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Research paper

Study of the effect of clay swelling on the oil recovery factor in porous media using a glass micromodel

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ABSTRACT

Formation damage due to incompatibility between the formation and injected low-salinity water decreases the relative permeabilities of oil and brine, increases residual oil saturation, and decreases oil recovery. In the presence of swelling clays, the shock effect of sudden water injection results in an increase in formation damage. Clay minerals may cause formation damage due to swelling and migration during the production of oil and gas. Therefore a good understanding of the damage mechanisms of clays helps us to prevent and remedy possible damage in reservoirs.

In this work, the effect of clay swelling behavior on the oil recovery factor at the pore scale by using a glass micromodel was studied. A clay-coated micromodel with sodium bentonite as the swelling clay was prepared. Using an image processing technique, the ultimate oil recovery factors after flooding with low-salinity water (LSW) and high-salinity water (HSW) were estimated and the effect of clay swelling phenomena on the oil recovery factor was studied.

Final residual oil saturation was higher when LSW was used as the injection fluid compared to when HSW was used, and in fact it can be said that clay swelling somehow inhibits the film flow of injection fluid and causes more oil to be bypassed in the micromodel.

1. Introduction

Formation damage is a well-established problem in petroleum reservoir engineering, Krueger (1986) and Bennion et al. (1995) stated that this problem could be associated with every stage of development from drilling to production, as indicated in Fig. 1. Formation damage is a zone of reduced permeability within the vicinity of the wellbore as a result of the invasion of foreign fluid into the reservoir rock. This damage depends on many factors, such as the rock's mineralogical composition and the quality of the injected water.

Most reservoirs contain both interstitial waters and swelling clay minerals. Swelling clays may constitute only a few percent of the reservoir rocks, but they are predominant in terms of surface area. These types of clays are initially hydrated to a certain degree and are in equilibrium with the connate water. During drilling operations, water from mud infiltrates the sand, and the introduced water is probably not in chemical equilibrium with the original interstitial water. Hence, the existing equilibrium of the clay–water system is disturbed, which leads to swelling of clay particles, blockage of pore spaces, and a reduction in effective permeability. This problem may also occur when incompatible water is injected into the reservoir during water flooding or different EOR processes as shown schematically in Fig. 2.

Recently, water flooding is the preferred recovery technique for many reservoirs because of the higher sustained oil production rates and higher recovery factors compared to many expensive methods. Water flooding is relatively cheap, especially for offshore fields, because of the availability of seawater. Usually the introduced water has lower salinity than the connate water, which leads to swelling of the clay particles. In spite of the large amount of swelling clays in sandstones, relatively few studies have been devoted to addressing the issue of permeability and recovery impairment caused by swelling clays. Grim (1939) stated that all clays could be considered as belonging to one of three classes: kaolinite, illite, or montmorillonite. He stated further that kaolinite has little influence on petroleum recovery and the montmorillonites have the greatest influence. Similarly, the hydrogen forms are the least important and the sodium forms the most important in the processes of accumulation and recovery.

Moyer (1947) discussed analytically the effect of a decrease in sand permeability around the wellbore on the economic ultimate recovery. He showed that the influx of fresh water reduced the sand permeability by clay swelling and consequently increased the saturation of interstitial or immobilized water and decreased the ultimate oil recovery.

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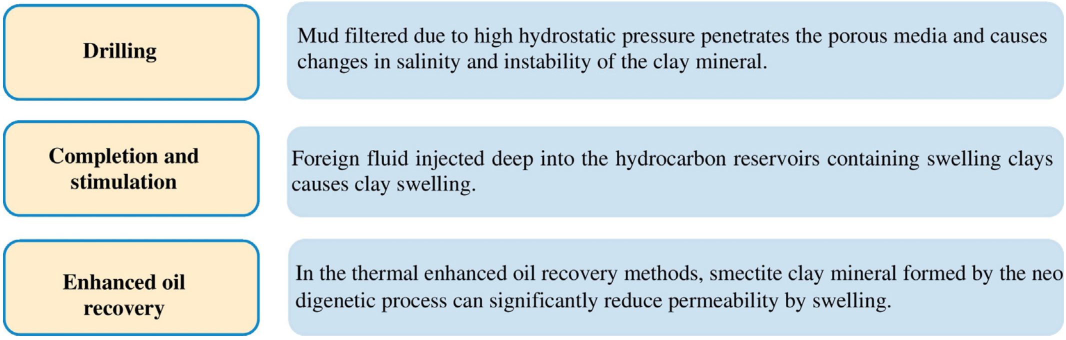

Drilling

Mud filtered due to high hydrostatic pressure penetrates the porous media and causes changes in salinity and instability of the clay mineral.

Completion and stimulation

Foreign fluid injected deep into the hydrocarbon reservoirs containing swelling clays causes clay swelling.

Enhanced oil recovery

In the thermal enhanced oil recovery methods, smectite clay mineral formed by the neo digenetic process can significantly reduce permeability by swelling.

Fig. 1. Formation damage due to clay swelling at different stages of development.

Somerton (1949) suggested that the lack of an effective water drive in several Californian reservoirs may be attributed to the high clay content of the reservoir sands.

Goldenberg et al. (1954) showed that a reduction in the static permeability due to the presence of the smectite group minerals led to a logarithmic reduction of total connectivity as a function of clay content.

Extensive laboratory studies by many researchers, including those by Norrish (1954), Foster (1954), Fink et al. (1968), Fritz and Max (1989), Zhang and Low (1989), Zhou et al. (1996) and Krishna Mohan et al. (1998), have concluded that clay swelling occurs by two mechanisms: crystalline swelling and osmotic swelling. Crystalline swelling occurs in all types of clay minerals, especially in the smectite group, as a result of hydration of cations located between the layers of clay. The hydration of cations by water increases the distance between the layers of clay. Mooney and Keenan (1952) observed this type of swelling in a laboratory study. Osmotic swelling is due to the exchange of cations between layers. If the cation concentration in the interlayer areas is higher than that in the water nearby, water molecules enter the area to dilute the concentration of cations and restore the cationic balance. Hence, the distance between layers of clay starts to increase and the clay swells. This type of swelling increases the volume more than crystalline swelling does.

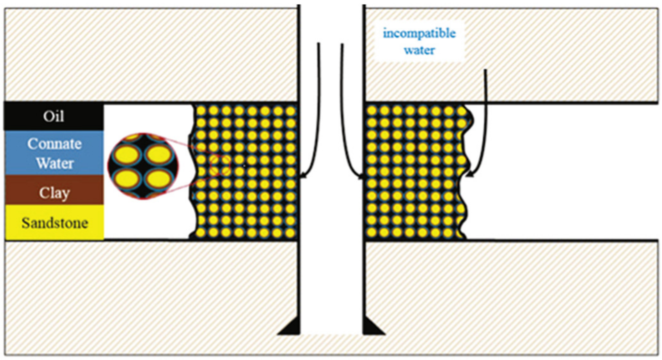

Fig. 2. Diagram of the damage caused by clay swelling in the reservoir and near the well.

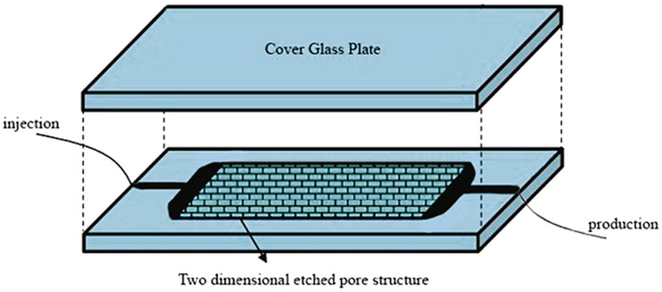

Fig. 3. Schematic of micromodel construction.

Ochi and Vernoux (1998) showed that clay swelling due to chemical effects leads to a greater reduction in permeability compared to hydrodynamic effects.

Davy et al. (2007) showed that the low connectivity in argillite sedimentary rocks containing large cracks during water movement is due to clay swelling.

Zhanxi and Huiqing (2013) studied the permeability reduction during steam injection in unconsolidated porous media. They observed that the injection of steam and condensate of low salinity irreversibly reduced the permeability by up to 43.52%. They showed that particle migration and hydrothermal reactions constitute the primary damage mechanisms.

Different core flooding tests, as mentioned in the above literature and many studies by other researchers such as those by Yuster (1945), Hughes and Pfister (1947) and Morris et al. (1959) have been done to investigate the effects of clay swelling on formation damage. However, the core flooding tests provide excellent insight into the response of clay swelling to fluid flow through the porous media, but they are something of a black box because visualization at the pore scale is not possible. Micromodels have been proven to be very practical and functional for studying essential and basic aspects of multiphase flow through porous media such as wettability (Grattoni and Dawe, 2003; Romero-Zeron and Kantzas, 2007), capillary pressure (Smith et al., 2005), and interfacial tension (Mackay et al., 1998). Various researchers utilized micromodels to analyse the detailed mechanisms and investigate the performance of different oil recovery techniques at pore scale including waterflooding (Wang et al., 2006) and carbonated water flooding (Kechut et al., 2010).

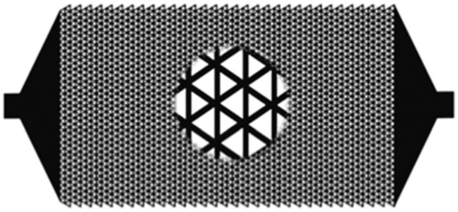

Fig. 4. Designed microporous pattern.

Table 1
Physical characteristics of the micromodel.

Length, L (mm)	150
Length, L (number of pores)	92.78
Width, W (mm)	80
Width, W (number of pores)	56.1
Pore volume (ml)	0.458
Porosity, Φ (fraction)	0.48
Coordination number	6