultimate oil recovery.

Reproducing representative core wettability in the laboratory is important for reliable SCAL or oil recovery test results to be obtained. These results are crucial when fluid flow in reservoir systems should be described, modelled, and upscaled to reservoir conditions in reservoir simulators. To re-establish representative wettability in reservoir cores, the process of cleaning cores to strongly water-wet by rigorous solvents followed by a dynamic flooding and aging period using fresh oil is probably not beneficial. In this case the original reservoir wettability has been erased completely, with a following attempt to re-establish the wettability by flooding some unknown amount of crude oil through the core. Because crude oils contain POC of different charges and reactivity it is important to be consistent with the crude oil volumes used in the core restoration processes. By continuously refreshing the crude oil in a dynamic flooding and aging process the cores are most likely overexposed to the highly reactive crude oil species.

The question of what a representative wettability is arises. In many cases a reservoir has only been filled once, however, certain areas in the reservoir have presumably had significant volumes of oil flooded through in the oil migration period. These areas could then be less water-wet than other areas where smaller amounts of POC have passed through. Therefore, recreating representative core wettability in the laboratories is a challenge, because of not knowing the necessary oil volumes to flood through the core in the restoration process. Another problem is the crude oil composition, which most likely is not the same as that of the oil originally wetting the reservoir rock, because of processes such as adsorption of POC onto the rock. As seen in Fig. 2 and Fig. 3, the crude oil flooded through chalk and sandstone core plugs contained decreased content of crude oil acids and bases. As an analogue to the reservoir, it can be assumed that the composition of the produced reservoir oil is not the same as that of the oil wetting the reservoir rock. Therefore, a better approach is maybe to preserve original core wettability by mild cleaning, followed by only introducing a limited oil volume of $(1-S_{wi})PV$.

4 Concluding remarks

To obtain reproducible wettability in the restoration of low permeable chalk and sandstone core plugs it was proposed to perform mild core cleaning, establish S_{wi} by desiccation and to limit the crude oil volume exposure to $(1-S_{wi})PV$. The mild core cleaning procedure aimed to preserve adsorbed POC on the rock surface and the wettability established in the previous restoration. Establishing S_{wi} by desiccation returns consistent S_{wi} -values. Limiting the crude oil volume between

restorations to $(1-S_{wi})PV$ fills the pores with crude oil without altering wettability significantly.

It was demonstrated that increased crude oil volumes in the restoration process led to less water-wet conditions in both chalk and sandstone core plugs.

Wettability was successfully reproduced in both chalk and sandstone cores by following the proposed procedure. For performing parametric wettability studies in the laboratory, especially on limited core material, the proposed procedure could be of value.

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