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A brief review of the correlation between electrical properties and wetting behaviour in porous media

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Abstract:
Wettability is a critical interface property for two-phase flow and reactive transport process in porous media. Wettability alteration is considered as the dominated mechanism for enhanced oil recovery during low salinity waterflooding. The conventional characterization of wettability by contact angle at a single substrate and Amott method at core are limited. In this minireview, we introduce recent improvements in characterization of the electrochemical properties of an interfacial layer formed at the mineral-water interface, and review the application of surface potential (i.e., zeta potential) as an invasive and reliable technique to characterise the wetting behaviour of sample core across different geochemistry conditions. In order to resolve the puzzle of the wettability alteration in an oil-brine-rock system, experimental studies combined with numerical simulations across multiscale and variable geochemistry conditions are required for the future investigation.

1. Introduction

The interfacial properties of porous media imposed significant influence on unsaturated flow, dynamics of reactive transport, and processes of adsorption and desorption (Heberling et al., 2014; Lutzenkirchen et al., 2018). The most important interfacial behaviour in the hydrogeology and petrophysics community is the wetting behaviour of the soil and rock surface (Khishvand et al., 2017). The wetting behaviour of porous media is critical to petroleum engineering, hydrogeological processes, and water purification technology (Sheng, 2014; Arif et al., 2017; Ding and Rahman, 2017; Khishvand et al., 2017). The wetting behaviour determines the hysteresis of capillary pressure and relative permeability in unsaturated flow. As for the pore throat with reactive mineral surfaces, the interface properties play an important role in the kinetic and adsorption process, wettability alteration (Kallel et al., 2017; Khishvand et al., 2017; Wu et al., 2017) as well as specific ions transport process (Werkhoven et al., 2018). A full understanding of the effect of surface charge on transport of ion through charged porous media is still missing (Tian and Wang, 2017).

In this paper, we review the surface characterization techniques including wettability and zeta potential measurements, then introduce the recent improvement in the correlation between the wettability and zeta potential, finally discuss the future investigation required to improve our understanding of the mechanism of wettability alteration correlated with its electrical properties.

2. Characterization of wettability alteration and zeta potential measurements

The wetting behaviour is affected by both the rock surface and fluid properties. Across different types of mineral surface, clay minerals and carbonates are more hydrophobic than silica sand. For a given type of mineral surface, the mineral surface structure and adsorptive organic materials at the mineral also affects its overall wetting behaviour. Apart from the solid phase, the groundwater chemistry also plays a role in the surface adsorption and its wetting behaviour. Due to the complexity of the wetting behaviour, the accurate experimental measurement is quite difficult to characterize the wetting behaviour (Ding and Rahman, 2017). The contact angle measured at a single substrate could represent the wetting behaviour properly (Mugele et al., 2016; Alhammadi et al., 2017). The Amott method used in reservoir wettability has a large uncertainty (Sheng, 2014; Jackson et al., 2016b).

The zeta potential can sensitively probe the electrochemical

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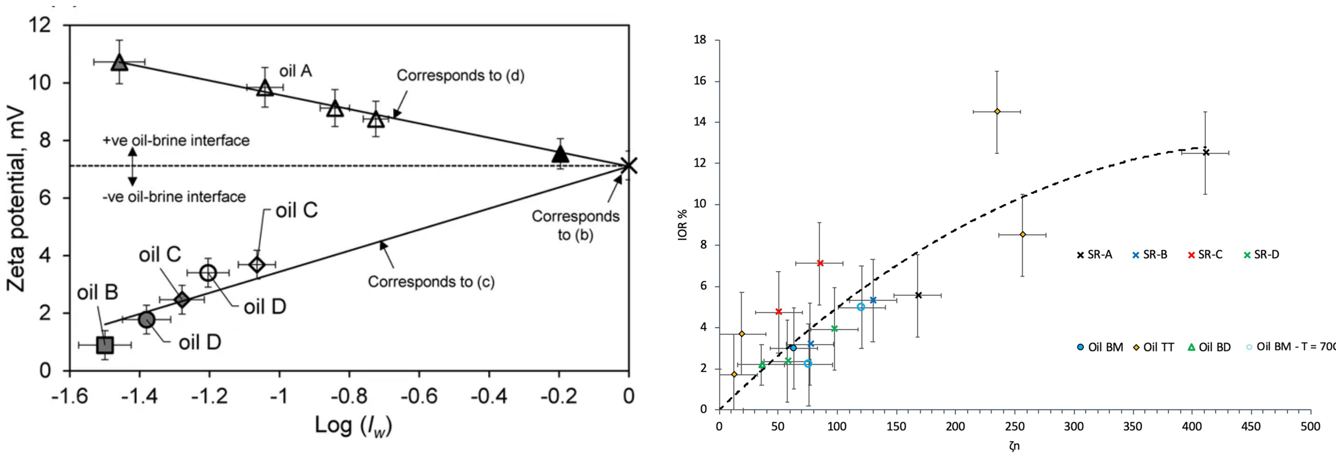

(a) (b)

Fig. 1. The correlation between zeta potential change and the Amott water index (a) (Jackson et al., 2016a) and its correlation with oil recovery (b) (Collini et al., 2020).

change at the nanoscale level. The streaming potential method has been widely employed from a single pore to intact core sample (Vinogradov et al., 2010; Walker and Glover, 2018). The macroscopic properties of streaming potential can be inferred to the zeta potential at the mineral-water interface accurately, and it is quite sensitive to the change of interface phenomena. As the electrical double layer formed at solid-water interface, the zeta potential is controlled by both rock physics properties and water chemistry (Walker and Glover, 2018) under given pressure and temperature (Al Mahrouqi et al., 2016). Thus, the zeta potential is a promising property which can characterise the mineral-water interaction in porous media.

3. The correlation between zeta potential and wettability alteration

Jackson et al. (2016a) proposed an alternative method to characterise the wetting behaviour by employing an electrical property, zeta potential. As the mineral surface in contact with electrolyte, the electrical double layer is formed at the mineral-water interface due to the deprotonation of surface functional group (Hunter, 1981; Eriksson et al., 2007). In their experimental study, they found a good correlation between the zeta potential change and wettability alteration during controlled salinity waterflooding, as shown in Fig. 1(a). The correlation of zeta potential change and enhanced oil recovery also has been quantitatively established. They found the electrostatic force plays a critical role in the wettability alteration and suggested that the injected brine to produce more oil only works when water chemistry induces the zeta potential to produce a repulsive electrostatic force at the mineral-water interface. The following experimental study (Collini et al., 2020) across different carbonates samples and crude oils also confirmed this correlation between the zeta potential and oil recovery (see Fig. 1(b)). Notice that these experimental results only occurred in the carbonates, but not for other types of mineral surface of clay and silica sand (Sheng, 2014; Jackson et al., 2016b). In addition, measurements of zeta potential at the mineral surface via streaming potential method has been proved successfully to characterize the electrochemical property of intact core sample (Vinogradov et al., 2010).

4. Discussion of the mechanism of wettability alteration with zeta potential

A theoretical description of the role of electrostatic force has also proposed to explain the rock surface interaction at the equilibrium state, such as Derjaguin, Landau, Vervey, and Overbeek (DLVO) theory (Jackson and Vinogradov, 2012; Jackson et al., 2016). The electrostatic force is an important contribution to the overall interaction compared to other surface forces including structure force, van der Waals force. The local force measurement has also been conducted by using atomic force microscopy and surface force apparatus (Gebbie et al., 2013; Brown et al., 2016; Dhopatkar et al., 2016; Xing et al., 2018). The local force and energy can be calculated analytically at the mineral surface from the thermodynamic prospective (Alshakhs and Kovscek, 2016; Eftekhari et al., 2017). But its application to explain and interpret the results for the representative volume element (RVE) and core scale is still limited.

During the wetting behaviour modification, the role of zeta potential at high salinity is difficult to explain (Vinogradov et al., 2010) as well as the thickness of the electrical double layer (Huang, 2018). Regarding the structure of the electrical double layer, a dynamic Stern layer model has been proposed to explain the anomalous behaviour of zeta potential trend (Werkhoven et al., 2018). Recently, Li et al. (2018) found an anomalous trend for the zeta potential measurements. The role of electrical double layer has gained more attention for wettability investigation based on the successful low salinity waterflooding in clayey sandstone (Jackson et al., 2016b).

The dynamic process of low waterflooding may influence the change of wetting behaviour with time, the zeta potential before and after is not enough to capture the transient be-

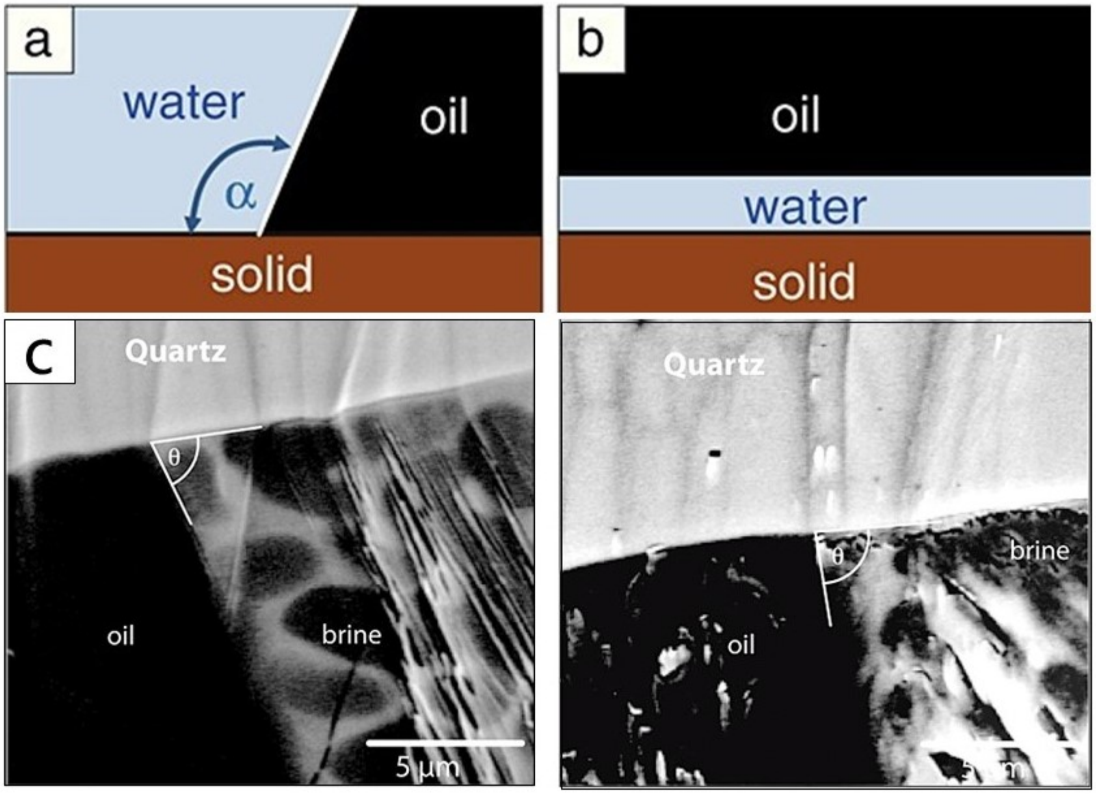

Fig. 2. The schematic picture of wettability of oil-water-mineral system can be altered from oil-wet (a) to water-wet (b), corresponding to the directly experimental visualization of the faceted quartz wetted by water and oil and three-phase contact point (c) (modified from Schmatz et al., 2015).

haivour. Theoretical and numerical simulation of the dynamic transport of flow and transport are needed. During the water flow, the role of electrical double layer is important for the interaction of solid-fluid interface. Karadimitriou et al. (2019) presented a micromodel experimental study to show that the flow rate and ionic strength also play an important role in the wettability alteration by validating the two-phase model with the experimental two-phase flow on the salinized polydimethylsiloxane (PDMS) micromodel. As shown in Fig. 2, the evolution of wettability during core flooding can be visualized experimentally (Schmatz et al., 2015). In a silica nanotube experiment, Lis et al. (2014) proved that flow rate could impact the surface charge density and eventually the streaming potential. The direct experimental evidence between flow dynamic and wettability alteration via surface charge change has not yet been reported. The coupling between solute transport in porous media and surface charge change has been simulated in a recent finite element study (Werkhoven et al., 2018).

5. Conclusions

In summary, the electrical properties and wetting behaviour are critical to the understanding of the mechanism of enhanced oil recovery. In addition to the electrostatic force at the mineral surface, the fluid flow and transport process could influence the overall oil recovery technology adapted in the petroleum engineering. The correlation between surface electrostatic force with wetting behaviour has been found in carbonates samples at static condition. The role of fluid flow and solute transport coupled with surface charge variation as well as the wettability alteration during low salinity flooding needs further experimental investigations.

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Conflict of interest

The authors declare no competing interest.

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