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Consolidation and mass transport properties of the Nordland Shale

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The carbon dioxide (CO2) injection at the Sleipner field, in the North Sea, is the first industrial scale CO2 injection project designed specifically to mitigate greenhouse gas emissions. While unlithified plastic clays are considered as good candidate seals for CO2 containment, time-lapse seismic data from the Sleipner project indicates a vertical migration of CO2 through a number of clay layers. To investigate possible mechanisms controlling gas flow in such unlithified sediments, a caprock sample from the Sleipner site was subjected to a series of hydraulic, consolidation, and gas injection tests. The results have been interpreted using numerical models and critical state theory to obtain estimates of the deformation and mass transport properties of the material.

After hydraulic flow testing of the sample, a consolidation phase was carried out, involving stepwise loading, rebound and reloading of the sample. The resultant irreversible strains observed are strongly indicative of deformation in the over-consolidated domain. A general trend of decreasing permeability with increasing effective stress was observed. The gas entry, breakthrough and capillary threshold pressures of the material were established for nitrogen. A progressive increase in gas permeability was observed throughout the test history, which may be explained by the formation of transient flow pathways as suggested by Harrington et al. (2009). Such behaviour is consistent with the findings of Angeli, et al. (2009), who observed physical property changes indicative of CO2 flow along defined pathways within shale. Comparison of results with those of previous studies also suggests that small changes in the compaction state of the clay have relatively minor effects on gas entry and breakthrough pressure, but may significantly alter the apparent permeability of the clay.

In addition, the pre-consolidation pressure was estimated using two well established methods. The critical stress approach provides an idea of the deformation expected for a given stress field, by defining a yield envelope in the mean effective stress (p') versus differential stress (q') space. The pre-consolidation stress can be approximated as the closure point of this yield surface. The results of this study indicate that field stress data may plot outside the failure envelope. We suggest that this inconsistency between data sets may be due to local variations in the stress field. Our results suggest that thin interbedded layers of clay, like those found in the Utsira reservoir, may exhibit a range of stress conditions due to differences in their physical properties and may be closer to failure than others as a result. Perturbation caused by super-critical CO2 injection could result in the failure of just some of these layers. Further detailed critical state analysis, based on laboratory studies, is essential to examine the validity of this tentative hypothesis. For a proper assessment of the safe operating limits of any reservoir, quality data is required in order to determine the critical state surface and the stress state of the caprock.

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