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Hydro-mechanical properties of the Red Salt Clay (T4) – Relevancy of the minimum stress criterion for barrier integrity

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ABSTRACT

The so-called Red Salt Clay (T4) is deposited as clay-rich clastic sediment at the base of the Aller-series forming a persistent lateral layer of up to 20 m thickness above the lower Zechstein-series. The clay layers may act as a protective shield in the hanging wall of gas storages or underground repositories in salt formations, thus resulting in a multi-barrier system. As a proof of its reliability comprehensive hydro-mechanical investigations were performed on clay samples recovered at different sites in Germany. Most important, rock tightness against various fluids was confirmed in the lab and field-scale. Remarkably, only if the fluid pressure equalises the acting minimal stress (i.e. violence of the "minimum stress criterion") a significant increase of permeability is observed ("pathway dilatation") but no macro-frac. However, the material properties from different locations showed a significant variability according to different burial depths. Thus the Red Salt Clay may act as natural analogue, representing the material variability of various indurated clays. In addition, the existing knowledge gained from practical mining activities can be used to evaluate extreme in situ loading conditions.

1. Introduction

In the assessment of a multi-barrier system the geological and hydro-geological features of the repository site are crucial as the safe confinement of the radioactive waste and its isolation from the biosphere has to be guaranteed for a long time. Besides crystalline rocks, clay and salt are the favoured potential host-rock candidates, due to their tightness against gases and fluids. Because both rock types are wide spread as layer sequences of different geological formations, they play also an important role as rock barriers for crude oil and natural gas deposits. Since salt rocks are highly soluble their barrier integrity against water inflow from the cap rock is a critical topic regarding their acceptability as host rock for radioactive waste repositories. However, argillaceous cap rocks or intercalated clay layers (e.g. the Red Salt Clay, T4) may act as protective shield in the hanging wall above a salt repository, thus providing a multi-barrier system (Böttge et al., 2003).

Independently from the geological medium a loss of tightness of barrier rocks becomes only possible if connectivity is created, i.e. interconnected pathways which may result from the following two different mechanisms, as pointed out by Minkley (2009):

(1) Deviatoric stress induced occurrence of microcracks and fissures → assessed by the dilatancy criterion.
(2) Fluid pressure driven crack and grain boundary opening and their interconnection → assessed by the minimum stress criterion.

At deviatoric stresses hydraulic conductivity is created due to formation of microcracks, as quantified with the term "dilatancy". Microcracking starts at the dilatancy boundary, as proven by comprehensive laboratory investigation, and proceeds until the rock failure with progressive evolution of macroscopic fracture planes, i.e. shear failure. Accordingly, the dilatancy criterion postulates that for preventing the rock tightness the deviatoric stress conditions must remain below the dilatancy boundary (Cristescu and Hunsche, 1998). However, whereas the general reliability of the so-called "dilatancy-concept" is demonstrated for salt rocks its applicability also for clay seems to be more difficult (Popp et al., 2008).

The physical background of the minimum stress criterion related to the acting fluid pressures is as follows. After reaching a fluid pressure in the order of the normal stress, which corresponds in the undisturbed state to the minimum stress, an opening of pores space will occur and, therefore, the interconnection of fluid accessible pathways.

However, in clay formations local "pathway dilatation" (creation of additional – secondary – pore space without causing any

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macro-fracturing) has been identified as reason for extended gas flow predominantly along the foliation already below the minimum stress (e.g. Marschall et al., 2005). To avoid word confusion with the dilatancy criterion (defined above), it has to be mentioned that the often used term "dilatancy"-created flow in argillaceous clays is only related to local pore space variations in a microscopical and not macroscopical scale, i.e. without a volumetric strain increase. In more detail, pathway dilation is usually thought to take place above certain pressure thresholds but due to the small-scale heterogeneity of stresses and material properties there is probably no sharp transition to the state according to the minimum stress criterion. However, it is consensus, that the conventional two-phase flow theory which is based on an inert rock matrix and solely saturation-dependent capillary pressures is not able to describe the effect of pathway dilation in clay adequately (NEA, 2001; Rodwell et al., 2003).

In Germany, an extensive state of knowledge about the hydro-mechanical properties of the Red Salt Clay has been obtained by geological in situ work and rock mechanical investigations mainly motivated by the use of mined underground openings in bedded salt formations for storage of conventional toxic waste (Minkley, 2009). Recently, the advantageous properties of the Red Salt Clay horizon have been identified as key factor which ensured that the barrier integrity in the hanging wall of the potash mine Teutschenthal was preserved despite the catastrophic event of a rock burst occurred 1996 in the salt mining horizon (Böttge et al., 2003). During the dynamical loading induced by the pillar failure of an old carnallitite mining area a surface subsidence of approx. 0.5 m occurred but the geological barrier remains intact.

The aims of our study are twofold:

(1) To characterise the mineralogical, hydraulical and rock-mechanical properties of the so-called Red Salt Clay (T4).
(2) To demonstrate the favoured barrier properties of an argillaceous layer at high gas pressures proceeding the minimum stress criterion where 2-phase fluid transport phenomena are assumed to be of minor importance.

The experimental work consists mainly of laboratory investigations. In addition, as a proof of the reliability of the obtained permeability lab data a field test has been performed in the salt mine Sigmundshall at a depth of ca. 500 m where gas was injected into the Red Salt Clay strata with pressures reaching the acting minimal stresses.

2. Geological conditions and material description

The so-called Red Salt Clay (T4) at the base of the Aller-series (Z4) is part of the normal permian evaporate sequence of the Central European Basin above the lower Zechstein-series (Braitsch, 1971). The sedimentary thickness of the clay-formation becomes smaller with decreasing distance from the border of the basin, i.e. from ~15 m at Roßleben, over 7 m at Bernburg to 3.5 m at Zielitz, all in Saxony-Anhalt, GER).

Salt is deposited as horizontal beds but because salt (and ductile clay) movement is an important component of sediment deformation two main types of salt have to be distinguished. Whereas predominantly in the North-western part of Germany salt diapirs are formed by salt halokinesis, mainly induced by buoyancy and triggered by local tectonics (e.g. Waltham, 1997), bedded salt with minor thickness dominates to the borders of the Zechstein Basin in the various regions of Middle Germany, e.g. Werra-region. Although, the local structural characteristics of bedded salt and domal salt are quite different, the general nature of the intercalated Red Salt Clay forming whether a persistent lateral (bedded salt) or a steep inclined layer at the flanks of a salt dome is preserved, as depicted in Fig. 1.

Due to the halokinesis the formely deep discharged salt clay (burial depth at 3000–4000 m) is exhumed to lower depth, thus representing a stage of high over-consolidation. In contrast, the primary sedimentary situation at the Teutschenthal site is mainly preserved corresponding to the lower depth of 600–800 m. However, the Red Salt Clay samples are not characterised by a distinguished visible foliation. In addition, also the experimental investigations gave no hints for anisotropy effects.

The massive redbed clay horizon is deposited as clay rich clastic sediment with anhydrite nodules and basal bed of anhydrite. In the lithological profile of Red Salt clay (as exposed in Teutschenthal in the so-called "Schneesalzquerschlag") various zones are distinguished due to the variable anhydrite contents, changing colours (i.e. characterised as bleaching zones) and variations of the clastic components (as indicated by the amount of residuals, Ø > 0.1 mm, after washing), as presented in Fig. 1c.

The mean water content as determined from the two locations is in the order of 5–6 wt.%, i.e. comparable to the Opalinus clay exposed in Mont Terri (e.g. Bock, 2001).

The mineralogical composition of the Red Salt Clay varies, e.g. average composition for the Teutschenthal area: clay minerals 54% (Chlorite: 8%; Illite/Muscovite: 46%); Quartz: 22%; Anhydrite: 15%; accessory Gypsum; Halite: 6%, Hematite: ~2%). The geochemical and mineralogical composition of the Red Salt Clay represents a final state of natural salt-clay-systems, thus standing as a natural analogue for bentonite-based sealing systems in contact with high-saline solutions (e. g. saturated NaCl-solution, solutions with various Mg^{2+}-, K^{+}-, SO_4^{2-}-concentrations) (Gruner et al., 2003). The transition to the stable conditions is characterised by the change of mineral composition from Montmorillonite to Illite – Chlorite. This process is accompanied with a decrease of swelling pressure to a minimum and the change of mechanical behaviour, i.e. a decrease of plasticity corresponds with increasing rock stiffness (Gruner et al., 2003).

Horizontal borehole cores (nominally 90/100 mm diameter) were drilled from the two investigation sites at the respective local mining depths, using compressed air as drilling medium. At the Sigmundshall mine the samples were recovered from several 2 m long drill holes at a depth of 940 m (Lager 12/Konvergenzstrecke) but due to loading effects induced by mining activities the cores were partly broken and disturbed (for the tests only macroscopically intact material were selected). At the Teutschenthal site the Red Salt Clay is only exposed in a single drift ("Schneesalzquerschlag") at around 600 m depth, but the drilled cores (boring depth some few metres) were in an excellent state without any visible pre-damage.

The cores were sealed with foil to avoid humidity and stored at the IfG Leipzig at atmospheric room conditions comparable to in situ (ca. 40% r. H. and 30 °C). Before the rock mechanical tests the sample cylinder surfaces and ends were flattened and polished in a lathe.

3. Rock mechanical investigations

3.1. Triaxial pressure devices

Triaxial loading and strength tests were performed in a standard Kármán-cell in the servo-hydraulic testing machine (RBA 2500, Schenk/Trebel Germany – using the MTS-Teststar software) allowing independent control of the radial ($\sigma_2 = \sigma_3 = p_c$) and axial stresses ($\sigma_{Ax} = \sigma_1$). Using special developed piston sets fluid pressures can be applied or alternatively the gas-permeability measured parallel to the sample cylinder axis (dimensions: 90 mm in