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Fines migration and compaction in diatomaceous rocks

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ABSTRACT

Reservoir rocks typically have clay and other fine material attached to pore surfaces. Fines mobilization is advantageous in that the removal of fines from pore walls exposes water-wet rock thereby aiding oil recovery. On the other hand, fines mobilization is deleterious if mobilized particles obstruct pore throats. In this work, waterfloods of diatomaceous cores up to 200 °C were conducted using field and outcrop samples to elucidate mechanisms of fines production at conditions potentially important to thermal oil recovery. Because the rock employed is also stress sensitive, it was necessary to also understand compaction in order to gauge any resulting changes in permeability. The effect of temperature on fines migration in situ was studied using time-lapse CT scanning and the resulting permeability reduction was measured and modeled. The temperature at which increased fines concentration is observed coincides with an increase in the range of oscillations of X-ray attenuation in an averaged area in the CT images. Permeability reduction of up to 80% was seen in some cases at high temperatures confirming the importance of temperature in the elution of fines. It was found that the permeability reduction is more sensitive to salinity and temperature in comparison to pH. Such modeling and experimentation provides guidance on appropriate mitigation strategies through completion or other methods.

Effluent brine analysis confirms that silica dissolution is an important factor in hot water or steam condensate movement with all of the tests indicating that silica dissolved in increasing quantities with increasing temperatures, even producing precipitates at 150–200 °C. Silica in solution leads to a general decrease in the effluent pH due to silicic acid. Ion exchange was also observed that is consistent with the Hofmeister series. Cations of large valency and smaller hydrated radii displaced cations resident in the rock.

The effect of confining pressure on permeability was investigated by repeated loading and unloading of outcrop cores at different intermediate pressures and temperatures. With increasing net effective stress, significant permeability degradation was observed with a noticeable acceleration at about 600 psia. Mercury porosimetry of damaged material indicates that changes may be due to pore collapse. Almost no permeability recovery was detected when the core was unloaded. Significant creep was observed with significant permeability reduction resulting from a constant applied confining pressure. Permeability reduction at a slightly smaller effective stress was observed for the high temperature cases but no significant material differences in the primary compaction curves were detected between 25 °C and 100 °C. Limited rebound suggests that the stress history of diatomites may be a significant factor in determining the degree of acceptable depletion in the field development planning for thermal operations.

1. Introduction

Diatomaceous Monterey formation reservoirs include Lost Hills, South Belridge, McKittrick, Midway-Sunset and Buena Vista. Diatomaceous rock is characterized by high porosity (40–60%) but low permeability (~1 mD) (Akin et al., 2000; Murer et al., 2000). Exploitation plans include vertical wells and tightly spaced horizontal laterals to implement steamflooding or cyclic steam injection. Depletion and subsequent injection processes alter the net effective stresses that exist in the field. Significant further potential is envisioned with the continuing and further development of these reservoirs that contain at least 10–12 billion barrels of oil in place (Ilderton et al., 1996). Thus, it is necessary to investigate the effect of temperature and stress on diatomites. Here, experiments are conducted to (1) visualize fines migration as a function of temperature, salinity, and pH using time-lapse CT scan imaging, (2) validate the permeability alteration that accompanies fines mobilization at varying temperatures and salinities, (3) model the permeability alteration as a function of temperature and salinity with a reduced physics model, and (4) measure permeability evolution as a function of net effective stress history.

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This paper proceeds with a literature review followed by a description of the apparatus and materials used. Experimental results are presented and modeled to gain additional insight. A discussion and conclusion complete the paper.

2. Literature review

Extensive field observations of produced sand/fines and decreased injectivity and numerous laboratory studies are present for the effect of temperature, pH, and salinity on fines migration and permeability evolution of sandstone reservoirs (e.g., Johnson et al., 1992). Generally, unfired sandstone cores exhibit a reduction in permeability with increased temperature and decreasing salinity when flooded with various brines (Mungan, 1965; Weinbrandt et al., 1975; Stottlemyre et al., 1981; Amaefule et al., 1984; Wei et al., 1986; Okoye et al., 1990; Schembre and Kovscek, 2005). Permeability decrease was mostly attributable to fines migration with clay swelling only a major contributor for cores with high smectite content (Mungan, 1965).

Diabira et al. (2001) found an almost instantaneous 60% drop in permeability of outcrop diatomite after forced imbibition of water began at elevated temperatures (80–121 °C) due to compaction, with slow permeability enhancement due to the dissolution of silica. Ikeda et al. (2007) further confirmed that spontaneous imbibition rates were accelerated by elevated temperatures due to a shift towards water wettability. Although permeability reduction of about 10% was observed, it did not affect the endpoint recoveries that increased with increasing temperature. It is assumed that the porosity increase of 5–30% offsets a greater decrease of permeability from fines migration.

Schembre et al. (2006a, 2006b) and Schembre and Kovscek (2005) implemented perhaps the most comprehensive investigation of the mechanism behind fines mobilization and wettability change as a function of temperature, accounting for factors that govern electrostatic surface forces that result in fines migration. It was confirmed that elevated temperatures decrease water relative permeability endpoints and residual oil saturation that are indicative of increasingly water-wet conditions. The type of oil was also found to affect the wettability state with clean mineral oil showing more water-wet behavior compared to crude oil. Significant differences were seen for diatomite rocks of different lithologies, with the Amott index to water being inversely correlated with the initial clay content.

Compaction and subsidence have been documented at field scale. Field-observed phenomena in Lost Hills and other California diatomite reservoirs show up to 30 ft of vertical displacement due to depletion from 1925 to 1977 (Bruno and Bovberg, 1992), with the subsidence linearly related to total fluid production from the center of the field. Diatomite compressibility, however, has been sparsely studied. Some authors (Bruno and Bovberg, 1992) have commented that diatomite deforms inelastically at almost all stress levels. The effect of loading and unloading on a diatomite reservoir is important because oil field operations can deplete the reservoir through production, increase the pore pressure by fluid injection or cyclically change the stress regime through cyclic steam injection. Large volumetric strains are attained prior to creep with deeper samples requiring larger stresses before the onset of pore collapse, presumably because they have already been reconditioned (Crawford et al., 2006). The same authors (Crawford et al., 2006) also observed accelerated pore collapse at high temperatures and lower unloading compressibilities, implying that thermal recovery may not reverse the effects of compaction.

The literature remains divided on the issue of compaction primarily due to uncertainty in the extent of Opal A to CT conversion (i.e., a transition from amorphous to microcrystalline silica rock phase). Thermal operations can stem the onset of subsidence due to the pressure support effects of injected steam. Dissolution of the rock may lead to pore collapse or more commonly argued, the transition from Opal A to CT leads to a denser rock matrix.

3. Experimental

Fig. 1 presents the apparatus for both fines migration and compaction experiments. The setup is similar to that used by Schembre et al. (2006a) and Ikeda et al. (2007). The core inlet is approximately at the center of the coreholder, allowing injected fluids to be heated at the set-point temperature. A backpressure regulator on the downstream end of the apparatus ensures the system pressure is above the water vapor pressure at the temperature set-point.

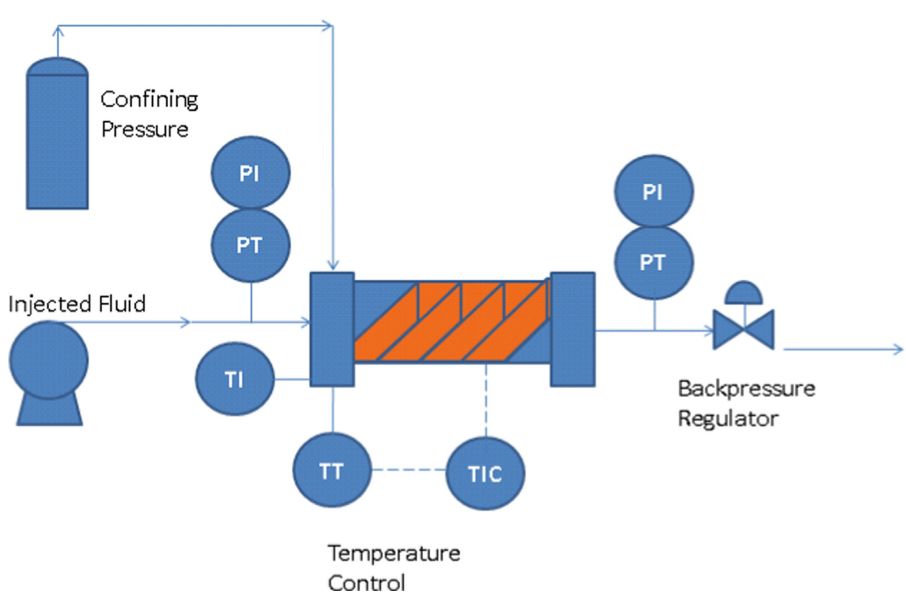

Fig. 1. Schematic of the core setup.