PS Permeability Anisotropy in Mudstones - An Experimental Study*

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Abstract

Mudstone permeability is critical for fluid flow modelling, pore pressure prediction, top-seal evaluation of hydrocarbon traps and CO_2 storage reservoirs and optimal production of shale gas. This study investigates permeability heterogeneities and anisotropy in well characterized synthetic mudstones. A total of 9 brine-saturated synthetic mudstones of varying textural and mineralogical compositions were compacted mechanically in a triaxial cell (K_0-test) while the vertical (K_v) and horizontal (K_h) permeability were measured at different stress levels. The samples were mixtures of known amounts of smectite, illite, kaolinite and silt-sized quartz grains. The results show that both the vertical and horizontal permeabilities of synthetic mudstones vary significantly as a function of clay mineralogy, grain size and the amount of silt in silt-clay mixtures. The vertical and horizontal permeabilities of all synthetic mixtures differ by a factor of 104 at the same stress level. Silt mixture has the highest permeability compared to other mixtures while clay-rich samples with dominantly kaolinite have relatively higher permeability than those with illite and smectite. The K_v/K_h ratio is used to quantify the permeability anisotropy. Pure silt has isotropic permeabilities but about 30% clays in silt mixture strongly reduced the permeability and increased the anisotropy. The highest K_v/K_h ratio of >1.6 is observed in a silt-illite (70:30) mixture whereas the minimum K_v/K_h ratio of <0.4 is observed in a silt-smectite mixture (70:30). The K_v/K_h ratio in illite-kaolinite (30:70, 50:50 and 70:30) and illite-silt (50:50 and 70:30) mixtures varies from 0.4 to 0.8 and 0.8 to 1.2, respectively, demonstrating the importance of different clay minerals, grain size and silt content on permeability anisotropy development in mudstones. Overall the experimental results show that the anisotropy produced by mechanical compaction alone is rather small but significant. Natural mudstone may have much higher permeability anisotropy than found in this study due to a more extensive primary depositional lamination formation than produced in the compaction experiments and also from chemical compaction. The use of permeability distributions and vertical-to-horizontal permeability ratios (K_v/K_h) derived in this study can readily be tested on cap rocks and shale gas reservoir models at relatively shallow depth where mechanical compaction is the dominant process.

References

Mondol, N.H., 2009, Porosity and permeability development in mechanically compacted silt-kaolinite mixtures: SEG Extended Abstract 2139-2143.

Mondol, N.H., K. Bjørlykke, J. Jahren, 2008, Experimental compaction of clays: Relationship between permeability and petrophysical properties in mudstones: Petroleum Geoscience, v. 14, p. 319-337.

Yang, Y. and A.C. Aplin, 1998, Influence of lithology and compaction on the pore size distribution and modelled permeability of some mudstones from the Norwegian margin: Marine and Petroleum Geology, v. 15, p. 163–175.

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1. Introduction

Mudstone permeability is critical for fluid flow modelling, pore pressure prediction, top-seal evaluation of hydrocarbon traps and CO_2 storage reservoirs and optimal production of shale gas (Mondol, 2009; Yang and Aplin, 1998). This study investigates permeability heterogeneities and anisotropy in well characterized synthetic mudstones.

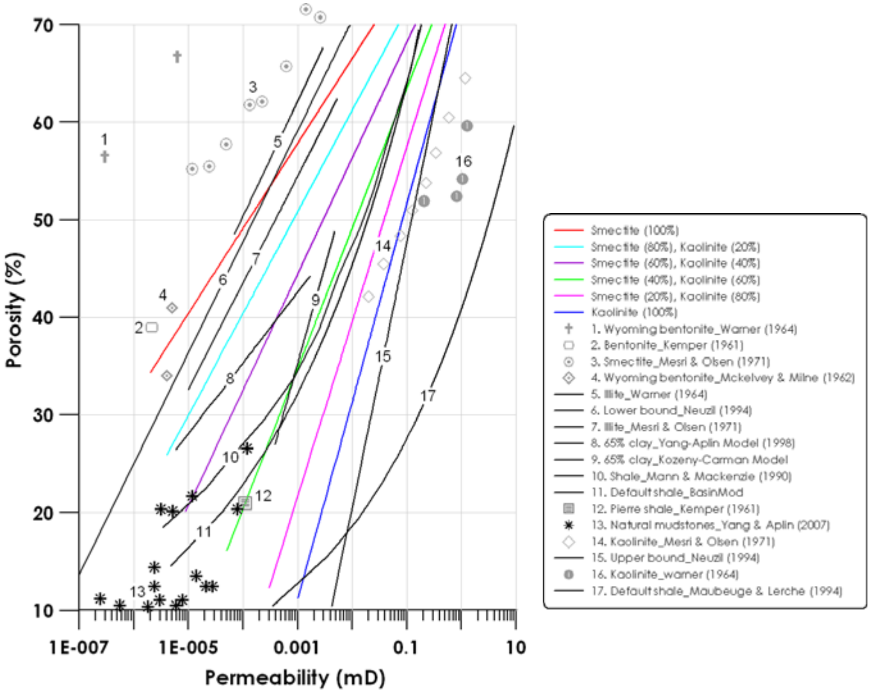

Fig. 1. Published porosity-permeability trends for natural and synthetic mudstones and shales. An enormous variations of permeability is observed in mudstones and shales where smectitic mudstones have significantly lower permeability compared to kaolinitic mudstones at the same porosity level (adapted from Mondol et al. 2008).

2. Materials and Methods

A total of 9 brine-saturated synthetic mudstones of varying textural and mineralogical compositions were compacted mechanically in a triaxial cell (K_0-loading) while the vertical (K_v) and horizontal (K_h) permeabilities were measured at five different stress levels. The samples were mixtures of known amounts of smectite, illite, kaolinite and also silt-sized quartz grains.

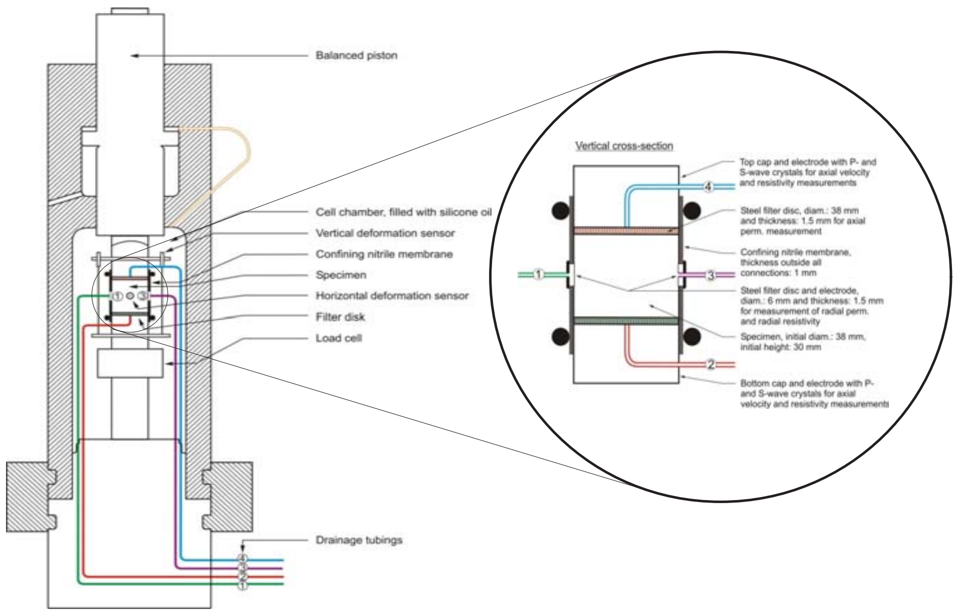

Fig. 2. Vertical cross section of a triaxial cell and schematic drawing of specimen with end cap and confining membrane. A vertical close-up view of specimen with filters, sensors and tubings for lateral and vertical drainage is also shown.

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3. Numerical simulation for calculation of κ_h

The main purpose of performing numerical analysis was to be able to find an equivalent radius of a cylinder defining the average 3D flow field between the filters. When the filters are smaller than the sample diameter, a 3D flow pattern will develop. The highly permeable and conductive filter will affect the 3D flow pattern to some degree dependent on size, permeability and conductivity of the filters. Also the 3D flow field is dependent on size of specimen (diameter and radius), direction of flow (axial or radial) and permeability anisotropy in the material.

Table 1. Overview of the varied parameters in the simulations.

ID	Filter Diameter		Sample Geometry		Permeability	Conductivity
	Vertical	Horizontal	Diameter (mm)	Height (mm)	κ_v/κ_h	(Filter)
a	38.2	5	38.2	30	1	10000
b	38.2	5	38.2	30	0.5	10000
c	38.2	5	38.2	24.5	1	10000
d	38.2	5	38.2	24.5	0.5	10000
e	10	5	38.2	30	1	10000
f	10	5	38.2	30	0.5	10000
g	10	5	38.2	24.5	1	10000
h	10	5	38.2	24.5	0.5	10000

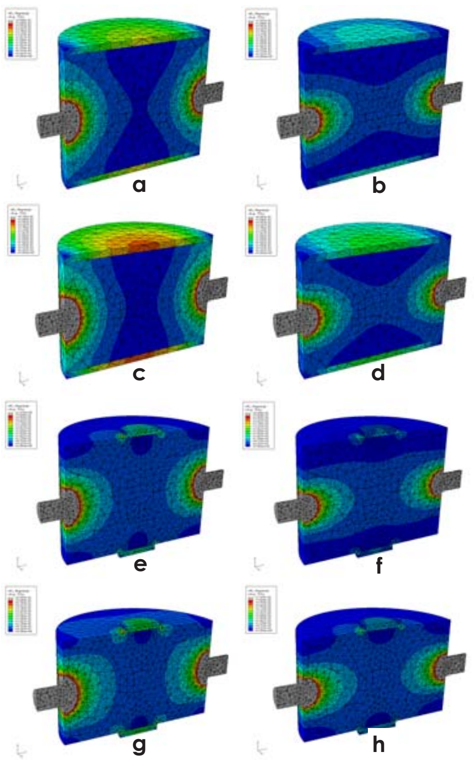

Fig. 3. Contour plots of the heat flux per unit area of the varied parameters in the simulations. Detail information given in Table 1.

4. Results

4.1 Stress-permeability relationships

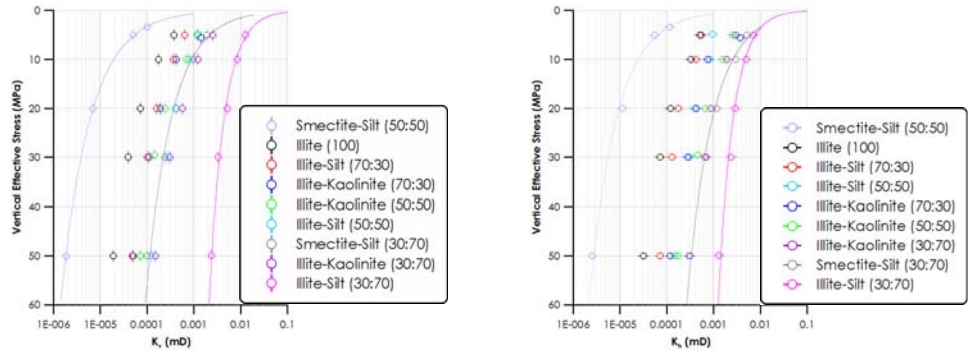

Fig. 4. Cross plots of vertical (K_v) and horizontal (K_h) permeabilities of **nine** mechanically compacted, well characterized synthetic mudstones as a function of vertical effective stress where type and distributions of clays play significant role for permeability development.

4.2 Permeability anisotropy

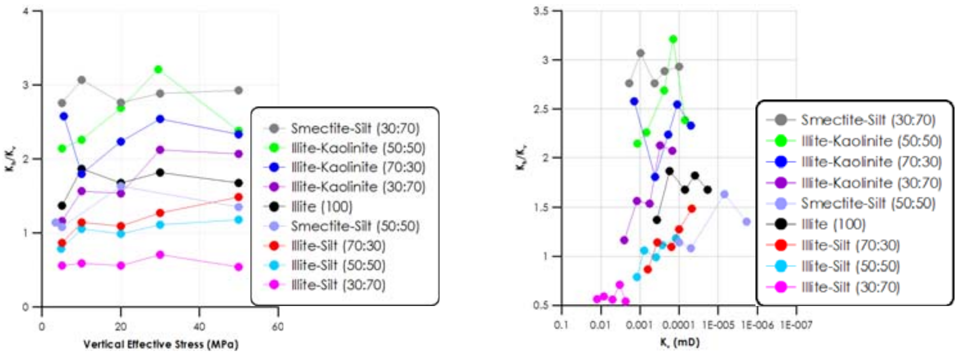

Fig. 5. Cross plots of permeability ratio (K_h/K_v) versus vertical effective stress (left) and permeability ratio versus vertical permeability (right) where the distribution of clays and their mineralogy show clear influence on permeability anisotropy in synthetic mudstones. Different degrees of stress sensitivity on permeability anisotropy are observed in the different samples.

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4.3 Porosity-permeability relationships

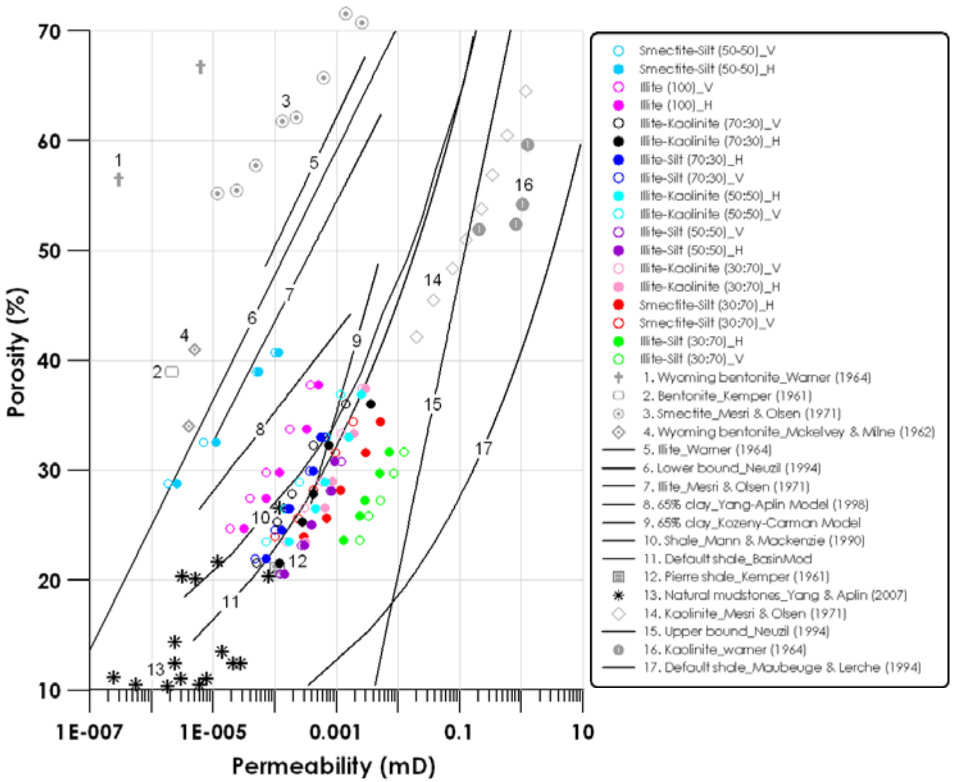

Fig. 6 A comparison of published porosity-permeability relations of a series of natural and synthetic mudstones and shales and experimentally compacted porosity-permeability trends of 9 recently prepared, well characterized, brine-saturated synthetic mudstones (modified after Mondol et al. 2008).

5. Conclusions

Our study shows that the anisotropy produced by mechanical compaction alone is rather small but significant. Natural mudstone may have much higher permeability anisotropy than found in this study due to a more extensive primary depositional lamination than produced in the lab experiments and also from chemical compaction. The K_h/K_v ratios derived here can readily be tested on cap rocks and shale gas reservoir models at relatively shallow depth where mechanical compaction is the dominant process. However, the results can be valid at greater depths in sedimentary basins with low geothermal gradients where compaction will mostly be mechanical down to 4-6 km depth.

6. References

Mondol, N.H. (2009). Porosity and permeability development in mechanically compacted silt-kaolinite mixtures, SEG Extended Abstract, 2139-2143.

Mondol, N.H., Bjørlykke, K., Jahren, J. (2008). Experimental compaction of clays: relationship between permeability and petrophysical properties in mudstones. Petroleum Geoscience, 14, 319-337.

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