Cavern abandonment
- Generall aspects -

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- ❖ Pressure build-up in closed caverns
- ❖ Pressure-driven percolation in salt rock
- ❖ Concept for cavern abandonment
- ❖ Successful long – term safety proof

Aim of cavern abandonment

- Ensuring long-term stability (exclusion of collapse)
- Reduction of the cavern convergence by building up pressure in the closed cavern
- Recovery of the original isotropic rock stress state

  and thus elimination of creep deformations
- Limitation of induced subsidence at the surface
- Acceptance by authorities / population
- Economics

Proof of evidence from a rock-mechanical point of view

- Assessment of the geological situation

  (hanging and underlaying barrier, potash etc.)
- Description and evaluation of the cavern history

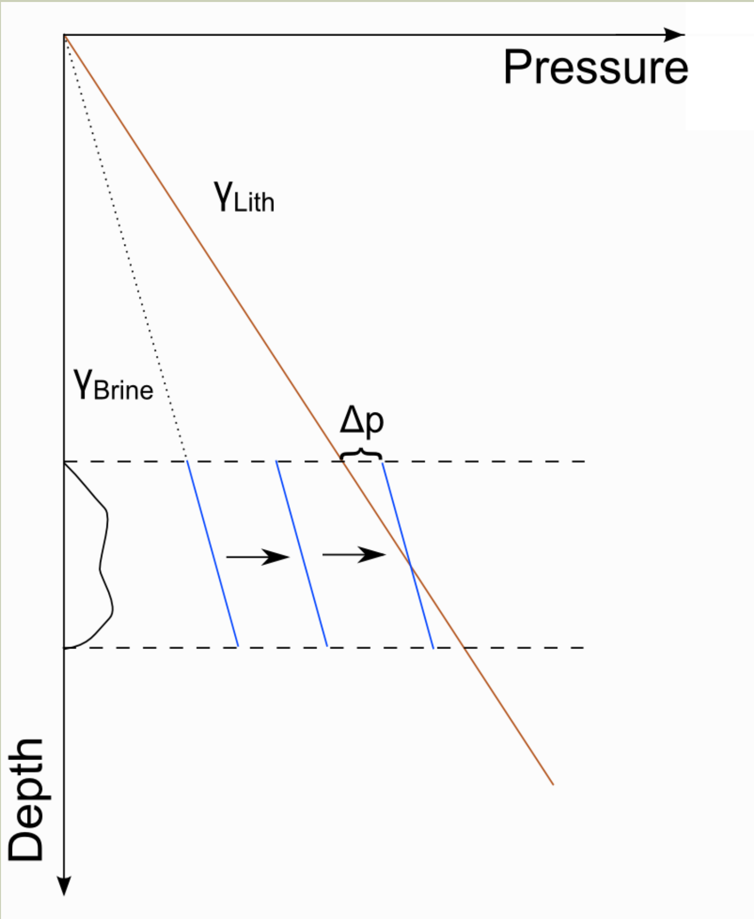
  (leaching, production …)
- Evaluation and assessment of active and passive pressure build-up rates
- Evaluation and assessment of temperature profiles
- Evaluation and fixing of the sealing element

Rock mechanically relevant processes during abandonment

Process	Effect on the fluid pressure	Period
Salt creep	Monotony pressure increase with decreasing rates	Ongoing process, most intensive after sealing
Heat transition	Breine warming / expansion, pressure increase with decreasing rates	Most intensive decades after sealing
Salt solution / saturation	Increasing cavern volume , decreasing temperature Decreasing pressure	Most intensive month after sealing
Percolation of the cavern fluid to the surrounding rock mass	Pressure decrease	partly long-lasting
Percolation of the cavern fluid to the sealing elements	Pressure decrease	partly long-lasting

Hydraulic over pressurization at the top

In the beginning a worst case scenarion was assumend



Berest & Brouard (2003) Safety of Salt Caverns Used for Underground Storage. Oil & Gas Science and Technology – Rev. IFP, Vol. 58 (2003), No. 3

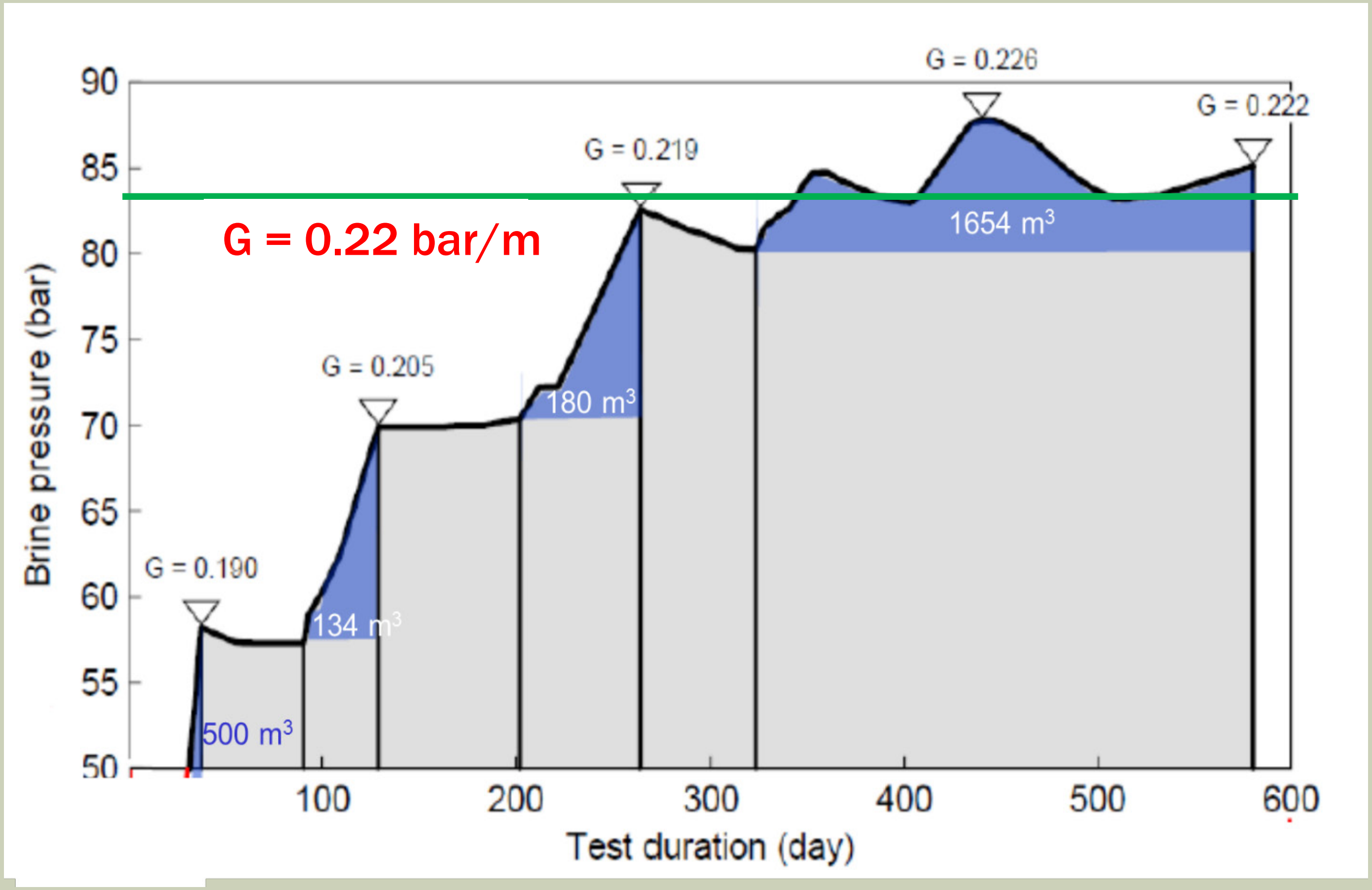
"It is expected that creep ends when the cavity pressure balances the overburden pressure. In fact, as pointed out by Wallner (1988) and Ehgartner and Linn (1994), an exact balance is reached only at cavern mid-depth.

Salt rock is of higher density than brine and, in the final state, brine pressure at the cavern top will exceed the geostatic pressure by an amount that is larger when the cavern is taller.

If the cavern is tall enough, the rock tensile strength will be exceeded, and fracturing becomes likely."

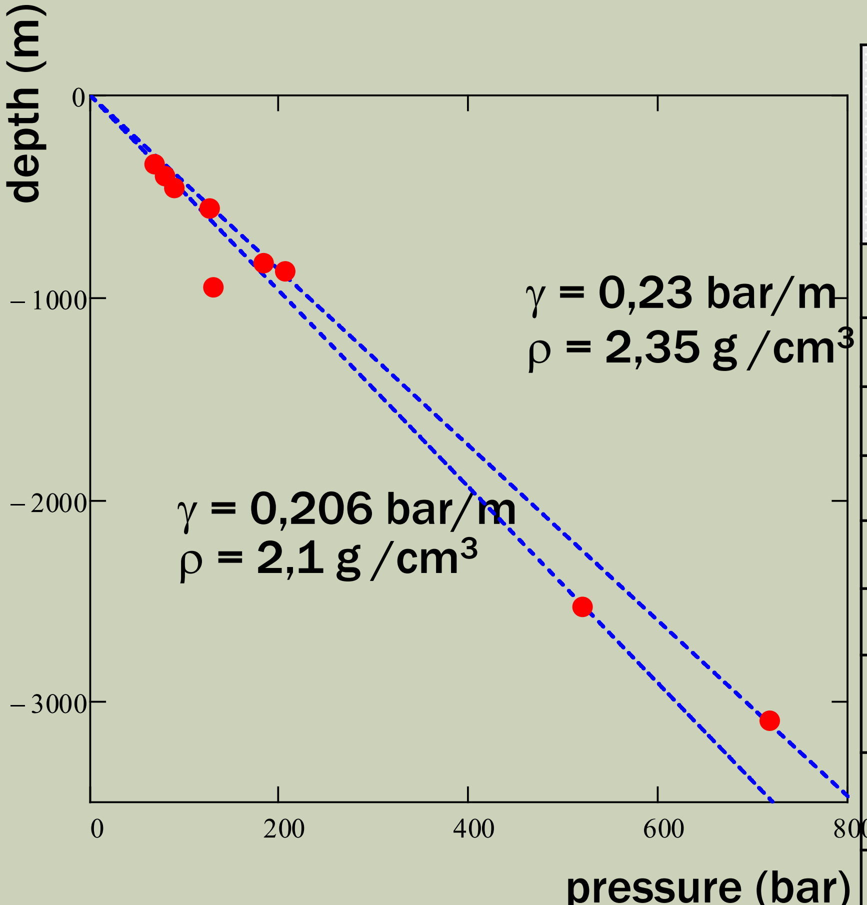
In situ-Test Kaverne K 102 in Etzel

Overpressurisation only by activ injection/pumping !!



Percolation threshold from leak off test in salt formations

Many test have been carried out to understand the behaviour of sealed caverns

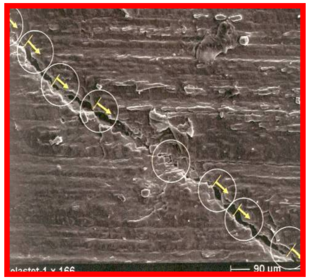


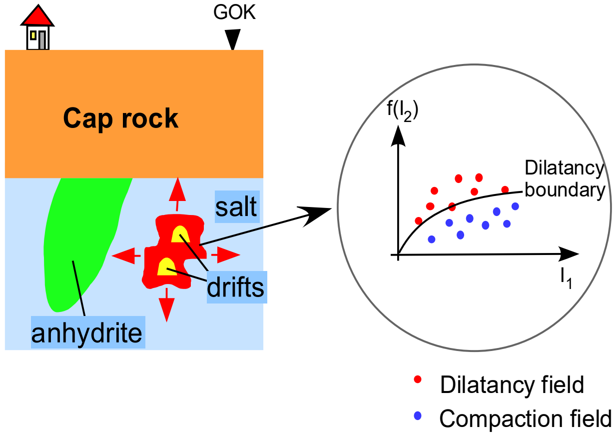
Test (Quelle)	Tiefe (m)	Test-volumen (m^3)	Druck-medium	Perkola-tions-schwelle Druck (bar)	Perkolations-schwelle Druckgradient (bar/m)
IfG Springen, Bohrschacht (Minkley et al., 2013)	340	50	Pressluft	68	0,200
Kaverne S102 (Bannach & Klafki, 2009)	400	13600	Sole	79,2	0,198
IfG Bernburg, Testkaverne (Brückner et al., 2003)	459	25	Sole	89	0,194
IfG Bernburg, Bohrlochtest (Minkley et al., 2013)	560	0,05	Stickstoff	126	0,225
GDF Bohrlochtest EZ58 (Durup, 1994)	871	7	Stickstoff	206	0,237
GDF Kaverne EZ53 (Berest & Brouard, 2003)	950	7500	Sole	130	0,137
Etzel Kaverne K102 (Staudtmeister & Rokahr, 1994)	830	233000	Sole	183	0,220
Kaverne BAS-2 (van Heekeren et al., 2009)	2533	210000	Sole	520	0,205
GDF SUEZ Bohrlochtest Altmark (Wundram, 2014)	3096	2,1	Schwer-spülung	718	0,232

Mechanically or hydraulically induced permeability

Deviatoric stresses induce damage which results in the opening and **percolation of micro cracks**

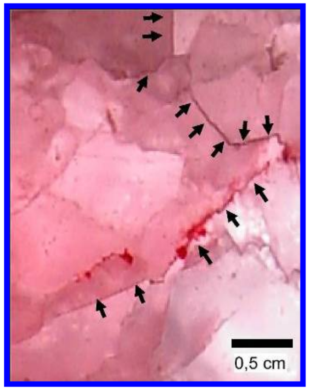
⇒ **Dilatancy criterion**

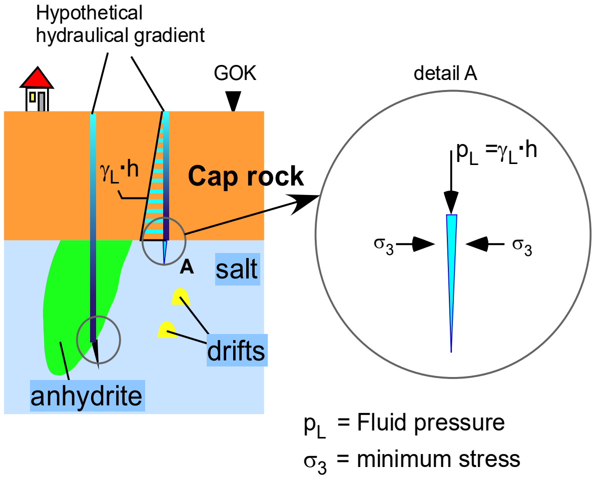




Hydraulically induced pathway opening or fracturing which results in **percolation of micro cracks**

⇒ **Minimum stress criterion**





Fundamental assumption:

The impermeability of a saliferous barrier will already be lost if one of these two criteria:

- (1) minimum stress criterion or
- (2) dilatancy criterion

is violated!

- *Note, most critical for the integrity of saliferous barrier is the minimum stress criterion because the importance of the dilatancy criterion is limited to the EDZ!*

Relevant criteria for integrity of salt rock barriers

- Pressure-driven percolation
  (minimal stress criterion, fluid pressure or frac criterion)

- Shear strength (or dilatancy) criterion
  i.e. damage due to stress above dilatancy boundary

- Tensile strength criterion — damage due to tensile stresses

Note: damage criteria most relevant close to excavations (seals, plugs)

Terminnology

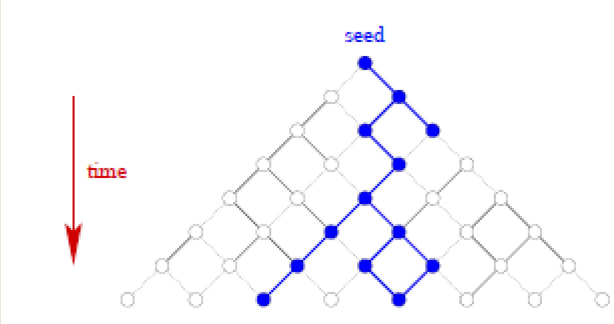
Sand stone

- Permeability
- Permeation
- Infiltration

➢ Darcy - Model for porous media:
Flow in an interconnected pore space

- Percolation

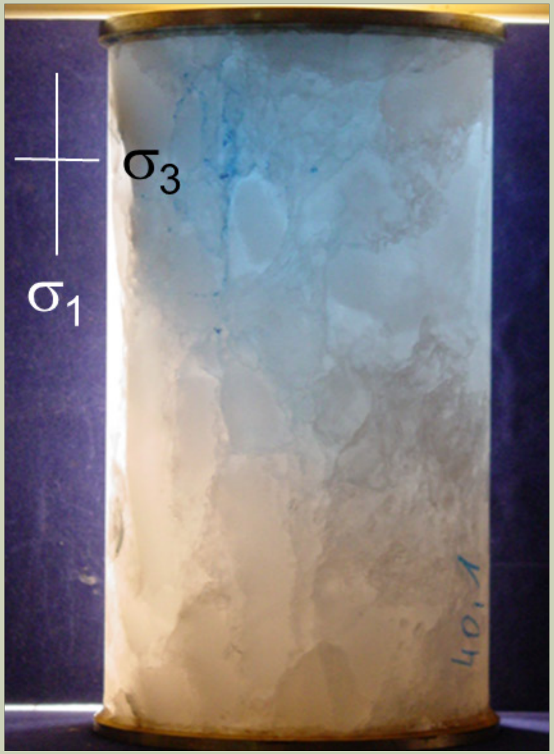
➢ Opening and creation of an interconnected network of flow paths after transgression of a percolation threshold:
$\Rightarrow$ Generation of connectivity



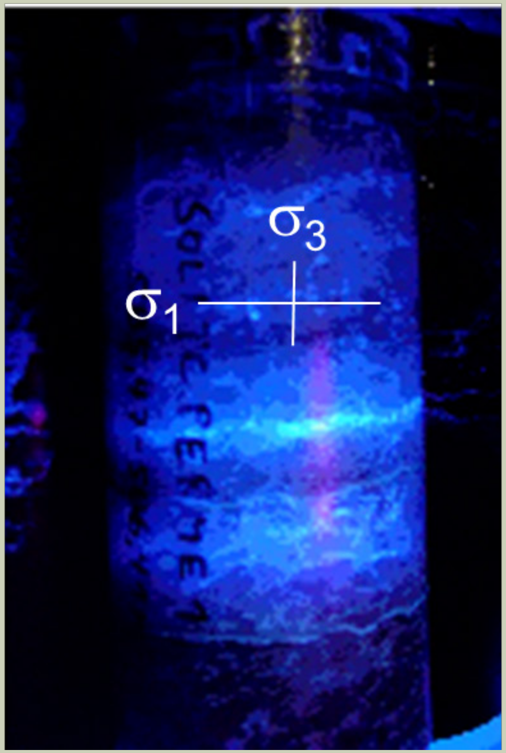
Rock salt

Directed pressure-driven generation of hydraulic flow paths in an anisotropic stress field

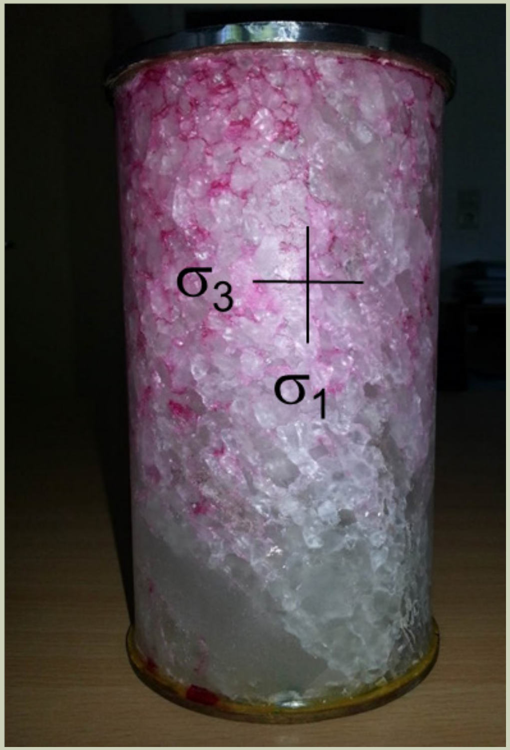
compression test



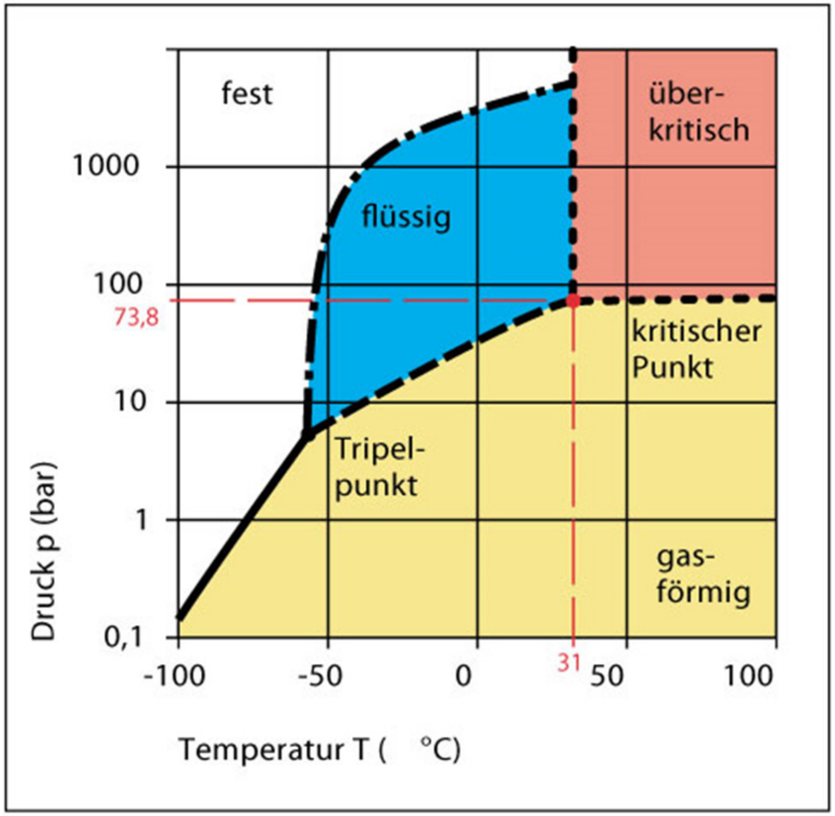
extension test



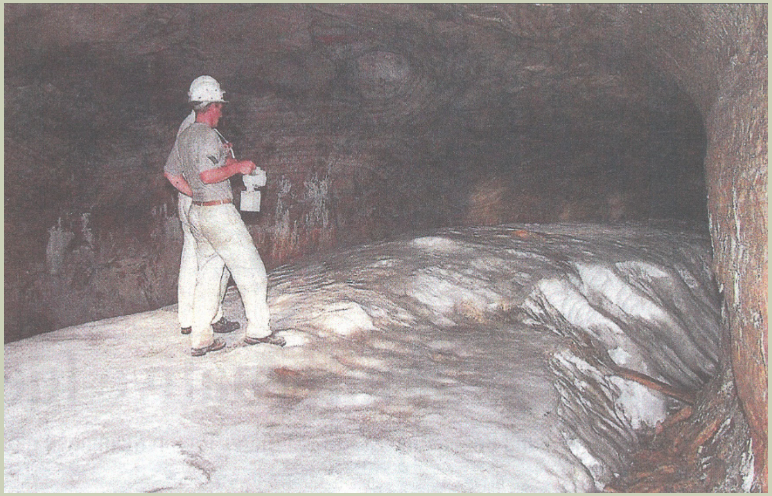
isotropic test



Natural analogue:
Long term storage capacity of high pressurized fluids in salt



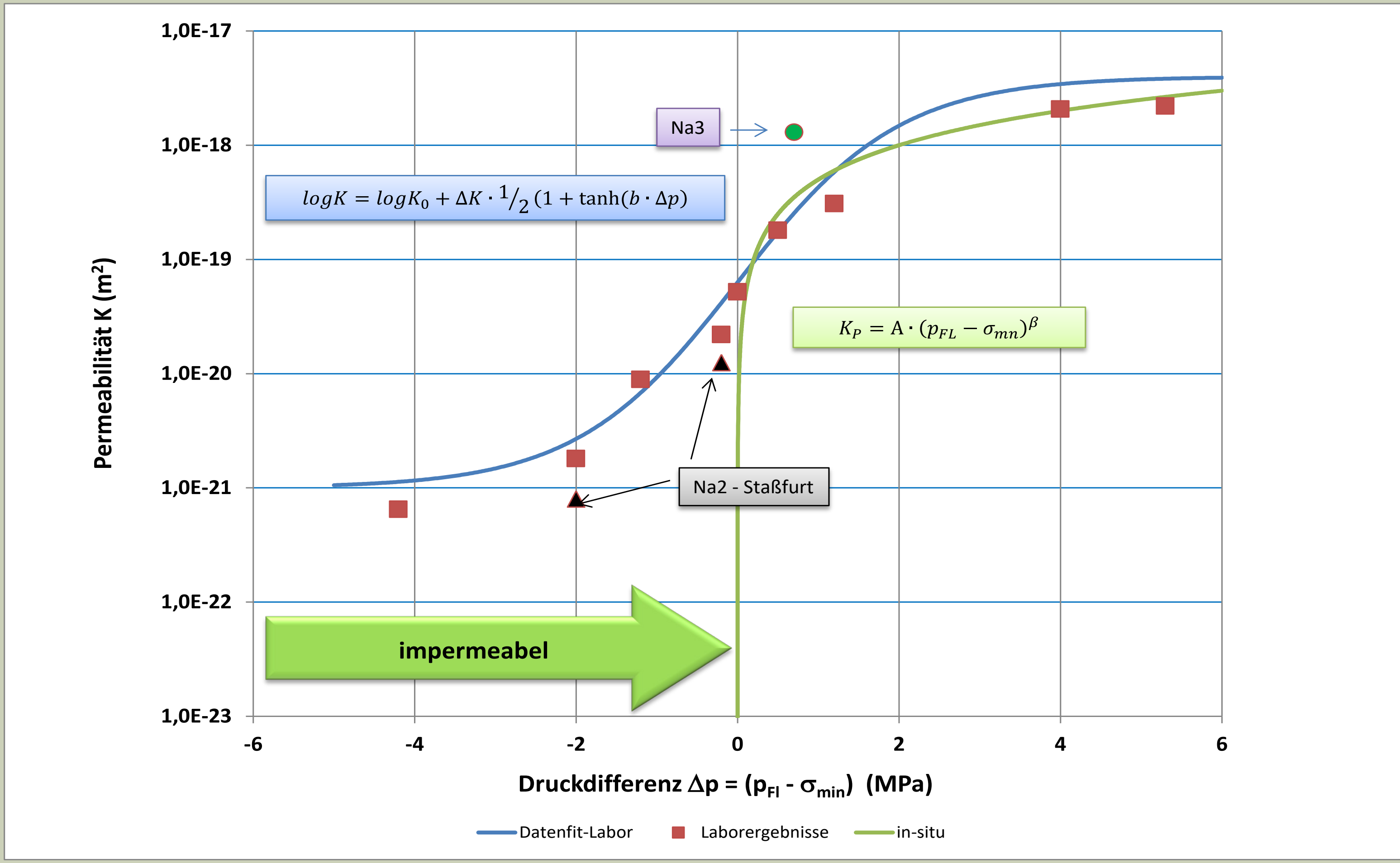
p, T-Diagramm von CO_2



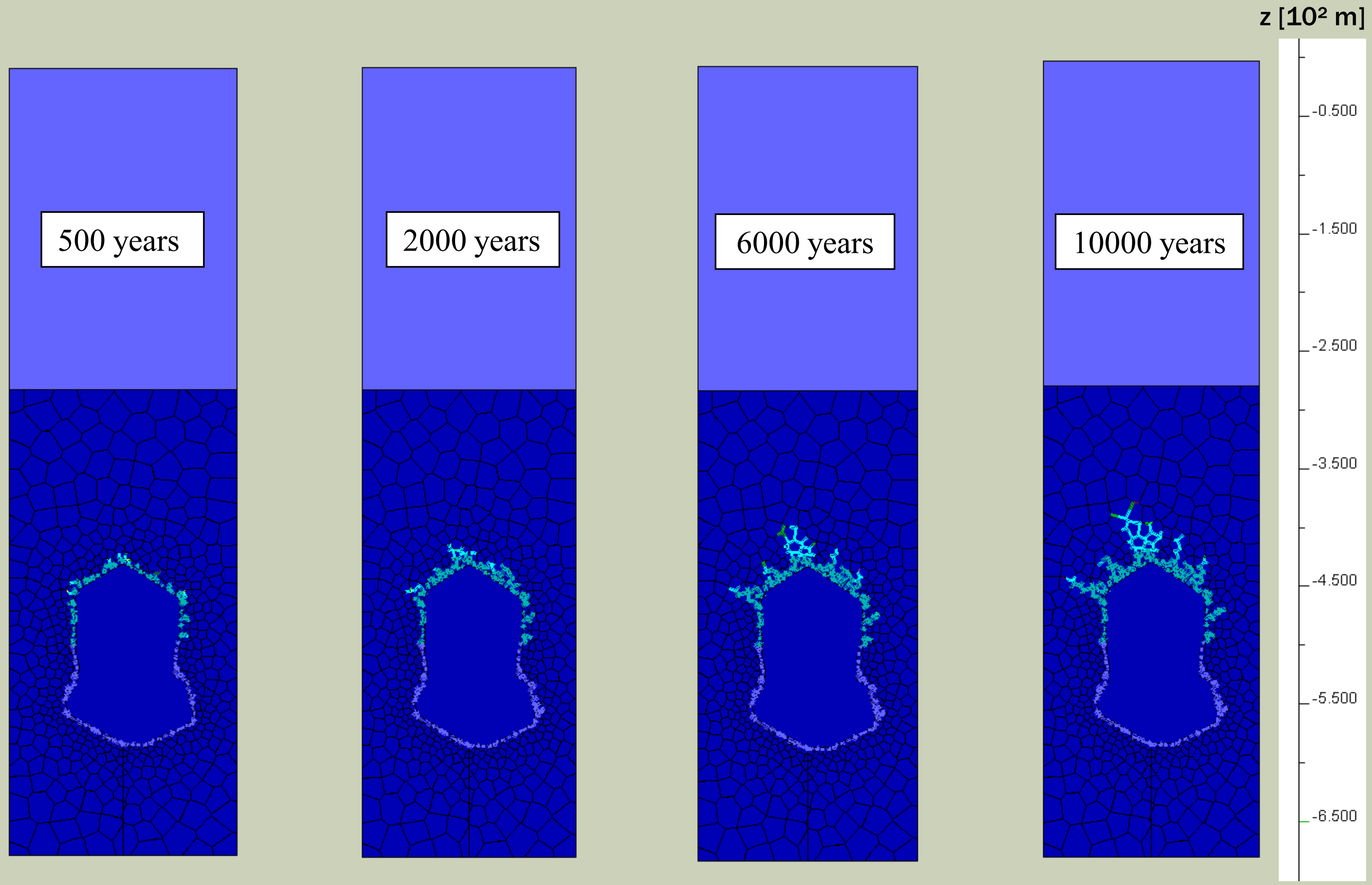
2003 - salt mine "Unterbreizbach"
CO_2-glacier after an underground blow- out

(CO_2 becomes solid below -70 °C)

Rock mechanical approach - rock salt permeability



Time-dependent percolation of brine into the rock salt

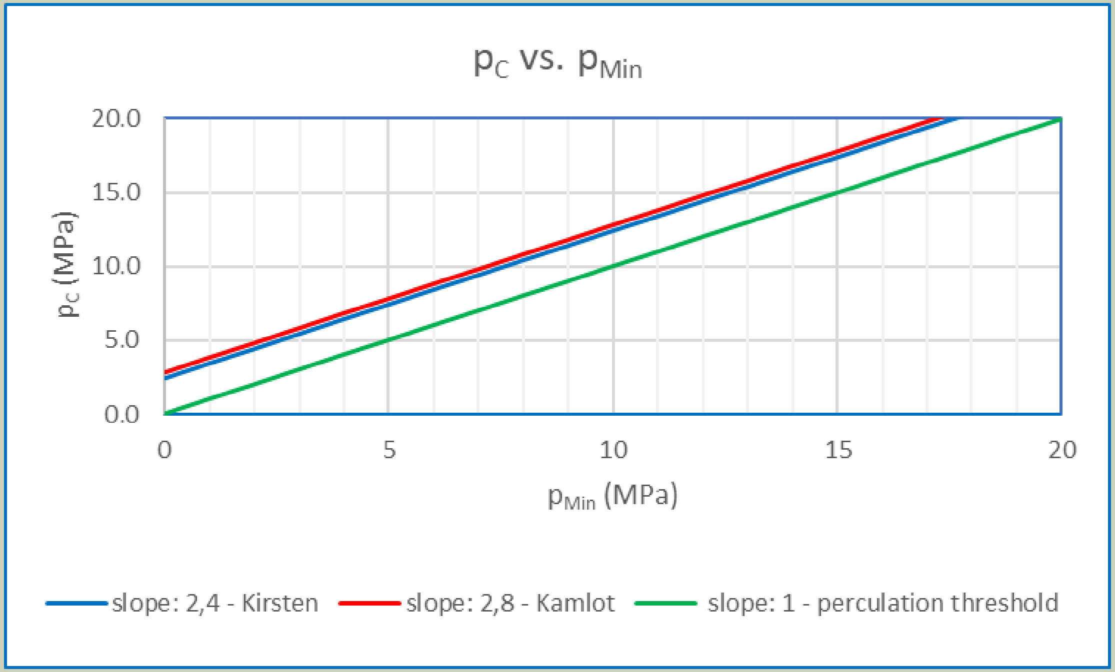


Pressure threshold vs. Frac

From Hydro-frac testing the critical breakdown pressure p_C was determined at different axial/minimum pressure.

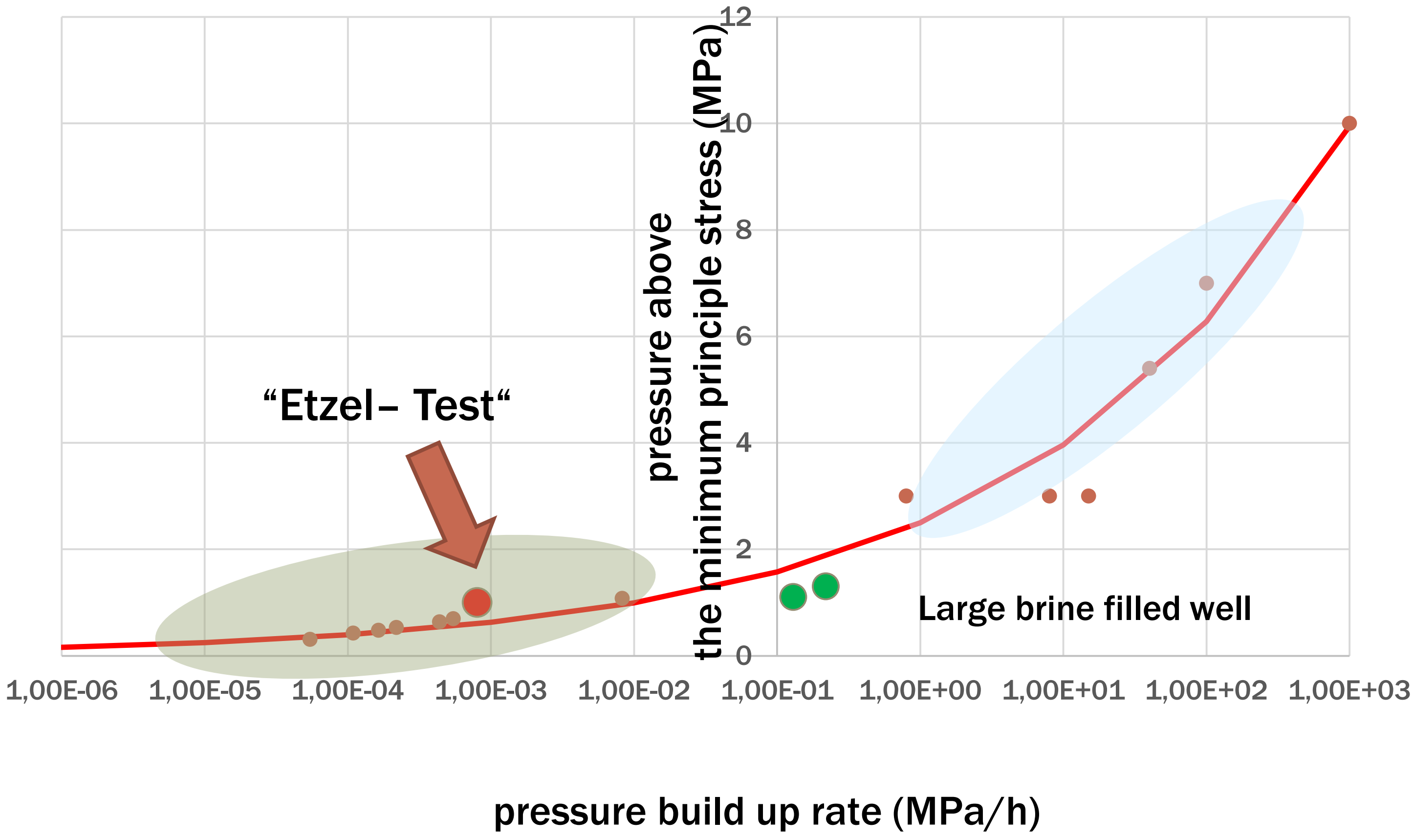
P. Kirsten: "Laboratory Hydraulic Fracturing Experiments in Rock Salt" ; KBB Hannover in "Mechanical Behavior of Salt II"; 1988 page 223 ff

P. Kamlot: "Gebirgsmechaische Bewertung der Geolog. Barrierefunktion des Hauptanhydrits in einem Salzbergwerk" Habilitationsschrift; TUBAF; Veröffentlichung des Instituts für Geotechnik Heft 2009-3, Freiberg 2009



Investigated Pressure range 25 MPa and 40 MPa
@ 8 MPa/h and 20 MPa/h respectively

Test results



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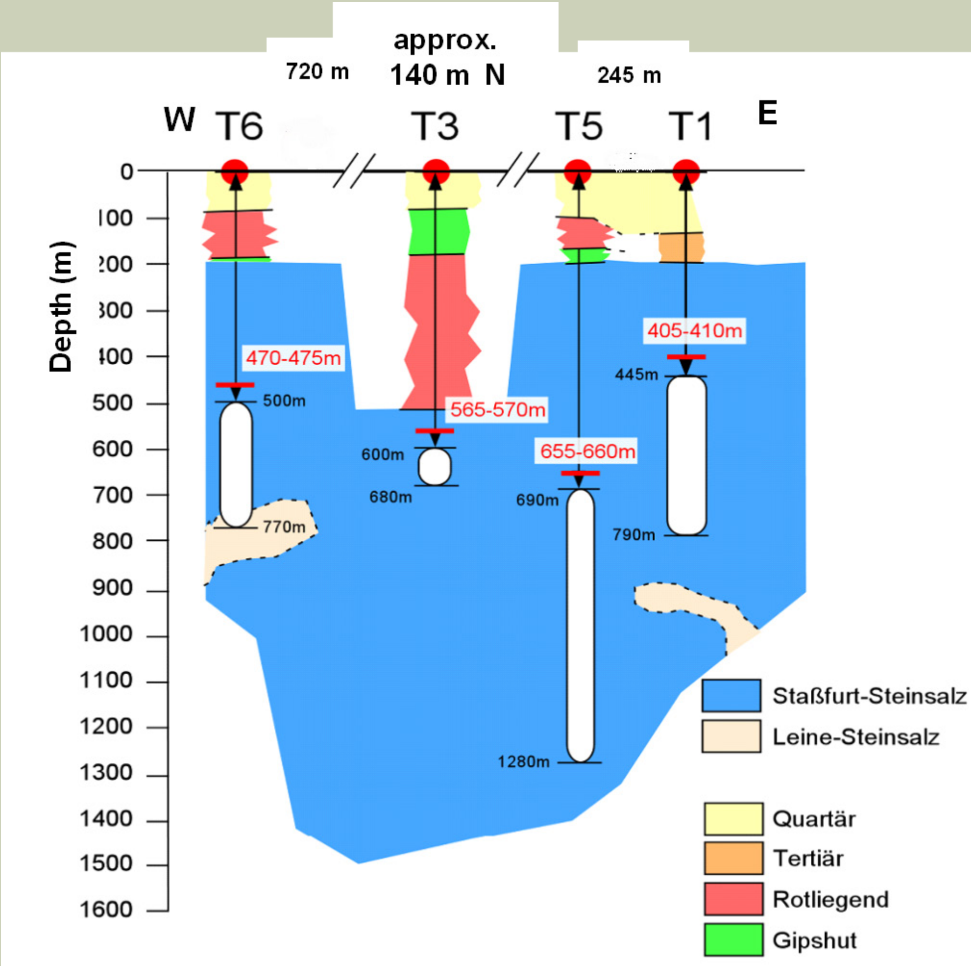
Successful CSA – project cavern field “Stade”



Cavern T1

leaching volume: **1.353 Mio. m³**

Cavern T3

leaching volume: **0.077 Mio. m³**

Cavern T5

leaching volume: **1.54 Mio. m³**

Cavern T6

leaching volume: **1.053 Mio. m³**

Aim of the rock mechanical and geotechnical concept

Aim: Discharging the operator from the government supervision by mining authorities

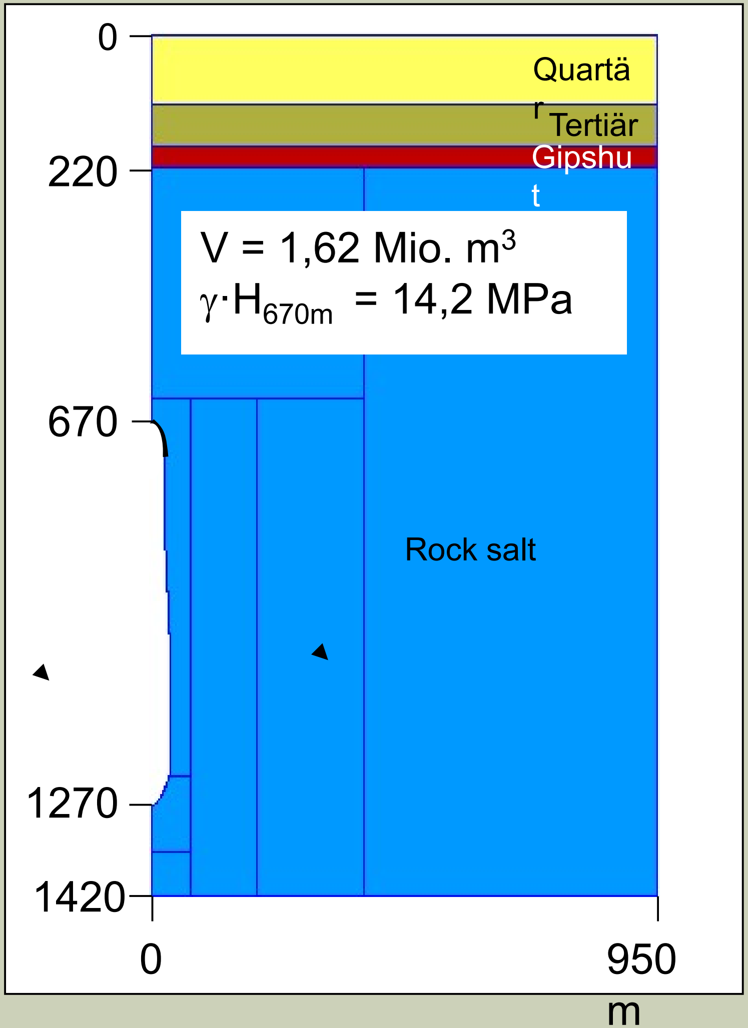
Basis:

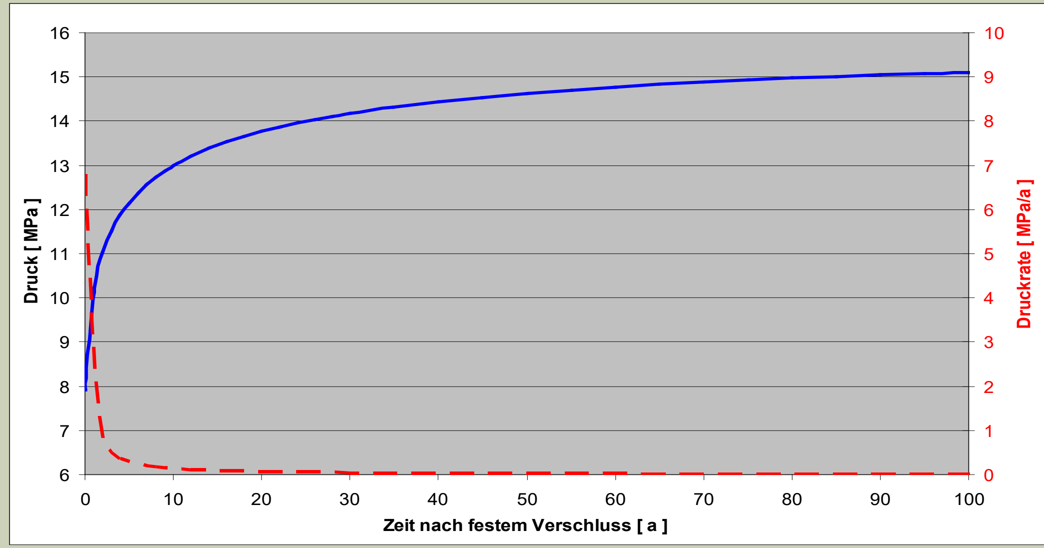
- Available data concerning the geological and geomechanical situation
- Consideration of existing mining and drilling conditions

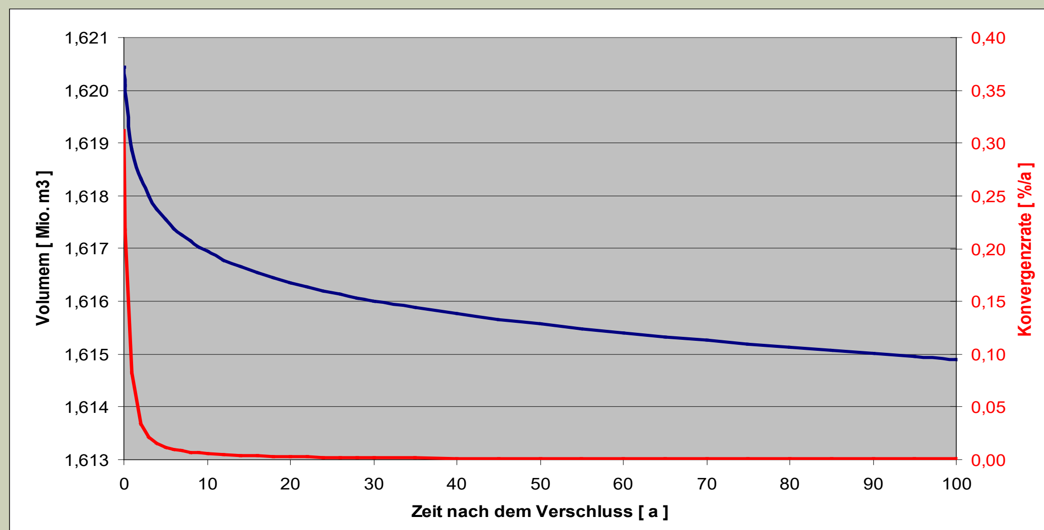
Principles:

- Realization of geotechnical measurements (ultrasonic survey, pressure build-up tests, precision leveling at the surface for initial subsidence)
- Leaving the cavern in a brine filled state
- Sealing the cavern against the surface-leading well straight above the cavern roof
- State of the art backfill of the cavern wells
- Providing evidences of the geotechnical safety of the abandoned cavern field during the post-operation period by rock mechanical modeling

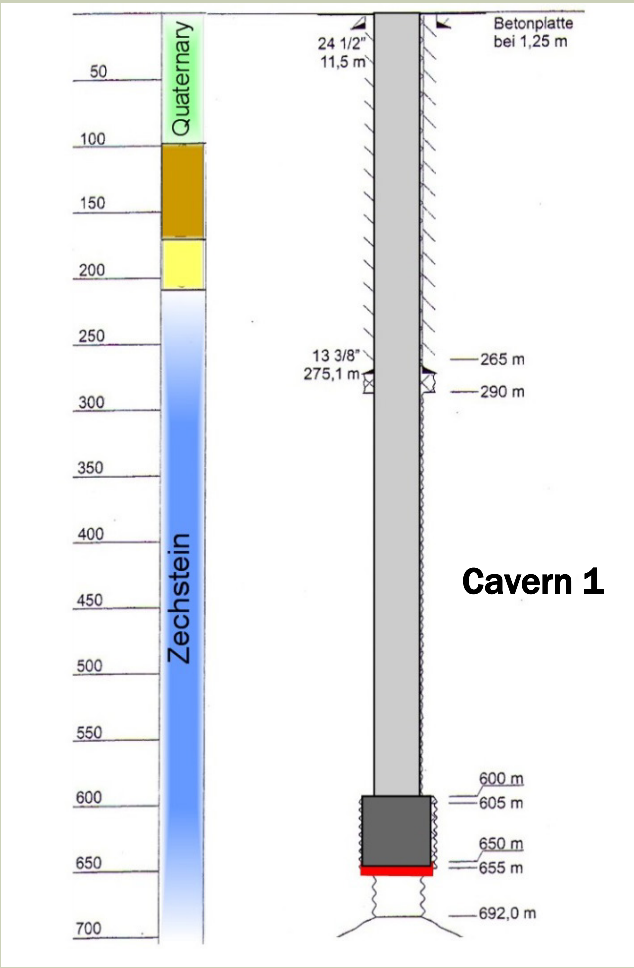
Long-term safety proof of a sealed cavern







Cavern abandonment a location depending solution

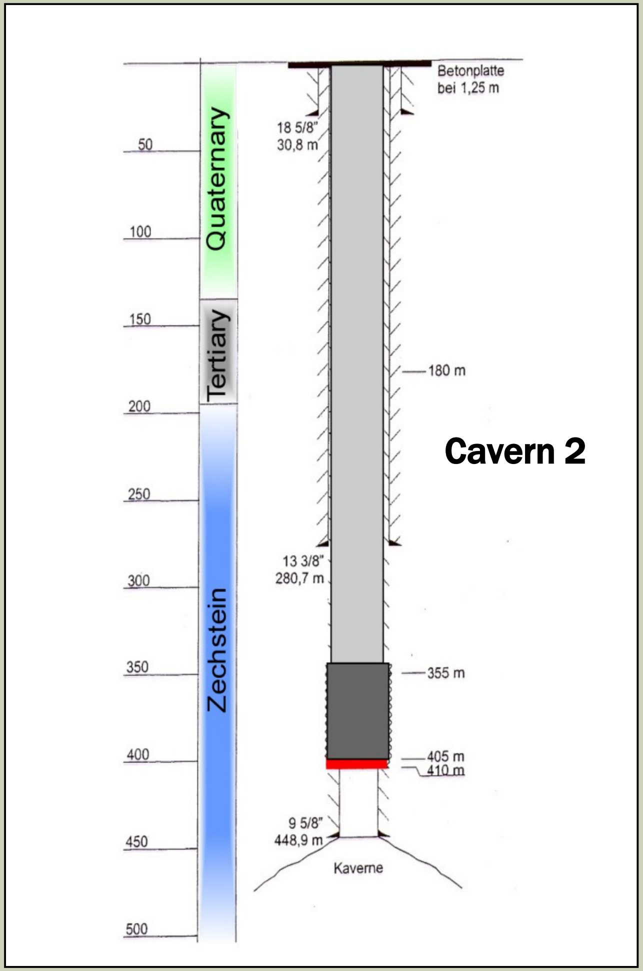


End plate

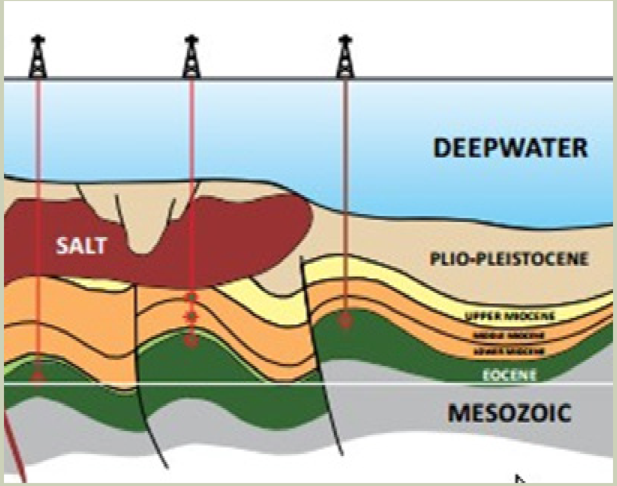
Backfill column
of the well

First cementation
In the rock salt

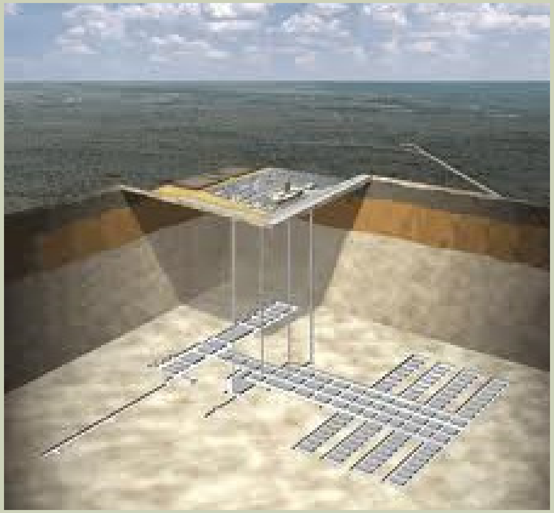
Bridge plug

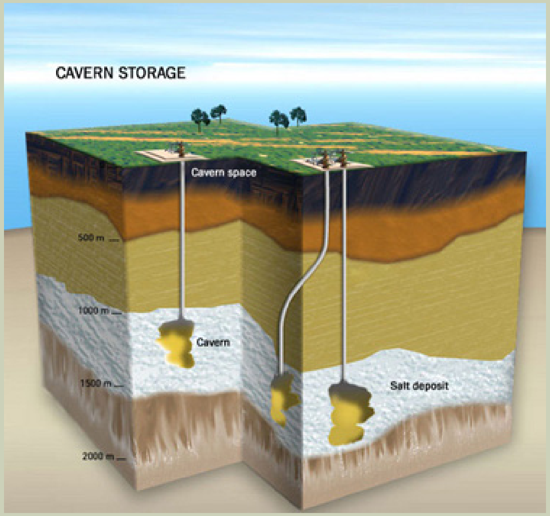


Conclusion - Rock Salt is World's Best Natural Barrier



Generally:
Rock salt is tight





Deformations:

$\varepsilon \Rightarrow$ 100 %

$\dot{\varepsilon} \Rightarrow 10^{-14} \ldots 10^{-11}\ s^{-1}$

Stress:

$\sigma \approx$ few MPa

Temperature:

$T \approx 270 \ldots 400$ K

Forecast periods:

$\Delta t \approx 1 \ldots 10^4$ a