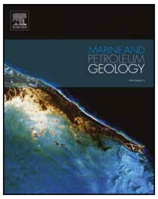
ARTICLE IN PRESS

Marine and Petroleum Geology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo



Research paper

# The variation mechanism of petrophysical properties and the effect of compaction on the relative permeability of an unconsolidated sandstone reservoir

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## ARTICLE INFO

*Keywords:*
Petrophysical properties
Relative permeability
Compaction
Unconsolidated sandstone

## ABSTRACT

This study investigated the influence of compaction on the variation mechanism of petrophysical properties and the relative permeability of unconsolidated sandstone. Firstly, triaxial mechanical experiments, CT scans, and mercury injection experiments were performed to analyze the microstructural characteristics and the macroscopic mechanism of changes in the petrophysical characteristics under different pressure. Secondly, a modified permeability test approach was adopted on reservoir cores in which a constant flow rate was maintained by changing the pore fluid pressure. The factors which affect the porosity and permeability of unconsolidated sandstone under compaction were investigated. Finally, two-phase displacement tests were performed to assess the influence of compaction on oil production. The results demonstrate that the porosity, permeability, and pore-throat size of loose sandstone are reduced with increasing compaction. Although the relative rigidity of the grains makes the reduction in porosity comparatively smaller, the permeability shows a sharp decline and the change is irreversible. The irreducible water saturation and residual oil saturation increase and the position of two-phase flow zone narrows with decreasing porosity and permeability. These changes act to weaken the percolation flow capacity and lead to a decline in oil-well productivity in areas where water injection is not timely or is insufficient. The understanding of compaction mechanism can be used to optimize the development of compacting reservoirs to take advantage of the compaction.

## 1. Introduction

The burden exerted by the upper strata of a reservoir is borne by the rock framework and pore fluid. Formation fluids are extracted continuously during depletion leading to pore-pressure reduction and large strain and plastic deformation of the reservoir rocks, with serious consequences such as reservoir compaction, subsidence, permeability and porosity damage, and reservoir impairment, which affect oil well productivity (Settari, 2002; Hettema et al., 1998; Hol et al., 2015). Although more than half of known oil and gas reserves are found in carbonates (Chilingar et al., 1972; Jiang et al., 2008), many wells have been drilled in sandstone reservoirs. Many reservoirs, such as those in the Bohai Sea, Gulf of Mexico, Athabasca (Canada), and the Tertiary reservoir of Indonesia, are in unconsolidated sandstone (Wong et al., 1997; Graham et al., 2003; Brignoli and DiFederico, 2004; Fortin et al., 2005; Dautriat et al., 2009; Crawford et al., 2011).

Several laboratory studies have focused on the compaction behavior of siliciclastic rock, mainly sandstones. Most previous studies had used conventional test methods to study the correlation between physical properties and the effective pressure by changing the confining pressure (Fatt and Davis, 1952; Shen, 1995). To understand variations in porosity better, the factors that affect sandstone porosity such as compaction, cementation, and grain size were studied (Schutjens et al., 1996; Houseknecht, 1989). Liu et al. (2006) investigated the effect of compaction on the properties of sandstone reservoir by the simulation experiments of compaction, and the results suggested that the porosity and permeability of feldspathic sandstone varied rapidly at first and then slowly during compaction. A new method has been proposed to predict the porosity with known surface porosity, mineral composition, and amount of sediment compaction (Lu et al., 2013). The influence of

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https://doi.org/10.1016/j.marpetgeo.2017.12.006
Received 22 September 2016; Received in revised form 4 December 2017; Accepted 4 December 2017
0264-8172/

Please cite this article as: Xiong, Y., Marine and Petroleum Geology (2017), https://doi.org/10.1016/j.marpetgeo.2017.12.006

the stress path on the mechanical behavior and coupled permeability evolution of unconsolidated sand and weakly consolidated sandstone were investigated by isotropic compaction tests and a new stress-sensitive simulator (Jin et al., 2000; Nguyen et al., 2014; Monfared and Rothenburg, 2016). Microscopic mechanical data and the stress-path dependency of permeability have been measured in the elastic, brittle, and compaction regimes. AlHomadhi (2014) obtained new correlations of permeability and porosity versus confining pressure, by varying factors such as compaction, cementation, grain size, and arrangement mode. Meanwhile there are divergent views on the influence of pressure on relative permeability. Ali et al. (1987) studied the influence of pressure on relative permeability and the conclusion was that with overburden pressure increasing, rock porosity and permeability reduced; irreducible water saturation and residual oil saturation increased, resulting in the reduction of relative permeability of sandstones. Gawish and Al-Homadhi (2008), Guo et al. (2012), Fang et al. (2015) obtained the similar conclusion of gas-water relative permeability with different pressure conditions. Huo and Benson (2016), Zhang et al. (2017) investigated the influence of temperature on the oil–water relative permeability for sandstone reservoirs, and the experimental results suggested that irreducible water saturation increased linearly, residual oil saturation decreased nonlinearly, and both oil and water relative permeability increased under the same water saturation with temperature increase. Kim and Lee (2017) reported the variation of relative permeability due to clay types and contents in low salinity water-flooding. Their studies indicated that the moving range of the relative permeability curve was proportional to the clay contents and end-point relative permeability curves could be determined by the proposed index.

Although a lot of work has been done, however, research on the variation mechanism of petrophysical properties and seepage characteristic with compaction has been relatively lacking, especially concerning variations in pore size distribution and micro-structural variation mechanism. Thus, it is important to obtain a systematic understanding of the variation mechanism of petrophysical properties and the effect of compaction on production capacity in unconsolidated sandstone reservoirs. In this paper, we tested sandstone samples from the Minghuazhen formation in Bohai Bay. The first part of this study considered rock triaxial mechanical experiments with three samples (1-1,1-2,1–3), computed tomography (CT) scanning the sample 2-1 before and after compaction and four groups of mercury injection experiments with four samples (3–1,3-2,3-3,3-4) to assess the evolutionary characteristics of the rock pore-throats as shown in section 3.1. Then an experimental study of high-permeability unconsolidated sandstone (4–1) by a modified testing method that employs changes in the pore pressure to study variations in petrophysical properties under compaction was researched as presented in section 3.2. Finally, the characteristics of oil–water seepage and their effect on oil well-productivity were explored with core 6–1 through routine tests under compaction as shown in section 3.3.

## 2. Experimental methodology and materials

### 2.1. Experimental setup

The triaxial mechanical experiments were carried out with a rock mechanics testing system (RTR-1000). The main elements of this equipment were a triaxial cell, an axial compression system, a confining pressure system, an automated data acquisition and the control system. The CT scanning was conducted with a MicroXCT scanner and the main elements were a X-ray source, a sample holder, a X-ray detector, and a workstation for data storage and processing. The mercury experiment used a GS-1 mercury porosimeter, including a core chamber and a metering pump.

The displacement experiments were conducted with a high-pressure, 2.54 cm core holder. The main elements were a syringe pump, core holder, transfer cylinder for injecting oil and formation water, confining pressure pump, temperature controller and pore-pressure pump as well as a data acquisition system for the accurate recording of pressure across the core holder, and an electronic balance with high precision (Fig. 1). The differential pressure transducer is an important part for permeability measurement. There were two drainage ports at each end of the specimen, which allowed the direct measurement of differential pressure across the specimen with the differential pressure transducer, avoiding errors due to loss of pressure head in tubing.

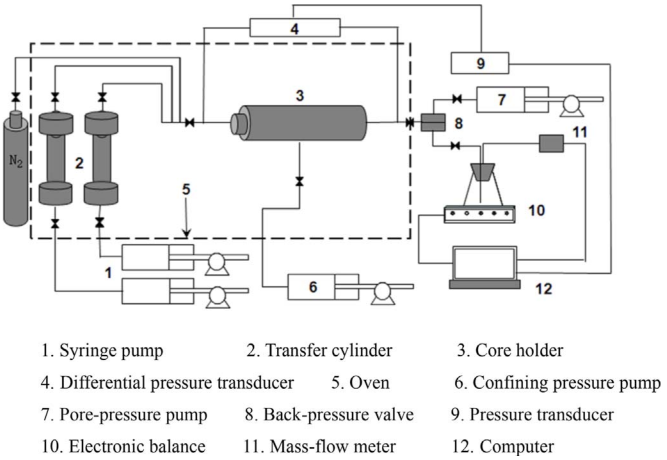

**Fig. 1.** Schematic diagram of the equipment for the displacement experiments including petrophysical property test and two-phase displacement test.

### 2.2. Rock and fluid properties

The reservoir was buried at a depth from 900 to 1500 m relative to the sea surface and the samples were from the Neogene Minghuazhen formation in Bohai Bay at the depth of 1282–1491 m. Rock density varied from 1.56 to 1.81 g/cm$^3$ and average value was 1.65 g/cm$^3$. Using X-ray diffraction(XRD), the sandstone was composed of quartz, feldspar, clays, dolomite and calcite as shown in Table 1. From thin sections, the reservoir lithology was mainly well-sorted lithic feldspar sandstone, comprising of subrounded–subangular grains (Fig. 2). Fig. 3 showed that the interstitial material was mainly clay minerals dominated by montmorillonite (range 45–94%), kaolinite (range 3–51%), and illite (range 1–20%), respectively. Point contact was observed apparently between particles in thin sections and SEM images. The cemented type were mainly porous cementation and contact cementation and the adglutinate was mainly clay minerals, which indicated that the particles were weak cemented. Meanwhile cementation of the rock could be described by cementation index, which is calculated with Archie's formula (Archie, 1942). Cementation index is referred to as the exponent on porosity in the porosity-formation factor relationship measured by a LCR meter. The average value of cementation index was about 1.41 which showed the rock was mainly weak and extremely weak cementation (Fig. 4).

The experimental samples were unconsolidated sandstone with favorable petrophysical properties as listed in Table 2. The porosity was measured from both weighing and gravity saturation ranged from 25% to 45%. The absolute permeability was measured by an air permeameter and a mass flow meter, determined with Darcy formula varied from 500 to 4000mD. Fig. 5 revealed the samples contained a certain elastic deformation zone of A, an elastic–plastic deformation area of B and a plastic deformation zone of C. Generally speaking, unconsolidated sandstone has the characteristics of poor cementation, loose structure and low compressive strength.

The water phase for all experiments was distilled water, $NaHCO_3$ and other salts with a low salinity of 6000 mg/L, consistent with the properties of the formation water as listed in Table 3. The major