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A Calibrated Model for the First Decade of the Sleipner CO_2 Plume Development

Andrew J. Cavanagh[1, 2] and R. Stuart Haszeldine[2]

1) The Permedia Research Group, Ottawa, Canada
2) The University of Edinburgh, Edinburgh, Scotland

The Sleipner experiment, offshore Norway, is the world's first and largest saline aquifer storage site for industrial CO_2. 10 Mt of injected CO_2 has ascended and ponded beneath a number of flow barriers over the decade 1996-2006. The observed plume remains trapped beneath the caprock of Nordland Group mudstones and within the Utsira sandstone aquifer, approximately 800 meters below sea level. Six seismic reflection surveys over the last decade ('99, '01, '02, '04, '06, '08) clearly portray the emergence and spreading of nine principal layers. However, a mass balance for the plume has eluded observers due to the resolution limits of remote geophysical observations with respect to layer thickness.

The observed injection rate and ascent rate favours capillary-dominated flow as the probable migration mechanism. The 'pancake stack' distribution of layers and apparent breaching of multiple, laterally extensive mudstone barriers can be accurately modelled using an invasion percolation simulator. We present the first calibrated 3D flow simulation of the Utsira plume. The model quantifies the relationship between mass balance and CO2 layer thickness (a critical uncertainty in the remote geophysical monitoring of carbon sequestration), and provides an accurate mass balance for the only complete set of published plume data (CO2 layer mapping circa 2002, published circa 2008). Extremely low buoyancy pressures (50 kPa) are required to breach the barriers vertically and calibrate the model to the observed plume distribution. We infer that the mudstone barriers within the Utsira sandstone storage site have been microfractured, and do not act as seals. We quantify the inferred microfractures within the reservoir, and presents a novel hypothesis for their origin: a brief and intense episode of overpressure related to Pleistocene ice sheet melting.

The unusual behaviour of the intra-formational barriers is thought to differ from the mudrocks of the overlying Nordland Group caprock where published laboratory tests indicate much higher threshold pressures (4 MPa). We therefore infer that CO2 loss by seepage through the caprock has not occurred. We interpret published underestimates and overestimates of mass in place as predominantly a function of layer thickness assumptions.

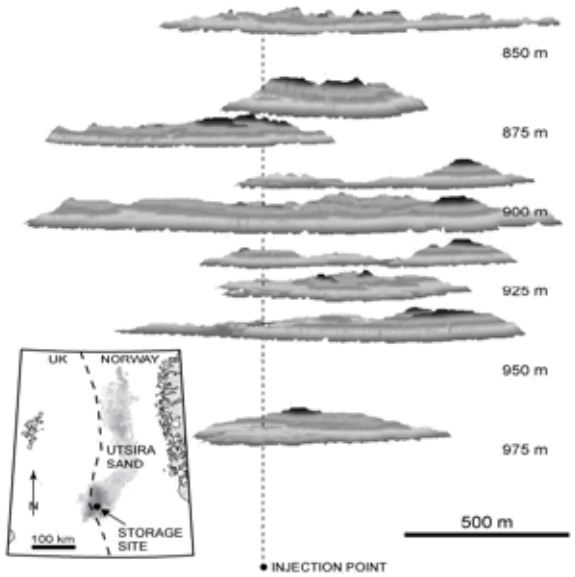

Fig. 1. A nine-layered plume model for Utsira

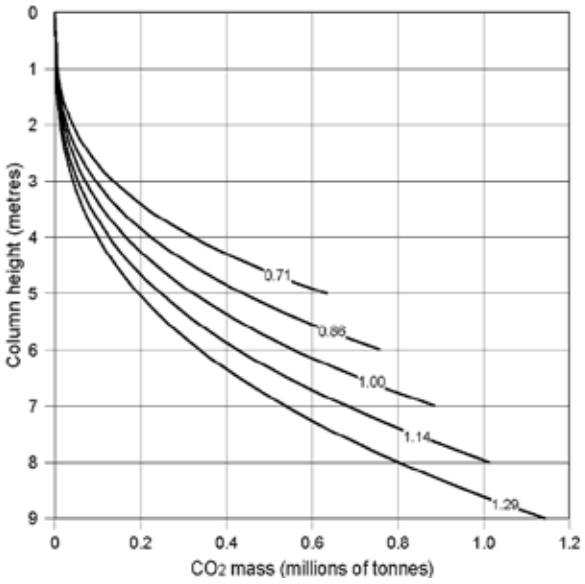

Fig. 2. The layer thickness-mass relationship