Geophysical Research Abstracts
Vol. 20, EGU2018-11968, 2018
EGU General Assembly 2018
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3D Microstructures and Fracture Properties of Kimmeridge Shale

Waruntorn Kanitpanyacharoen (1) and Lowell Miyagi (2)

(1) Basin Analysis and Structural Evolution STAR, Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok, Thailand (waruntorn.k@chula.ac.th), (2) Department of Geology and Geophysics, University of Utah, Salt Lake City, UT, USA (lowell.miyagi@utah.edu)

Seismic anisotropy in shale is mainly controlled by the preferential alignment of constituent clay minerals. Preferred orientation is also known to cause fracture anisotropy, which can affect mechanical properties such as fracture toughness and fracture orientation. Despite the extensive studies of shale characteristics, there is little information about microstructures, mineral orientation, and fracture properties of shale during the fracturing process. This study thus aims to investigate microstructual and mechanical changes of Kimmeridge Shale from the North Sea by using advanced synchrotron X-ray techniques to simulate the fracturing process at high pressure and temperature conditions. The large deformation apparatus (D-DIA) in conjunction with synchrotron X-ray diffraction is used to deform a shale sample to 240 MPa while simultaneously heated to 100 ºC, continuously collecting diffraction and radiography images. The sample is mainly composed of quartz (33%), illite-group clays (53%), kaolinite (7%), pyrite (5%), and other minor minerals (2%). Mineral volumes remain fairly constant throughout the experiment except for that of illite-smectite, which gradually decreases due to dehydration from heating. Illite-mica and illite-smectite (2.3 - 4.4 m.r.d.) exhibit much weaker degrees of mineral alignment that those of kaolinite (5.4 - 7.3 m.r.d.) due to their poorly ordered structures and small grain sizes. Illite-smectite being the most dominant phase accommodates the majority of the strain and thus has the highest differential stress (2 - 3 GPa) and largest texture change. In addition, synchrotron X-ray microtomography is used to document 3D fracture orientations, porosity, and organic materials before and after deformation experiments. The geometry and distribution of micropores change substantially from mostly rounded and scattered in the sample to mostly elongated and aligned parallel to subparallel to the horizontal bedding plane. Microporosity decreases from 3.3% to 1% due to the closure of pre-existing microcracks and the development of new microcracks. Organic content also decreases from 14.8% to 10% due to heating, which further enhances the growth of microcracks. Microfractures become most prominent (2.3%) during decompression and align oblique to the bedding plane. The average fracture angle oblique to the direction of the major principal stress of the Kimmeridge Shale is approximately 26º±3º, which is within the boundary of the Mohr-Coulomb criterion prediction of homogeneous rock at 33º. The development of microfractures and mineral alignment further influences anisotropy of physical properties such as permeability, which increases from <0.1 mD to 9.3 mD.