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Relationships among Porosity, Permeability and Seismic Velocity of Shales

N.H. Mondol* (University of Oslo & NGI)

SUMMARY

This study focuses on relationships among porosity, permeability and seismic velocity of shales. A total of thirty well characterized, brine-saturated (35000 ppm NaCl) synthetic shale of varying textural and mineralogical compositions were compacted mechanically both in triaxial and oedometer cells under controlled pore pressure and proper drained conditions. Results show that kaolinite dominated shales compact more but have higher permeability and seismic velocity compared to smectite dominated shales at same stress/depth. Permeability differs a maximum five orders of magnitude at the same porosity for different shales. For velocity-permeability relationship between kaolinite- and smectite-dominated shales, a maximum four orders of magnitude are observed. Velocity/porosity can therefore not be good proxy to estimate reliable permeability in shales. Comparison of experimental and published data show a good agreement and illustrated that a better understanding of mineralogical and textural relationships can be significantly improved to establish relationships among porosity, permeability and seismic velocity of shales. In addition to the existing database, the new experimental data (this study) can improve the calibration of fluid flow modeling, seismic and well-log interpretation and evolution of shale rock properties. The experimental results may also be of importance for structural design, slope stability analysis and waste disposal efforts.



Introduction

Shales are the most abundant lithologies and fill 70-80% of the world's most sedimentary basins. The permeability of shales and its relationships with porosity and velocity are thus fundamental to quantify a range of geological processes and geo-engineering applications such as (a) fluid flow modeling and the development of overpressure; (b) top seal evaluation of hydrocarbon traps, radioactive waste disposal and storage of CO₂; (c) optimal production of shale gas; (d) subsurface geological processes, such as erosion and flow slides and (e) evaluation of foundation settlement and landfill liner design. This study focuses on relationships among porosity, permeability and seismic velocity of natural and reconstituted shales. New experimental data in addition to literature data analyzed to establish the relationships. A series of experimental mechanical compaction tests of brine-saturated synthetic shales (sand-silt-clay mixtures) performed at various effective stresses. The well-characterized synthetic shales represent known amount of sands, silts and clays and provided well-defined rock compositions that help to constrain the porosity-permeability-velocity relationship in shales.

Materials and methods

A total of thirty well characterized, brine-saturated (35000 ppm NaCl) synthetic shales of varying textural and mineralogical compositions were compacted mechanically both in a triaxial cells (Ko-loading) and a high stress uniaxial oedometer under controlled pore pressure and proper drained conditions. The samples were mixtures of known amounts of smectite, illite, kaolinite and also silt-sized quartz grains. All experiments were performed at room temperature, which was between 190C and 210C. Uniaxial strain condition was obtained by controlling the triaxial cell oil pressure directly applied onto the specimen enclosed in a rubber membrane so that no radial strain occurs. The rate of strain was adjusted so that excess pore pressure at the undrained bottom should preferably not exceed about 7% of the effective stress at top of the specimen. Porosity reduction, density variations, vertical and horizontal velocities (both Vp and Vs) and vertical and horizontal permeabilities were measured at different stress levels during progressive compaction from 0 to 50 MPa.

Results and discussion

Results show that kaolinite dominated shale compact more and possess higher density, permeability and velocity than smectite dominated shale at same stress level. The differences of porosity, permeability and velocity are relatively small at low stresses but increase drastically with increasing effective stress. Permeability differs over a range of 5 orders of magnitude at the same porosity for different shales (Fig. 1). The fact that kaolinitic shales may have permeabilities that are several orders of magnitude higher than smectitic shales should be considered when evaluating shales as source/reservoir/seal for hydrocarbon exploration. Applications of the Kozeny-Carman equation, relating porosity to permeability in shales, would therefore produce highly erroneous results. Furthermore, laboratory investigations demonstrate that the smectite content is critical to build up overpressure in shales and reduce the permeability in cap rocks and gas shales. For relationships between velocity and permeability in kaolinite and smectite dominated shales, maximum differences up to a 4 orders of magnitude were observed. Velocity and porosity can therefore not be useful to estimate reliable permeability of shales without knowing mineralogy and textural relations. The dependence of Vp on permeability for a wide range of synthetic mudstones is indeterminable due to a large scatter. When the samples are grouped into identical porosities



the scatter is reduced and Vp increases with decreasing clay content. The effect is attributed to both porosity reduction and clay mineralogy. The magnitude of intrinsic velocity anisotropy is particularly high in compacted, low-porosity kaolinite dominated shales compared to their high-porosity equivalents caused by rearrangement of clay particles due to higher stress. Laboratory investigation also shows that the shale rock properties depend not only on the strength of the sediment particles (mostly clay minerals), but also on their surface properties and chemical bonds which are controlled by the composition of the pore fluids.



Figure 1 A comparison of published porosity-permeability relations of a series of natural mudstones, uniaxially compacted remoulded mudstones (Mondol et al. 2008) and triaxially compacted synthetic mudstones (this study).

Conclusions

Shales should not be treated as single lithology in connection with basin analyses, seismic interpretation and well log analysis, but in reality, they span a wide range of properties determined by the diversity of mineral composition and grain-size distribution. Permeability of shales varies greatly as a function of primary textural and mineralogical composition and it is nearly impossible to accurately predict the effective permeability of a sequence of shales forming flow barriers. Shales permeabilities are also direction dependent, with higher values usually parallel to bedding. This phenomenon reflects two factors: particle alignment and material heterogeneity. Material heterogeneity relates primarily to sediment deposition (e.g. provenance and depositional environments) and is most obviously linked to conditions leading to the formation of sand-silt-clay lamination. Data from this experimental study can simulate mechanical compaction. However, in cold basins with low geothermal gradients, it could be useful at greater depth.