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Effect of clay minerals on the effective pressure law in clay-rich sandstones

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ABSTRACT

The relative sensitivity of permeability to pore fluid pressure P_p and confining pressure P_c of rocks can be expressed as the effective pressure coefficient n_k. To investigate the effect of clay minerals on n_k, permeability data were measured in clay-rich sandstones under conditions of lowering P_p at different constant-confining pressures, and the effective pressure coefficients were subsequently calculated using a method based on our observation that the effective pressure law was linear. The values of n_k in I/S-sandstones and chlorite-sandstone agreed with the clay shell model, while the values of n_k in kaolinite-sandstones were consistent with the clay particle model. However, the n_k values of our kaolinite-sandstones were less than 1.0, which is different from previous observations showing n_k greater than 1.0. The n_k value of our I/S-sandstone saturated with formation water was greater than 1.0, consistent with the previous results, but the n_k value of our I/S-sandstone saturated with dried nitrogen was lower than 1.0. Thus, the coefficient n_k was affected by the type of clay mineral, the preparation of the samples, and the type of the pore fluid.

1. Introduction

This study is a continuation of the study of Zhao et al. (2011), which aimed at further understanding the effects of clay minerals on the effective pressure law (EPL) for permeability in clay-rich sandstones. Usually, the EPL can be written in the following form (Bernabé, 1986, 1987; Al-Wardy and Zimmerman, 2004; Zhao et al., 2011; Li et al., 2009, 2014):

$$P_{eff} = P_c - n_k P_p \tag{1}$$

where $P_{\rm eff}$ is the effective pressure, $P_{\rm c}$ is the confining pressure, $P_{\rm p}$ is the pore fluid pressure and n_k is the effective pressure coefficient for permeability. The advantage of the effective pressure concept is that it is simpler to use one single variable ($P_{\rm eff}$) instead of two independent variables ($P_{\rm c}$ and $P_{\rm p}$). Thus, applications of the EPL have been widely discussed (Robin, 1973; Shafer et al., 2008; Ghabezloo et al., 2009; Li et al., 2014).

The effective pressure coefficient n_k for permeability in clay-rich sandstone is commonly reported to be greater than 1.0 and to increase with the increase in clay content (Zoback and Byerlee, 1975; Nur et al., 1980; Al-Wardy and Zimmerman, 2004; Shafer et al., 2008; Zhao et al., 2011). This behaviour has been explained with different microstructural models, such as the clay shell model (Zoback and Byerlee, 1975), the clay particle model (Al-Wardy and Zimmerman, 2004) and the “two-constituent porous medium” model (Berryman, 1992). It was also found that the clay particle model and the “two-constituent porous medium” model were in somewhat closer agreement with previous experimental observations. However, the change of the coefficient n_k with clay content in kaolinite-sandstones, which were tested with oil, brine or distilled water (Zoback and Byerlee, 1975; Nur et al., 1980; Al-Wardy and Zimmerman, 2004), was different than the change in I/S-sandstones tested with nitrogen (Zhao et al., 2011; I/S: mixed layer illite/smectite). This phenomenon may be attributed to the different types of clay minerals in the rocks or the different pore fluids, or to a combination of these.

To further study the effect of clay minerals on the effective pressure coefficient n_k, permeability measurements were carried out in five clay-rich sandstones subjected to cycles of confining

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Table 1
The properties of the tested sandstones.

Sample	Depth (m)	φ (%)	k_a (mD)	F_c (%)
263-1	2097	8.65	0.143	29.2
31a-6	2047	11.09	0.366	8.70
103-1	2146	6.99	0.171	19.2
5-17	2446	6.80	0.200	15.5
373-2	2390	8.40	0.131	23.6

pressure and pore pressure with different types of pore fluids, and then the experimental data were analysed using a simplified method to obtain the values of n_k. The present and previous results demonstrated that the values of n_k had different relationships with the clay content when the sandstones had different types of clay minerals or were tested with different types of pore fluid.

2. Materials and measurements

2.1. Rock samples

In our study, five clay-rich sandstone cores, which were flushed and dried to remove the hydrocarbons, were used. The porosity φ and representative permeability k_a (at P_c equal to 2.75 MPa; P_p equals the atmospheric pressure) are reported in Table 1. These rocks were fine-medium feldspathic detritus sandstones without fractures or microcracks (see Fig. 1). On the basis of X-ray diffraction analysis, the clay content F_c ranged from 8.70% to 29.2%. Moreover, the weight percentage of each clay mineral in only sample 373-2 was identified, and we found that I/S was the main clay mineral (I/S: 56%; illite:15%; Kaolinite:5%; Chlorite:14%; C/S:10%. For the other four samples, nothing remained for further analysis). From SEM micrographs, four types of clays were observed, mainly foliaceous chlorite in sample 31a-6, fibrous I/S and illite (I) in samples 263-1 and 373-2, and book structure kaolinite (K) in samples 103-1 and 5-17 (Fig. 2). Additionally, when these sandstones were saturated with different pore fluids (①dried nitrogen, ②formation water [15,438.8 ppm $CaCl_2$, 1236.1 ppm $MgCl_2$, 790.3 ppm $NaHCO_3$, 248.5 ppm Na_2SO_4, 22,086.6 ppm NaCl, 5321.5 ppm HCl], ③distilled water), no appreciable changes in kaolinite or chlorite (C) could be detected, but the edges and corners of I/S with formation water or distilled water were not sharp, showing that I/S tends to grow thicker with these than with dried nitrogen (see Fig. 3).

2.2. Experimental procedure and data

We used the pulse decay technique to perform the permeability measurements with pore fluids of dried nitrogen gas (samples 103-1, 5-17 and 373-2) and formation water (samples 263-1 and 31a-6). The pulse decay technique was described by Brace et al. (1968) and Jones (1997). When the pore fluid was nitrogen, the permeability data were calculated with Jones' method (1997). Nitrogen pressure was larger than 5 MPa so that the Klinkenberg corrections could be neglected (Li et al., 2009, 2014). When the pore fluid was formation water, the permeability data were calculated by using the method of Brace et al. (1968).

To obtain the effective pressure law for permeability, permeability measurements were carried out with cycling procedures similar to those in Al-Wardy and Zimmerman (2004) and Li

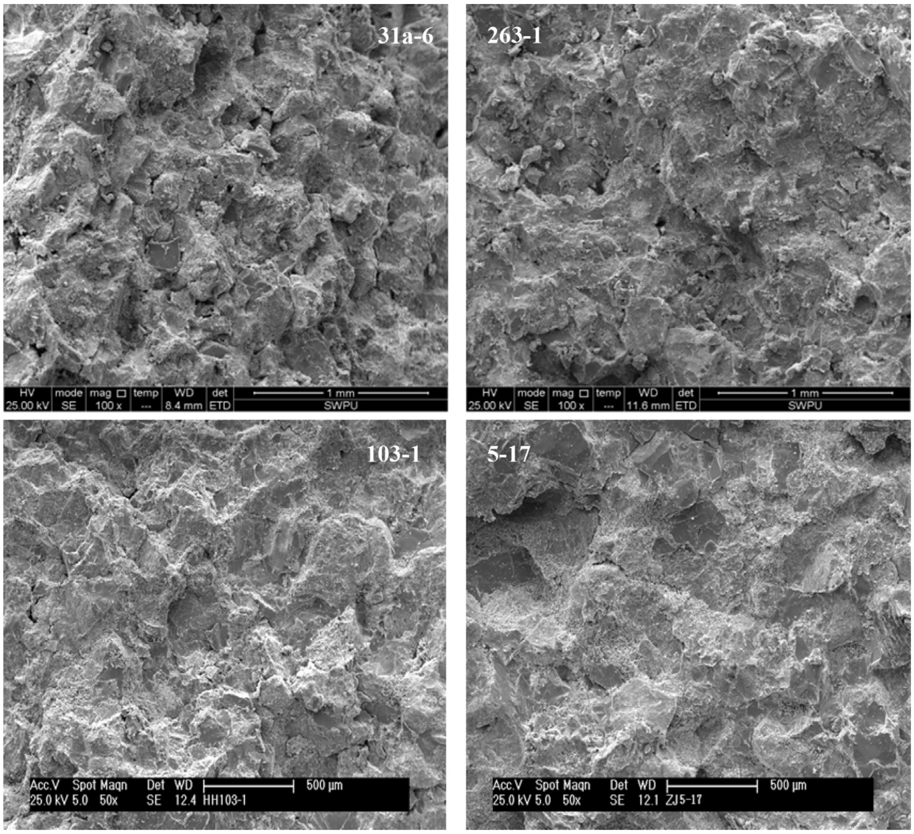

Fig. 1. Examples of SEM micrographs showing that there are no fractures or microcracks in our sandstones.