Effect of temperature on sandstone permeability - DTU Orbit (27/04/2019)

Effect of temperature on sandstone permeability: Mineral-fluid interaction

Hot water injection in geothermal sandstone aquifers is considered for seasonal energy storage in Denmark. However, an increase in the aquifer temperature might reduce permeability, and thereby increase production costs. An understanding of the factors that control permeability is required in order to address the effects of temperature on permeability. Therefore, different aspects of sandstone permeability are investigated in this research project. Data from a range of sources including: published literature; a database containing over 120 tight gas sandstone samples; new flow-through experiments on Berea sandstone, which is often used as a reference material to reservoir sandstones; and flow-through experiments on Danish Gassum Formation sandstone and Bunter Formation sandstone, were analysed. Polished thin sections were studied by using the electron microscope in order to relate permeability to sandstone texture. The simple physically based Kozeny (1927) equation, relates permeability to porosity and specific surface per pore volume, or equivalent pore size, for a homogeneous porous medium with a uniform pore size. As pore sizes in sandstones can range from nanometres to micrometres, additional assumptions would be required in order to estimate sandstone permeability based on the Kozeny equation. An effective specific surface area per pore volume for permeability was estimated by using image analysis and pore size distributions as from nuclear magnetic resonance (NMR) transverse relaxation data. The smaller pores in the pore size distribution appear to control permeability in sandstones with a low clay-free intergranular porosity. Presumably in those sandstones larger intergranular pores are only connected through smaller pores, which therefore limit the flow rate in larger pores. In sandstones where larger intergranular pores do form a connected flow path, the higher permeability in these pores would have the dominant effect on the measured permeability, whereas the effective specific surface reflects the specific surface of the framework grains.

A characteristic equivalent pore size can also be determined based on the Klinkenberg (1941) procedure, which accounts for effects on permeability of gas slip on the fluid-solid interface by means of separate permeability measurements with different pore pressures. A comparison between the equivalent pore sizes as estimated using the Kozeny equation and the Klinkenberg procedure showed the expected correlation between the two measures, however, differences could be around one order of magnitude. In tight gas sandstones, permeability is often sensitive to net stress, which might change due to the pore pressure change in the Klinkenberg procedure. Besides affecting the Klinkenberg procedure, the combined effect of slip and changes in permeability would affect production during pressure depletion in tight gas sandstone reservoirs; therefore effects of gas slip and net stress on permeability were combined in a model based on the Klinkenberg equation.

A lower permeability to brine than to gas is often observed, which might be due to interaction between the mineral surface and the pore fluid. By modelling a layer of immobile fluid on the fluid-mineral interface permeability to brine was estimated, based on both the pore size distribution from NMR combined with the Kozeny equation and the Klinkenberg procedure. Both methods overestimated the measured brine permeability; this suggests that additional factors, possibly related to clay morphology, contributed to a lower brine permeability.

Thermal expansion would have a negligible effect on permeability as estimated based on the Kozeny equation. Accordingly, a literature survey indicated no effect of heating on permeability in experiments with an inert pore fluid; in tests with distilled water or brine, heating reduced permeability in sandstones containing kaolinite clay minerals. Both heating and reduction of the salinity of the pore fluid can increase the electrical double layer repulsion between quartz grains and kaolinite particles in Berea sandstone, which could lead to kaolinite mobilisation and permeability reduction. Heating increases the magnitude of the mineral surface charge, whereas salinity reduction increases the range over which the surface charge acts. Flow-through experiments in Berea sandstone samples indicated differences between the effect of temperature and salinity on permeability. A permeability reduction at 20°C due to salinity reduction was not reversed by restoring the salinity; a permeability reduction due to heating to 80°C was reversible by restoring the temperature to 20°C. A reversible permeability increase with increasing flow rate was observed at 80°C, but not at 20°C. Therefore, it was suggested that mobilised kaolinite particles affect permeability by a different mechanism at 80°C than at 20°C; at 80°C the main effect might be due to an alteration of pore fluid rheology, whereas at 20°C particles might be filtered in pore constrictions. DLVO theory (Derjaguin and Landau (1941); Verwey and Overbeek (1948)) was used to compare effects of temperature and salinity on surface interaction forces.

Quantitative analysis of images, in which mineralogy was mapped based on backscatter electron microscopy in combination with energy dispersive X-ray analysis by using the QEMSCAN® system, was used to compare a tested sample to an untested Berea sandstone sample. During the experiment, in which an 80°C NaCl solution was injected for 150 days, apparently siderite dissolution released iron, which was oxidised and precipitated as iron hydroxides. Lamination appears to be enhanced by precipitation of iron hydroxides predominantly in finer grained, lower porosity, lamina. The effect of enhanced lamination, as estimated based on the specific surface to the pore from image analysis, was negligible; accordingly, the experimentally measured permeability at the end of the test was only 20% lower than at the start of the test.

This investigation indicates that clay morphology and abundance has a strong effect on: the fraction of the porosity that is effective for permeability, the difference between brine and gas permeability, and the effect of temperature. Hot water injection might induce clay particle mobilisation and mineral dissolution; however, these effects would depend on the mineralogy and pore fluid composition. Therefore, results from one formation cannot directly be generalised to other formations.

General information
Publication status: Published
Organisations: Department of Civil Engineering, Section for Geotechnics and Geology
Contributors: Rosenbrand, E.