CCC - integrated multiscale study of salt cavern abandonment in the Netherlands

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ABSTRACT: The KEM-17 project of the Dutch State Supervision of Mines presented a critical review of concepts of cavern abandonment and related science. It recommended that analyses of cavern abandonment are done as an integrated project, addressing (i) micro-scale physical processes, (ii) cavern scale models based on field scale experiments and numerical models, (iii) the salt dome scale, to model the far field of the salt caverns. The Cavern Closure Consortium (CCC) project is based on this, focusing on the Haaksbergen and Heiligerlee cavern fields in the Netherlands. We build on (i) innovative deformation experiments, integrated with state of the art microstructural analysis to define constitutive equations for deformation and permeation, focusing on the poorly understood domain below 8 MPa differential stress, (ii) numerical finite element models of the cavern field combined with cavern-scale field experiments to define the closure parameters and temperature evolution of the cavern, and (iii) state of the art numerical models at the scale of the whole salt pillow or salt dome to define the "ist-Zustand". All these contributions are closely integrated and will lead to much improved prediction of the evolution of the caverns after closure and abandonment.

1 Introduction

In the KEM-17 project (Baumann et al. 2019, Brouard et al. 2019, Urai et al., 2019), our consortium reviewed the micro- to macro scale aspects of the abandonment of brine-filled solution mining caverns, focusing on the cases where the surrounding salt is of such low permeability that close to lithostatic pressures will develop after abandonment. We proposed an improvement of current methods, using an integration of the state-of the art in materials science, engineering, and numerical modelling. This project follows the main lines of this recommendation and is organized in 5 main Work Packages (Figure 1), many of these involving cooperation by one or more partners. We thus present a novel approach where we integrate materials science, geophysical and engineering approaches, in order to reduce uncertainties in predicting the evolution of abandoned caverns over long time scales.

One critical question asked in this project is whether a close-to lithostatic brine pressure will develop in the caverns after abandonment. We approach this concern by integrating results of microstructural analysis, deformation and permeation experiments, numerical simulation of deformation and permeation at cavern and salt dome scale, and field testing in boreholes and in caverns. Another critical question is if and how the brine will be expelled from the salt

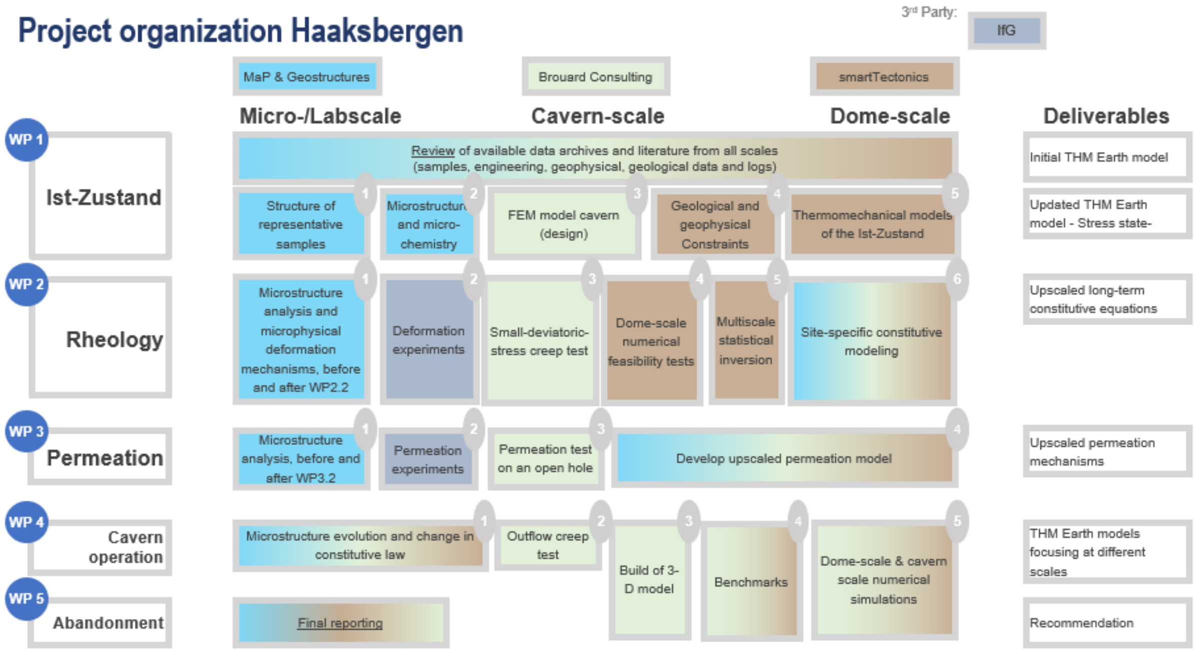

Figure 1: CCC- Project organization Haaksbergen.

formation. We outline the uncertainties and propose ways to reduce this uncertainty and test the predictions.

Finally in this project, we will present models of the patterns and timescales of brine pressure and brine permeation and discuss strategies for safe abandonment over long term.

Here, we present first results on the future Haaksbergen cavern fields of Nobian, present our preliminary findings and discuss upcoming analyses and cavern- and borehole- scale testing in future wells.

2 Ist-Zustand

The present-day structure and properties of the Haaksbergen pillow were characterised based on an improved geological model, detailed analysis of the drill core and geomechanical modelling. We conclude that Zechstein-1 salt has a deformed and recrystallized microstructure typical of tectonically deformed rock salt, with a median grainsize which varies between 1 and 3 mm (Figure 2), and variable amounts of dispersed and layered Anhydrite. During the evolution of the Haaksbergen pillow it experienced a maximum differential stress of around 2 MPa, and both pressure solution and dislocation creep were active microphysical processes.

Dislocation creep and pressure solution creep were the dominant deformation mechanisms during the formation of the Haaksbergen pillow. Grain boundaries in Halite are equilibrated with non-percolating fluid inclusions, suggesting exceedingly low permeability in-situ. However, polycrystalline Anhydrite in the core is microporous and could form fluid pathways. Based on microstructure, the rock salt's rheology (in the far field of the caverns) can be described by a two-mechanism creep law with a power law part and a change to Newtonian, pressure solution dominated creep at about 8 MPa, predicted using the grain sizes measured.

For numerical modelling, we propose three different mechanical units: (i) Pure Rock Salt - this has the rheology explained above. (ii) Massive Anhydrite - this, we infer at the scale of the cavern operation to be a highly viscous material, with a viscosity about 500x that of the Halite. (iii) Anhydritic Halite which is a fine layercake with effective properties used for modelling: for this we propose a higher viscosity 50x that of Halite.

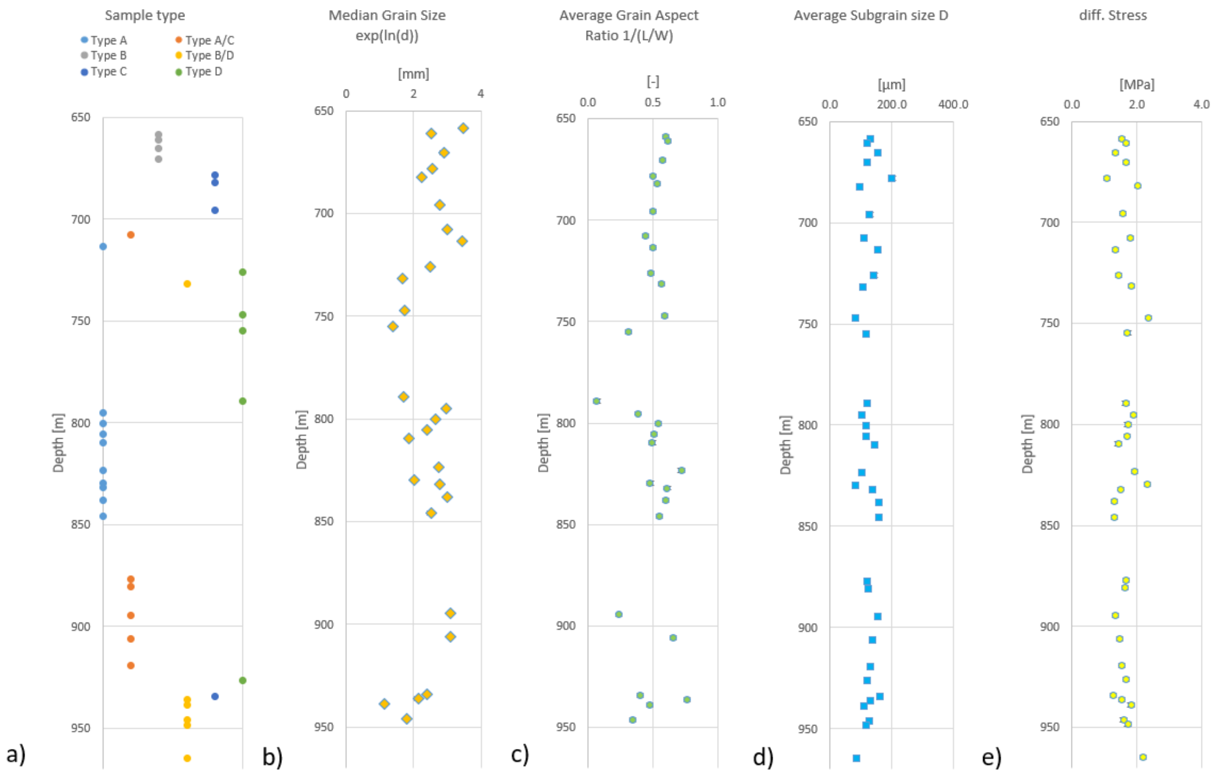

Figure 2: Summary of the results of measurement in relation to litho-classes, the median grain size, the average grain aspect ratio, as well as the subgrain size and the derived differential stress (Schleder and Urai, 2005)

2.1 Rheological model to describe the long-term creep of Haaksbergen rock salt

The long-term creep rheology of rocksalt is affected by relatively large uncertainties. Usually, the creep rheology is only inferred from laboratory-scale constraints. With the deformation tests in the laboratory at ~1 MPa or higher, typical strain rates are of the order 10^{-6} to 10^{-9} s^{-1}. Yet, typical strain rates for salt diapirs are of the order 10^{-17} to 10^{-13} s^{-1}. Thus, we need to extrapolate over many orders of magnitude to infer the stress state within a salt dome from lab-scale constraints. We aim to use the complementary expertise of the CCC consortium on different scales (micro, laboratory, cavern, and dome scale) and combine their constraints to derive a consistent long-term creep model for Haaksbergen rock salt with uncertainty intervals.

We develop a long-term rheological model for rock salt that incorporates the first-order effects of grain size kinetics on pressure solution creep and thus on the composite creep law consisting of pressure solution and dislocation components. The new concept introduces additional parameters to the standard long-term rheological model, which are used to parameterize microstructural phenomena of grain size evolution and grain boundary (de-) activation.

The total strain rate can be additively decomposed into the elastic, transient, dislocation, and pressure solution creep components, respectively, as follows:

$$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{tr} + \dot{\varepsilon}^{dc} + \dot{\varepsilon}^{ps}.$$

Here, we focus on the *long-term* creep and consider the following two components:

1. Dislocation creep:

$$\dot{\varepsilon}^{dc} = A_{dc} \exp\left(-\frac{Q_{dc}}{RT}\right) \sigma^{n}, \quad (1)$$

2. Pressure solution creep:

$$\dot{\varepsilon}^{ps} = A_{ps} \exp\left(-\frac{Q_{ps}}{RT}\right) \frac{\sigma}{TD^{m}}. \quad (2)$$

In the above equations A_{ps} and A_{dc} denote pre-factors of the creep mechanisms, Q_{ps} and Q_{dc} are the corresponding activation energy parameters, R is the gas constant, T is the absolute temperature, D is the average grain size, σ is the effective differential stress (square root of the second invariant of the deviatoric stress tensor), n and m are the dislocation creep and grain size dependence exponents, respectively. Figure 3a illustrates this classical view of the steady-state creep in a stress-strain rate diagram.

Yet, it is known from microstructural observations that pressure solution creep involves various complexities. One complexity is *grain boundary activity*, as pressure solution only operates if the grain boundaries are mobile which requires a connected fluid film to be present. Here, we parameterize this effect using a simplified, stress-dependent activation function ξ, which changes smoothly between 0 and 1. The state $\xi = 1$ corresponds to the fully activated grain boundaries surrounded by connected fluid films. The state $\xi = 0$ describes the situation when the fluid films get disintegrated, and pressure solution creep completely stops (KEM-17). Currently, it is not exactly clear what factor triggers the deactivation. However, various empirical suggestions indicate that it occurs in the case that differential stress drops below a certain low threshold σ_{crit}. We thus propose the grain boundary activity control to be parameterized in the following simplified manner:

$$\dot{\varepsilon} = \xi\, \dot{\varepsilon}^{ps} + \dot{\varepsilon}^{dc}, \quad (3)$$

with ξ being the smooth stress-dependent activation function, given by:

$$\xi = \frac{1}{1+\frac{\sigma_{crit}}{\sigma}}. \quad (4)$$

Figure 3b demonstrates the effect of deactivated grain boundaries at a typical critical stress level.

Using a Bayesian approach with a Markov chain Monte Carlo (McMC) method allows us to combine expert knowledge (a priori conditions) with measurements. It enables us to quantify the rheology in a probabilistic sense and derive credibility ranges for all model parameters.

The approach is well established, also for the specific application to creep rheology (e.g., Korenaga & Karato, 2008), even when it has not yet been applied to salt rheology.

We formulated the geometric elements of a geomechanical model to compute both salt pillow-scale and cavern-scale evolution, upscaling the contributions of multiple thin Anhydrite layers in the dominant rock salt section, including realistic long-term rheology of Anhydrite. This model predicts a 3D stress and temperature field of the Haaksbergen pillow which is much more realistic than the strongly simplified assumptions in most current models of cavern abandonment.

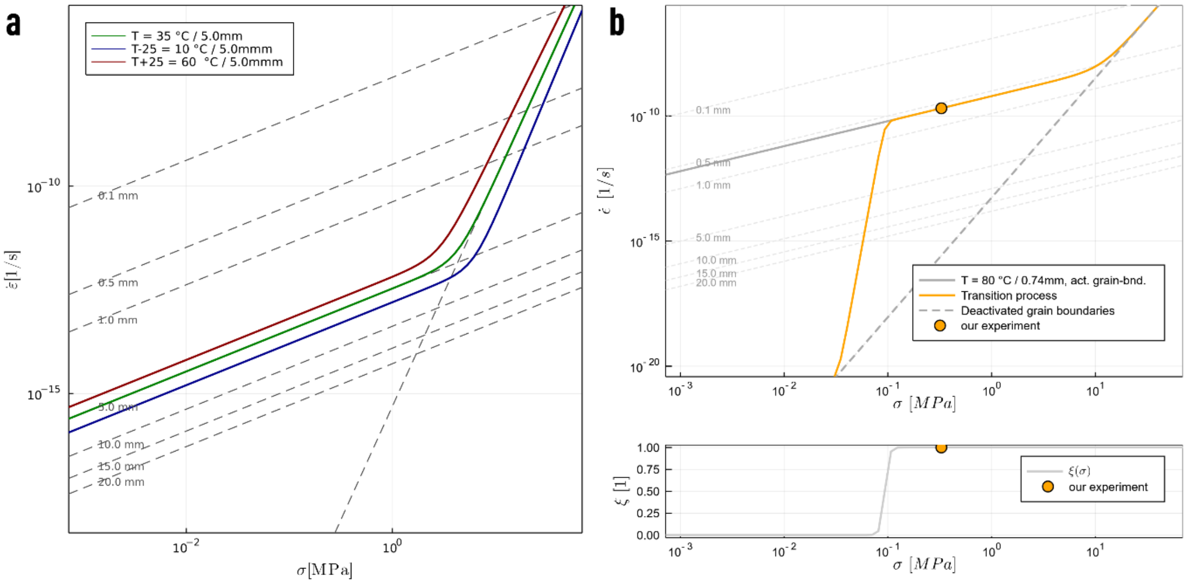

Figure 3: a: Classical stress-strain rate diagram with combined long-term creep composed of dislocation and pressure solution creep illustrated for a constant grain size of 1 mm at different temperatures with parameters from Spiers et al. (1990). Dashed lines correspond to individual creep components, *i.e.*, dislocation creep and pressure solution creep with other dominant grain sizes b: Combined creep model with critical stress level switch to simulate the deactivation mechanism of pressure solution creep at a critical stress level of $\sigma_{crit.}$=100 kPa. A smoothed logistic function describes the disintegration of the fluid films at this stress level.

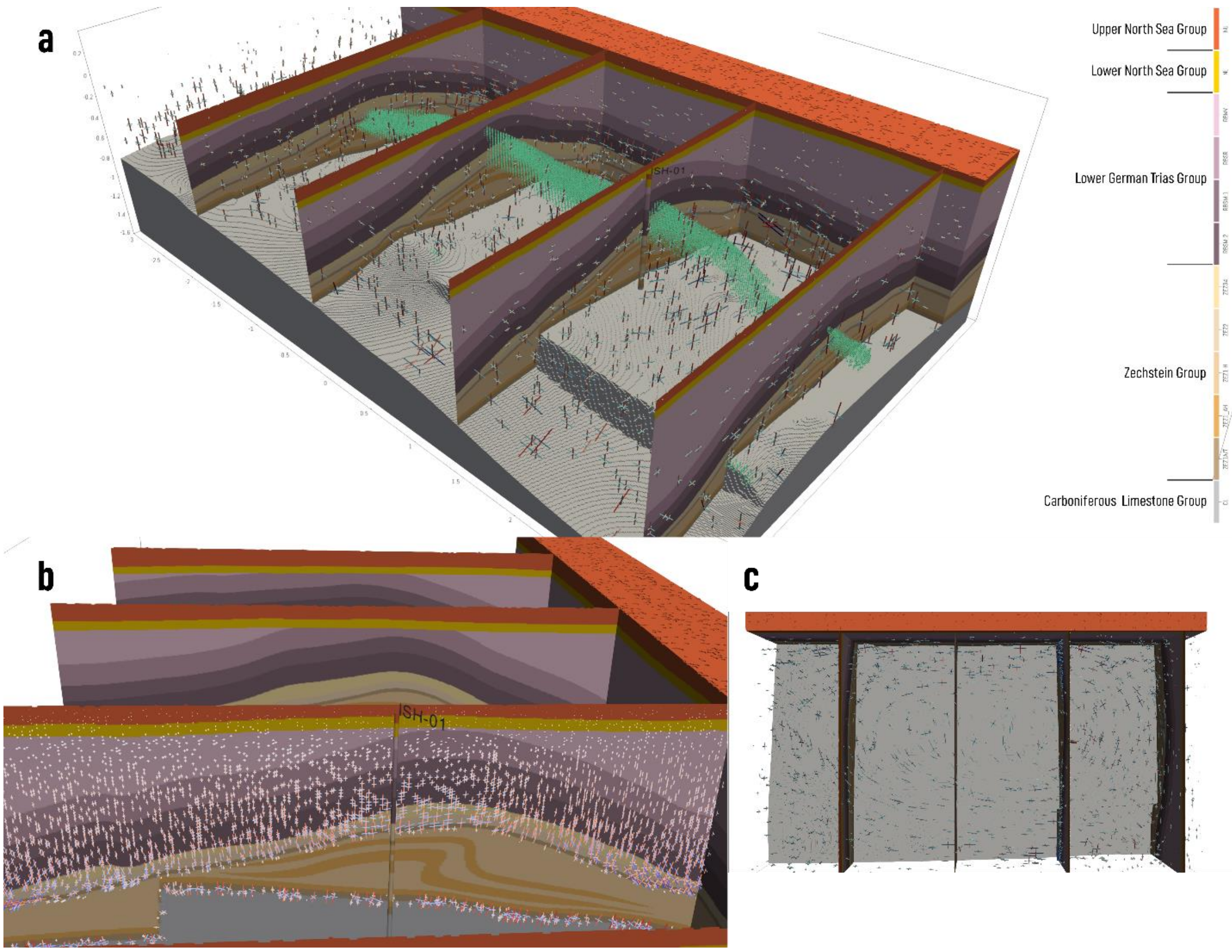

Figure 4: Thermomechanical modelling results on the salt-dome scale. Markers show the principal stress directions of the stress tensors throughout the model domain (a-c). The global pattern of the principal stress directions is primarily driven by the shape of the Top salt surface (b,c). Marker colours indicate the stress magnitude and sense. Green markers in (a) indicate plastic failure. See text for further details.

Although it needs to be confirmed by other end-member model results, our initial results indicate that the large-scale pattern of the principal stress direction is a relatively robust model feature primarily affected by the shape of the top salt surface. Our model results demonstrate that plastic failure occurs at distinct locations (the ridge of the salt pillow, Figure 4), consistent with seismic interpretations of faults in the overburden of salt structures. With the additional scenarios, we will explore the sensitivity of the stresses concerning the uncertain model input (e.g., salt rheology, temperature).

The rheology and permeation of laboratory samples is studied in two world-class facilities: the laboratories of IfG in Leipzig and the laboratory in the Altaussee mine in Austria, both providing unique and complementary data to answer the currently controversial question of the constitutive laws governing rock salt creep at low differential stress and very long-time scales of several years and longer. The samples were characterised extensively with state-of-the art microstructural tools to determine the deformation mechanisms.

The first series of 8 deformation experiments at IfG on wet core samples were set up to investigate the processes in salt close to a cavern, where high differential stress develops during cavern operation followed by long-term deformation at decreasing differential stress during abandonment. Results show that the samples completely recrystallize during these experiments, a process not yet recognised in cavern abandonment studies (Figure 5). Deformation mechanisms are dislocation creep and pressure solution creep and this allowed the results to be incorporated in the constitutive models. Grainsize will affect pressure solution creep rates and can be taken into account in future models of abandoned cavern evolution. Experiments in the Altaussee mine, that operate at even lower differential stress and are much more sensitive and accurate than the ones performed at IfG but last much longer, were set up and started, and are expected to reach stationary creep in several months' time.

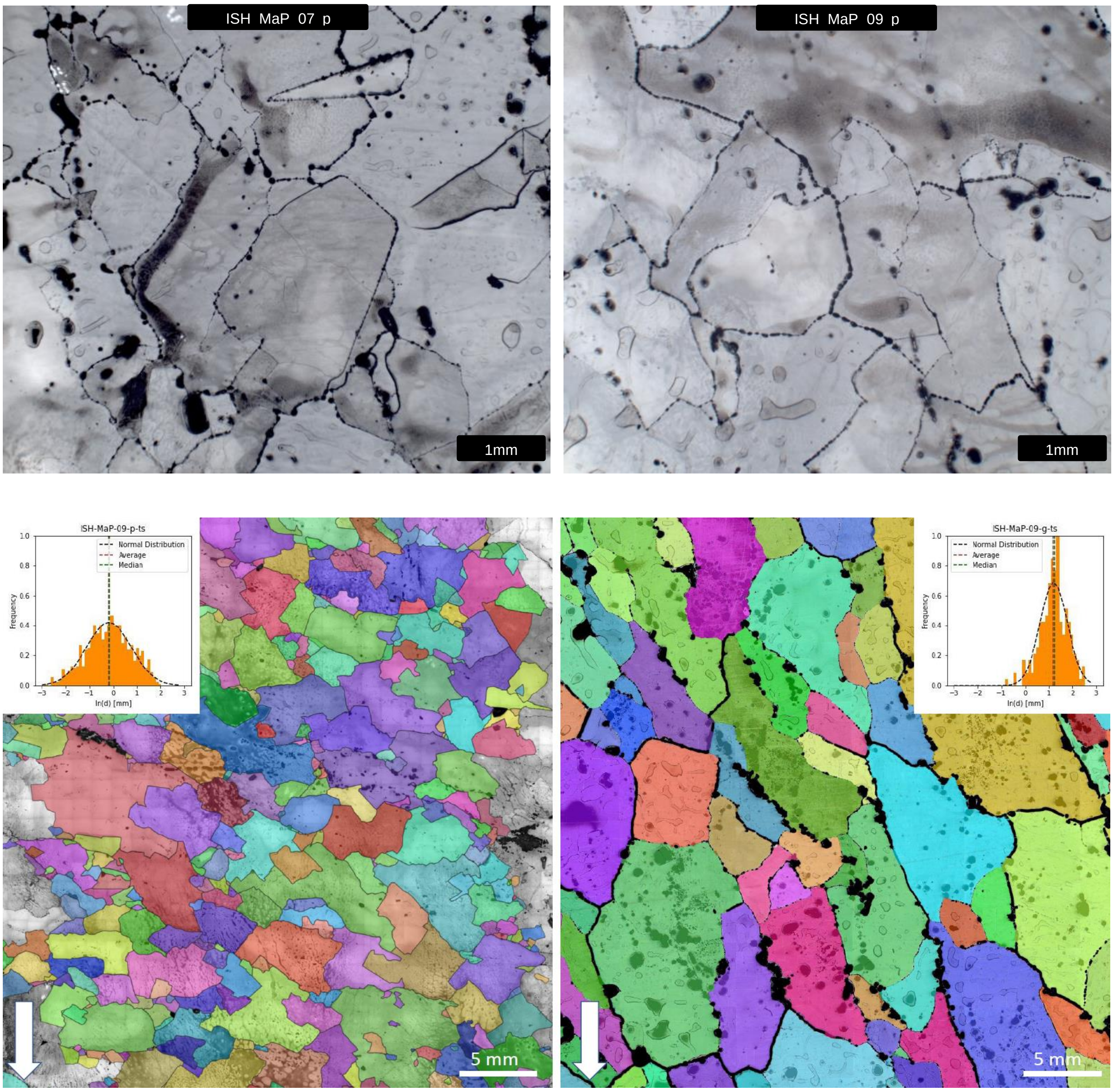

Figure 5: Top images show completely recrystallized microstructure of sample ISH_MaP_07 and ISH_MaP_09. Images underneath show the grainsize reduction of ISH_MaP_09_p (deformed) vs ISH_MaP_09_g (undeformed). This is the first time that salt subjected to stress at the cavern wall is demonstrated to recrystallize.

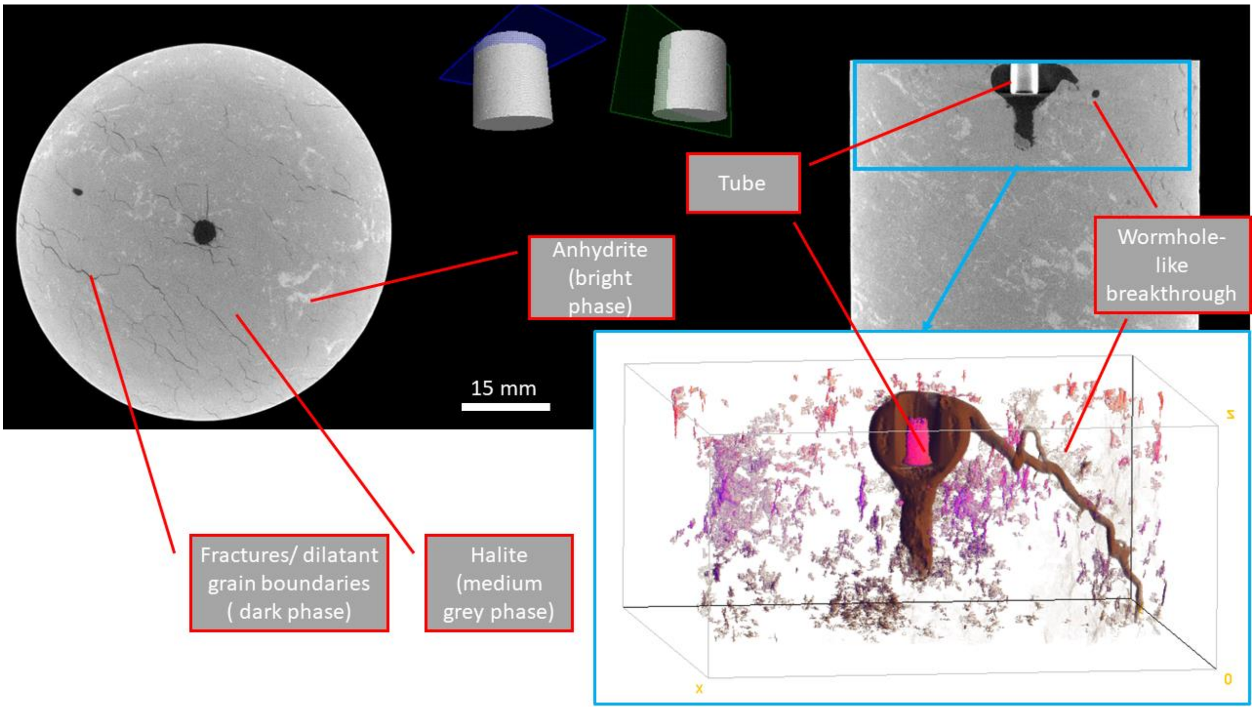

Figure 61: Micro-CT scan of the second permeation sample, showing the preliminary interpretation of fluid pathway during the permeation experiment.

The first permeation experiments with brine as pore fluid are in agreement with what is expected from microstructures: very low permeabilities until the fluid pressure exceeds the minimum stress by a few bars, followed by very rapid increase in permeability and heterogeneous permeation along dilatant pathways (Figure 6), mainly along grain boundaries.

This integrated model of geometry and mechanical properties was combined with the design of caverns by Nobian and implemented in a finite element model to compute the evolution during cavern operation and abandonment (Figure 7).

Because all parameters obtained to date are based on data on sample scale, we will combine these with measurements in the next well. In addition to the planned logging and coring programme, in the open hole it will be critical to measure the in-situ temperature of the salt, as well as the properties of the overburden. To test the properties of the whole salt section, permeation tests in an open hole are required to test the upscaling of the results from the laboratory; doing this is a critical measurement because it is well known that laboratory experiments can underestimate rock mass permeability by orders of magnitude, and miss the presence of permeable layers. We also recommend a pressure build up test in the open hole. Later in the life of the cavern field, the updated and integrated models' prediction must be compared to the results of a several months long, abandonment test ("trial and error test") which can validate the results at the cavern scale.

New drillings offer the possibility to measure the effective permeability at the scale of the caverns. The permeation test that has been proposed (Figure 8) will allow to assess if the formation is perfectly impermeable beyond a zone potentially damaged by the drilling.

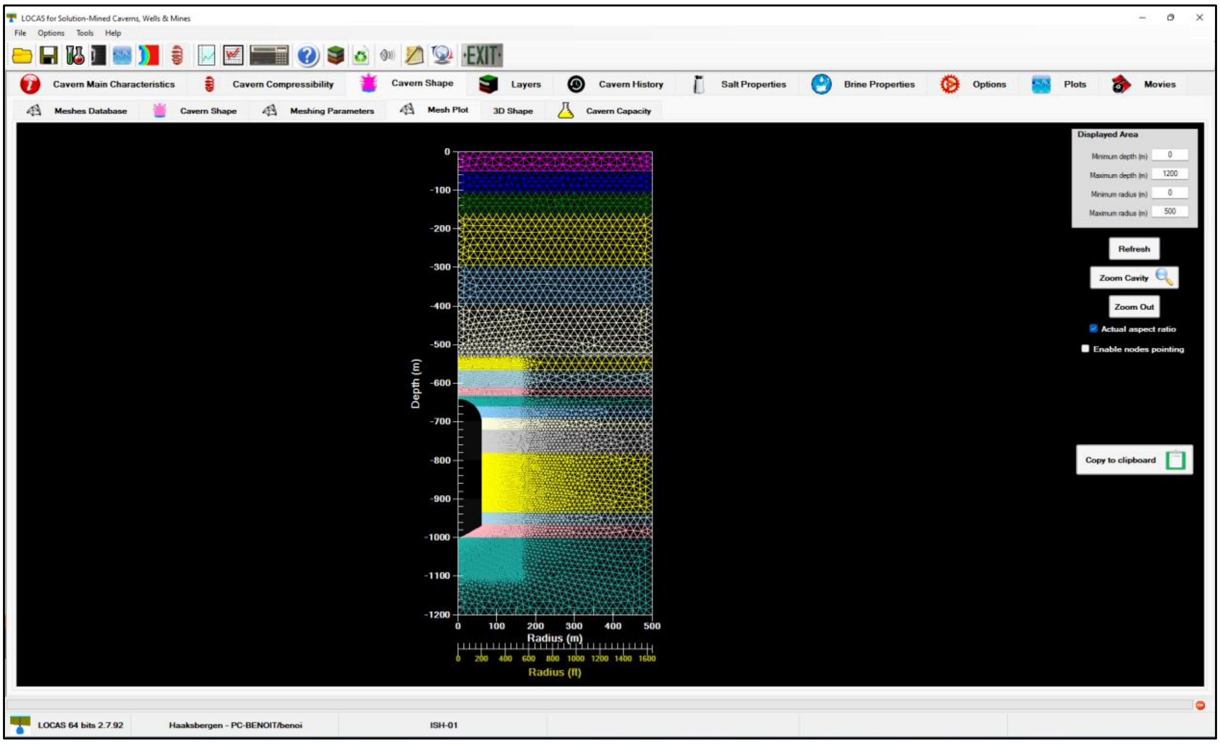

Figure 7: Mesh example [LOCAS software].

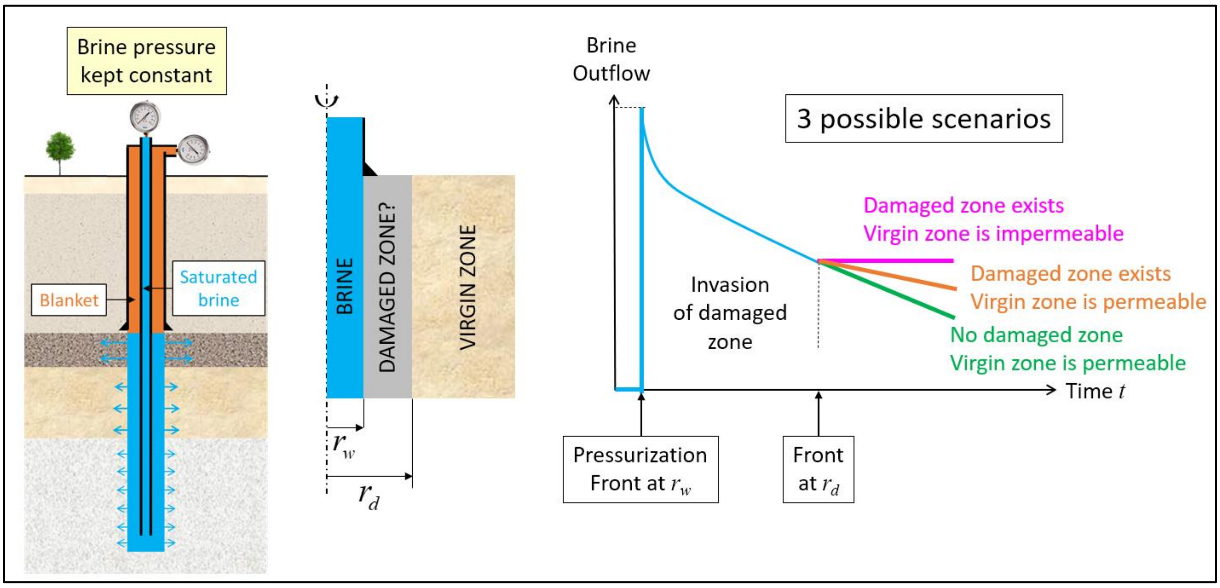

Figure 8: Openhole permeation test.

A more sophisticated permeation test, called WTLog, was also proposed. The WTLog aims at determining a profile of injectivity and permeability along an openhole (Figure 9). Whenever possible, it would be valuable to perform such a test first on the overburden and then along the salt formation.

A more complicated but crucial part of the models concern the predictions of fluid flow after the cavern pressure reaches lithostatic. In the KEM-17 study it was argued that this flow might be localized ("preferential fingering") and we will include aspects of this in our model, but a full, reliable prediction of this will necessarily have to be conservative.

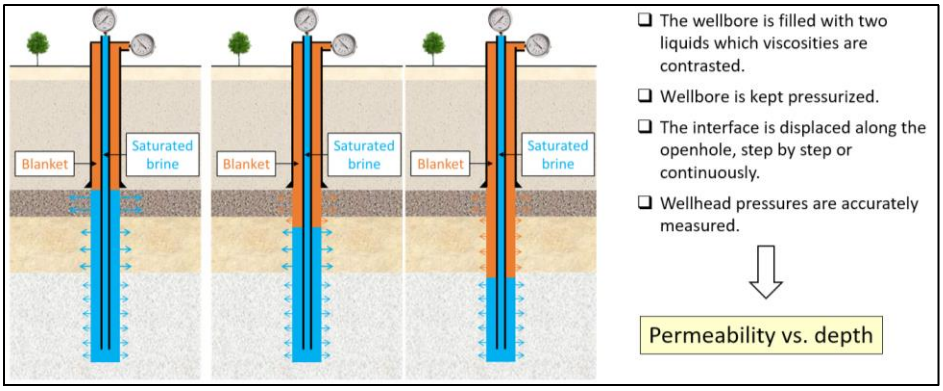

Figure 9: WTLog permeation tests allowing to determine injectivity/permeability as a function of depth along an openhole.

3 Conclusions

At this stage, these results give a good impression of the integrated methods and first results of our approach. However, the results must be considered as preliminary, and the predictions of cavern pressure evolution after abandonment may well change significantly once more results are integrated in the model.

Acknowledgements

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