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Elasticity and electrical resistivity of chalk and greensand during water flooding with selective ions

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ABSTRACT

Water flooding with selective ions has in some cases lead to increased oil recovery. We investigate the physical processes on a pore scale that are responsible for changes in petrophysical and mechanical properties of four oil-bearing chalk and four oil-bearing greensand samples caused by flooding with brines containing varying amounts of dissolved NaCl, Na_2SO_4, $MgCl_2$ and $MgSO_4$. Ultrasonic P-wave velocity and AC resistivity measurements were performed prior to, during and after flow through experiments in order to identify and quantify the processes related to water flooding with selective ions. Low field Nuclear Magnetic Resonance (NMR) spectrometry measurements were performed at full water saturation, at irreducible water saturation, after aging and after flooding. CT-scanning, X-ray diffraction (XRD), backscatter electron microscopy images (BSEM), mercury injection capillary pressure (MICP) curves and specific surface analysis (BET) reveal the mineralogy and texture of the rock samples before and after the injection. Low field NMR data indicates changes in the pore fluid distribution and wettability of chalk after aging of one of the samples. NMR data for other samples indicate that chalk is water-wet after flooding. Greensand remained mixed wet throughout the experiments. Electrical resistivity data are in agreement with this interpretation. The electrical resistivity data during flooding revealed that the formation brine is not fully replaced by the injected water in both chalk and greensand. Changes in the elasticity of chalk during flooding illustrate the softening effect of magnesium bearing brines as compared to the sodium bearing brines. The stiffness of greensand was not affected by water flooding with selective ions as determined from the elastic wave measurements. Precipitation of fines during flooding of chalk samples is indicated by an increase in specific surface area and a shift in the MICP to lower values but no fines were detected by NMR. No changes were observed for greensand samples.

1. Introduction

Waterflooding with selective ions can enhance the production of oil from reservoirs (Morrow et al., 1998; Seccombe et al., 2008). Previous studies, both in the field and in the laboratory, have validated the success of this class of procedures to increase oil production both from carbonate and siliciclastic reservoirs. Low salinity flooding has been successfully used in sandstone reservoirs (Seccombe et al., 2008; Vledder et al., 2010) and effects of changing the composition of the injecting water have been observed in limestones (Morrow et al., 1998; Strand et al., 2006; Austad et al., 2008). That said, the mechanisms by which oil production can be enhanced are not clear (Jackson et al., 2016; Yutkin et al., 2016), so we will by petrophysical monitoring of flooding experiments address three possible mechanisms related to waterflooding with selective ions: 1) the wettability alterations of chalk and greensand during aging and waterflooding; 2) the changes in the elastic properties of the rock due to solid/fluid interactions; 3) the generation of fines and precipitation or other substitution/adsorption phenomena on the pore wall of the rock due to the injection of water with various ions.

Wettability describes the solid-fluid affinity of a unique system of brine, oil and rock under certain conditions; such as temperature and pressure (Radke et al., 1992). By systematically varying wettability of

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Berea sandstone, Jadhunandan and Morrow (1995) showed an optimum in oil recovery by water flooding when the rock is water wet before the water injection. Several studies also report that increased flooding efficiency in chalk can be caused by alteration towards water wetness, due to the sorption of surface-potential-determining divalent ions (Austad et al., 2005, 2008; Strand et al., 2006; Puntervold and Austad, 2008; Yousef et al., 2011). In this context Hiorth et al. (2010) modelled mineral dissolution of chalk due to the injection of water containing divalent ions and discussed the effect of this dissolution upon the wettability of the chalk. We will use low field NMR and electrical resistivity to discuss sample wettability because the NMR signal from a fluid depends on the direct interaction with the mineral surface (Guan et al., 2002; Al-Mahrooqi et al., 2003); and because electrical resistivity of a saturated rock increases by alteration from water-wet to oil-wet (Sweeney and Jennings, 1960), so that we expect an increase in the n-saturation exponent from Archie's law.

A weakening of chalk when water or brines are introduced into the pore space was already noticed by Newman (1983) and is referred to as water weakening. Also stiffness is affected by pore fluid, and Katika et al. (2015) observed that chalks from Stevns Klint saturated with high salinity Mg-rich brines, are softer than chalks saturated with Na-rich brines. Korsnes et al. (2006) suggested that water weakening of chalk due to injection of seawater-like brines is related to substitution of Ca^{2+} ions with Mg^{2+} at the grain-to-grain contacts in the presence of SO_4^{2-}. On the other hand, experiments on Stevns and Leige chalk by Madland et al. (2011) demonstrated that sulphate is not needed to have a significant amount of deformation, although lower concentration of magnesium ions were found in the produced than the injected pore water. Two mechanisms were proposed; substitution of calcium and magnesium without the presence of sulphates in the pore water and the precipitation of magnesium as part of a new mineral phase (Madland et al., 2011; Andersen et al., 2012). Nermoen et al. (2015) observed the effect of various brines and oil on the elastic properties of Liege chalk from Belgium, as derived from mechanical testing. The proposed mechanism is that chalk saturated with brines which cause high electrostatic potential on the surface of chalk, are the weakest. Nermoen et al. (2015) introduced the repulsive electrostatic stress as a mechanism that separates the grains of chalk and therefore weakens the saturated sample.

Changing pore water composition can lead to precipitation of minerals onto the surface of solids in the rock or to precipitation of fines (Fathi et al., 2010; Madland et al., 2011; Yousef et al., 2011). In the above-mentioned study, Hiorth et al. (2010) proposed that a precipitation/dissolution mechanism can be the controlling factor that influences the oil recovery of carbonate rocks as observed in laboratory experiments in previous studies (Zhang et al., 2007; Austad et al., 2008).

2. Rock materials and brines

2.1. Reservoir chalk from the Gorm field

Chalk is a sedimentary carbonate rock of high homogeneity, but its petrophysical properties fall in wide ranges. Porosity and specific surface are main determining factors for permeability and capillary entry pressure, and partly for elastic moduli (e. g. Fabricius, 2007). The selected reservoir chalks of Tor Formation are from the Gorm (N-3X) field in the North Sea (Bæk, 2014). Five horizontal or vertical plugs (75 mm length and 37 mm diameter) were used for aging and flooding experiments and side and end trims were selected for the petrophysical investigation.

2.2. Reservoir greensand from Solsort field

The aged and flooded greensand is a mixture of quartz grains and chlorite aggregates from the Solsort field (Bæk, 2014) in the North Sea. The mineral responsible for the microporosity of the greensand is chlorite which is known for a high paramagnetic index (Hürlimann et al., 2004) and high stiffness (Wang et al., 2001). Five horizontal core plugs, of 50 mm length and 37 mm diameter, were used for aging and flooding experiments and side and end trims were selected for the petrophysical investigation.

Table 1
Composition of the Formation waters for the two reservoirs from which the cores were extracted.

Parameter	Gorm field (Chalk reservoir)	Solsort field (Greensand reservoir)
Na^+ (mg/L)	13500	11300
K^+ (mg/L)	100	360
Mg^{2+} (mg/L)	95	23
Ca^{2+} (mg/L)	250	105
Cl^- (mg/L)	21000	18225

Table 2
Dan field dead oil properties.

Dead oil	Mass density (g/cm^3)	Acid number (mg KOH/ g oil)	Base number (mg KOH/ g oil)	Asphaltene (%)	Viscosity (cp)
Dan Field	0.845	0.09	2.44	0.3	8.83

2.3. Brines and oil

The composition of the formation water for each field is given in Table 1, but for the sake of fluid compatibility, all plugs were saturated with brine corresponding to Dan field Brine and dead oil from the Dan field (Bæk, 2014) in North Sea (Table 2). Two sets of brines were used in the core flooding experiments; Na-bearing and Mg-bearing (Table 3). The resistivity of the injected brines were calculated from SLB chart 9 (Schlumberger, 2000).

The produced fluids were collected in effluent tubes during the flow through experiments. The amount of produced oil in each tube was measured by image analysis and by using the liquid scintillation method (Katika et al., 2016).

Table 3
Compositions of brines used for core flooding.

Na brines mol/kg H_2O	NaCl	Na_2SO_4	Mg brines mol/kg H_2O	$MgCl_2$	$MgSO_4$
0.6 Cl^-	0.6	–	0.6 Cl^-	0.3	–
0.3 SO_4^{2-}	–	0.3	0.3 SO_4^{2-}	–	0.3
0.3 Cl^- + 0.15 SO_4^{2-}	0.3	0.15	0.3 Cl^- + 0.15 SO_4^{2-}	0.15	0.15
0.6 Cl^-+ 0.75 SO_4^{2-}	0.6	0.75	0.6 Cl^- + 0.75 SO_4^{2-}	0.3	0.375
0.06 Cl^-	0.06	–	0.06 Cl^-	0.03	–

Table 4
Water and oil saturation of chalk from the Gorm field and greensand from the Solsort field before aging and water flooding at 60 °C (N-3X X02H and D08H were not flooded).

Sample ID	Water saturation, %	Oil saturation, %
N-3X 04H	5	95
N-3X 09H	13	87
N-3X 11H	12	88
N-3X 17V	13	87
N-3X X02H	5	95
D03H	46	54
D04H	33	67
D07H	38	62
D17H	34	66
D08H	44	56