Real Data from Pilot Seals from Repositories in Salt and their Utilization in a Safety Case

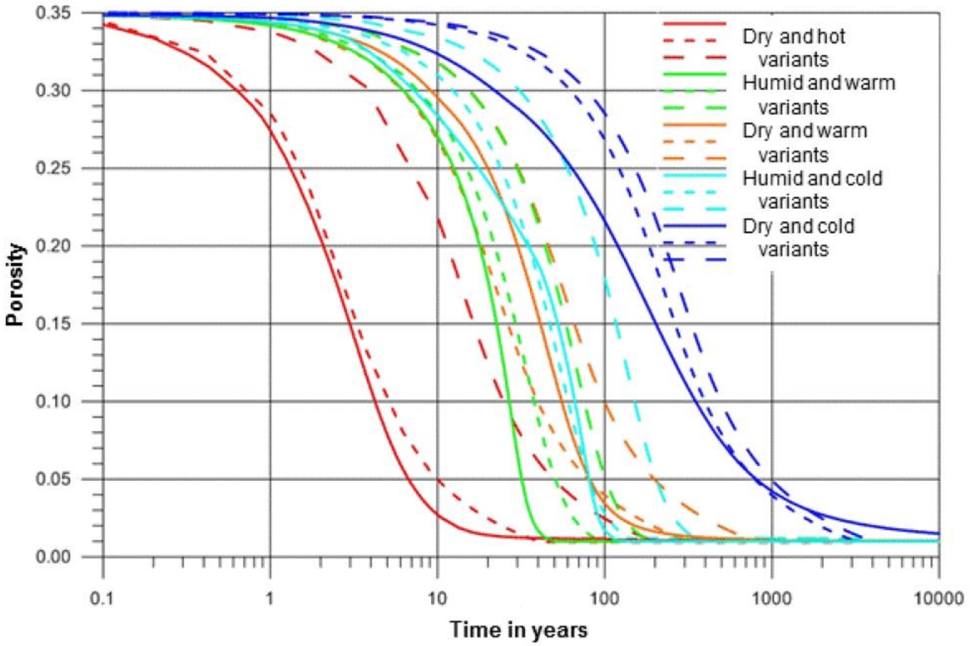
22nd Meeting of the Integration Group for the Safety Case (IGSC), 27 – 29 April 2021
Videoconference

Dr. Nina Müller-Hoeppe (BGE TECHNOLOGY GmbH)

Motivation

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

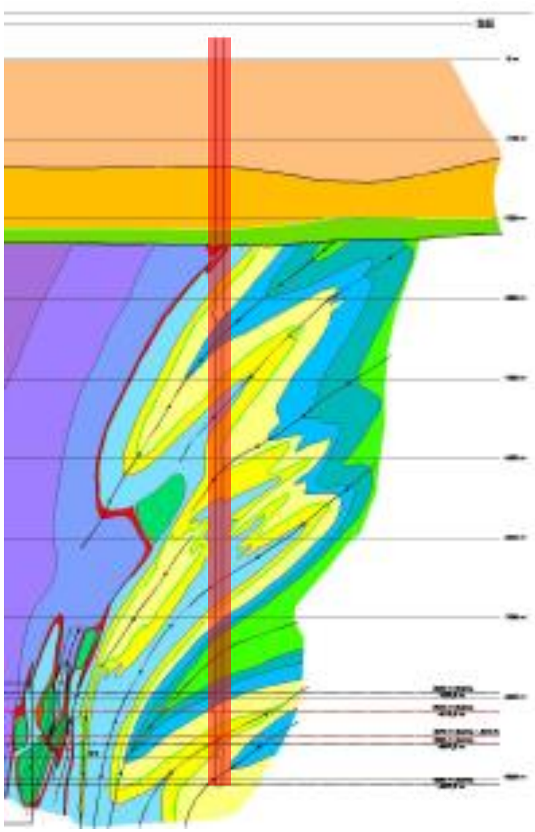
- Safe confinement of radioactive waste in a confinement providing rock zone (CRZ)
- Recovery of the intact salt barrier by compaction of crushed salt
- During the time period until recovery is finalized geotechnical barriers guarantee safe confinement
- Redundancy and spatial separation of geotechnical barriers → shaft and drift seals

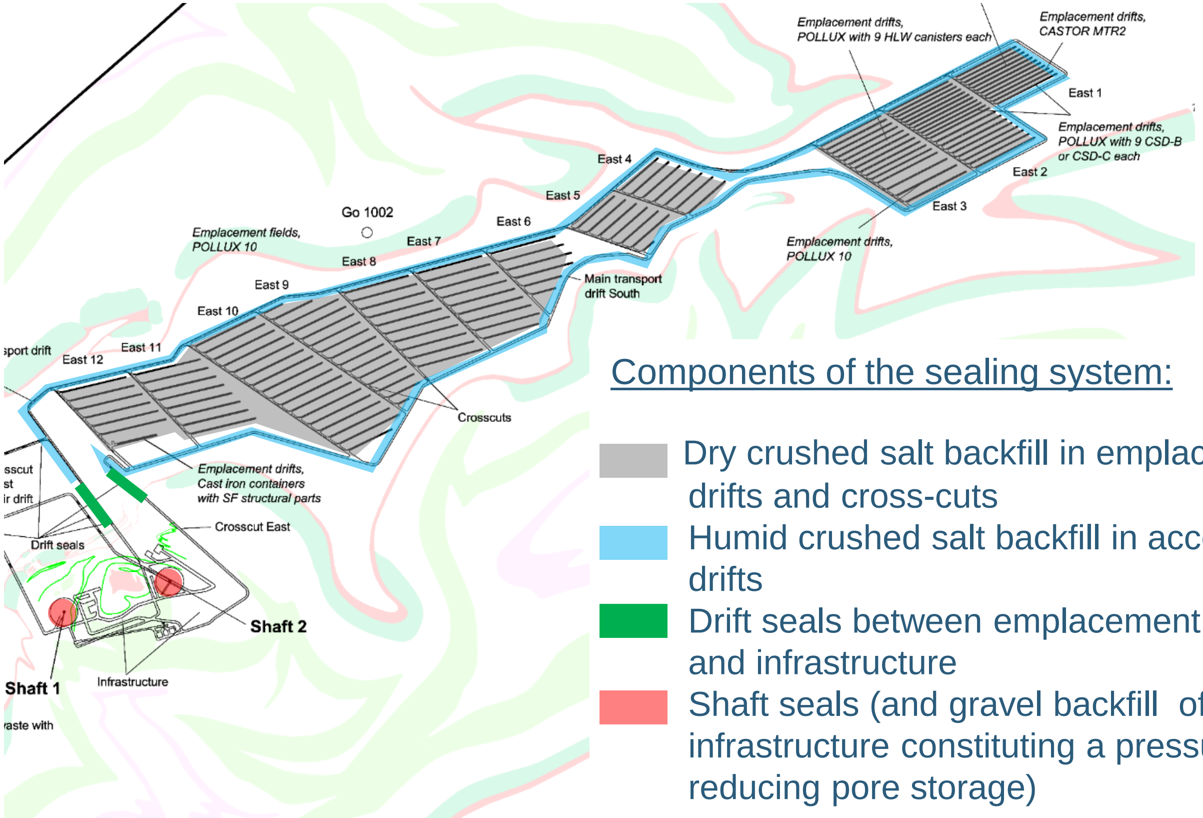


Compaction of crushed salt depending on operating conditions of a salt repository (extrapolated numerically)

Example
Preliminary safety analysis of the Gorleben site

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG





<u>Components of the sealing system:</u>

- Dry crushed salt backfill in emplacement drifts and cross-cuts
- Humid crushed salt backfill in access drifts
- Drift seals between emplacement areas and infrastructure
- Shaft seals (and gravel backfill of infrastructure constituting a pressure reducing pore storage)

Focus on drift seals – Salt/Sorel concrete

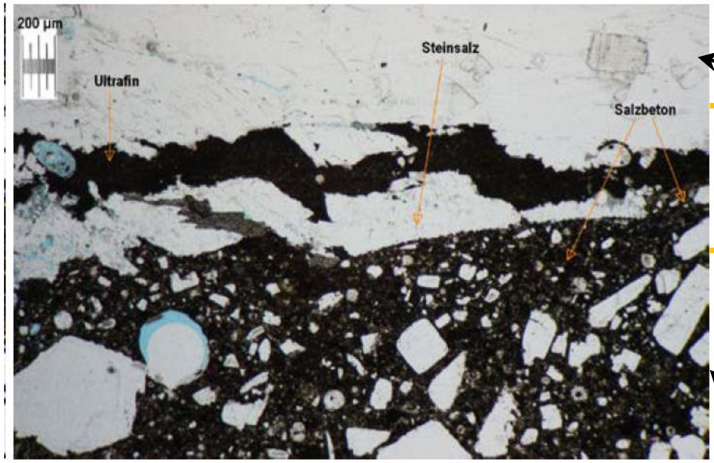
Mixtures (building site)	Binding agents	Mixing liquid	Aggregate	Additive
Salt concrete Type Asse (Asse)	Cement (380 kg/m³)	NaCl-solution (198 kg/m³)	Crushed salt (1,496 kg/m³)	-
Salt concrete M2 (ERAM)	Cement (328 kg/m³)	Water (267 kg/m³)	Crushed salt (1,077 kg/m³)	Coal fly ash (328 kg/m³)
Sorel concrete 29.6 A2 (Asse)	MgO (120 kg/m³) & calcinated dolomite (225 kg/m³)	$MgCl_2$-rich solution (490 kg/m³)	Crushed salt (900 kg/m³)	Slate powder (255 kg/m³)
Sorel concrete A1 (Asse)	MgO (218 kg/m³)	$MgCl_2$-rich solution (485 kg/m³)	Crushed salt (1,237 kg/m³)	-

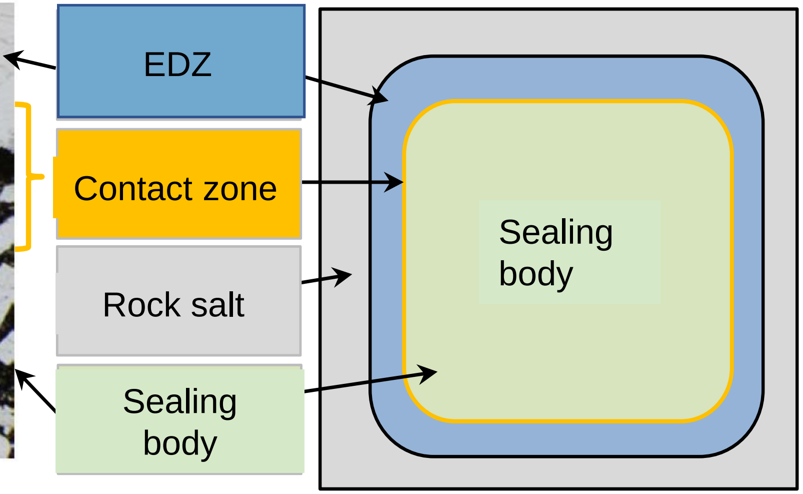
Elements of a drift seal

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Basically, a drift seal consists of three elements acting in parallel:

- The sealing body made of salt- or sorelconcrete
- The EDZ in salt close to the drift contour
- The contact zone between sealing body and EDZ





Tests <u>without</u> hydromechanical loading

Investigation of the Asse-Seal (salt concrete)

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Motivation

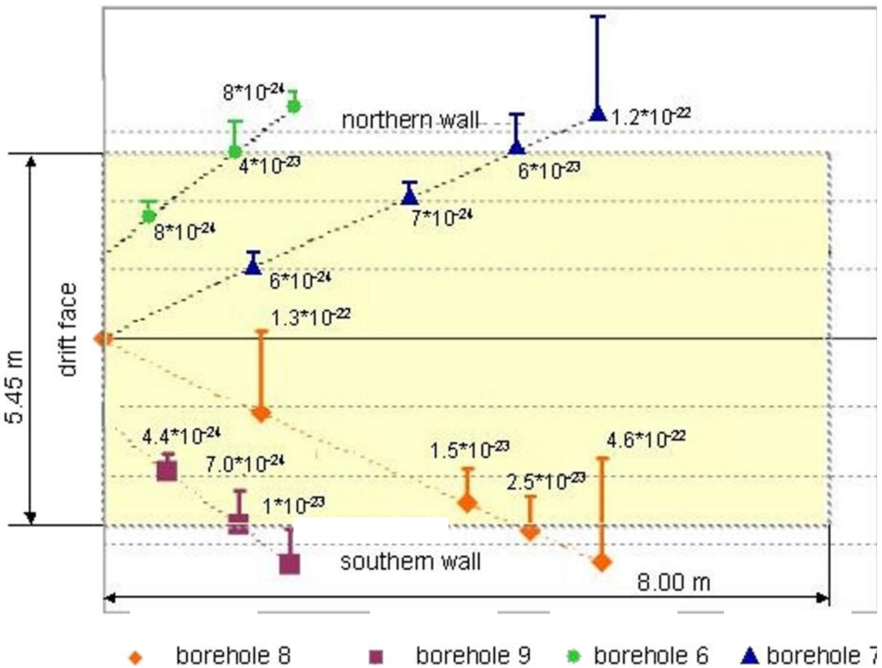
In the case of concrete structures constituting a barrier against water contaminants technical guidelines require investigations of contact zones at comparable structures as they may act as preferential pathways

- The Asse-seal made of salt concrete (abandoned in situ research project) was available as a comparable structure to the conceptual planning of ERAM drift seals
- The following in situ investigations were performed:
  - Permeability measurements in the contact zone and for comparison in the sealing body and the (former) EDZ as well
  - Stress measurements in order to transfer the stress state to ERAM in situ conditions
  - Ultrasonic measurements in order to detect imperfections of the overall contact zone

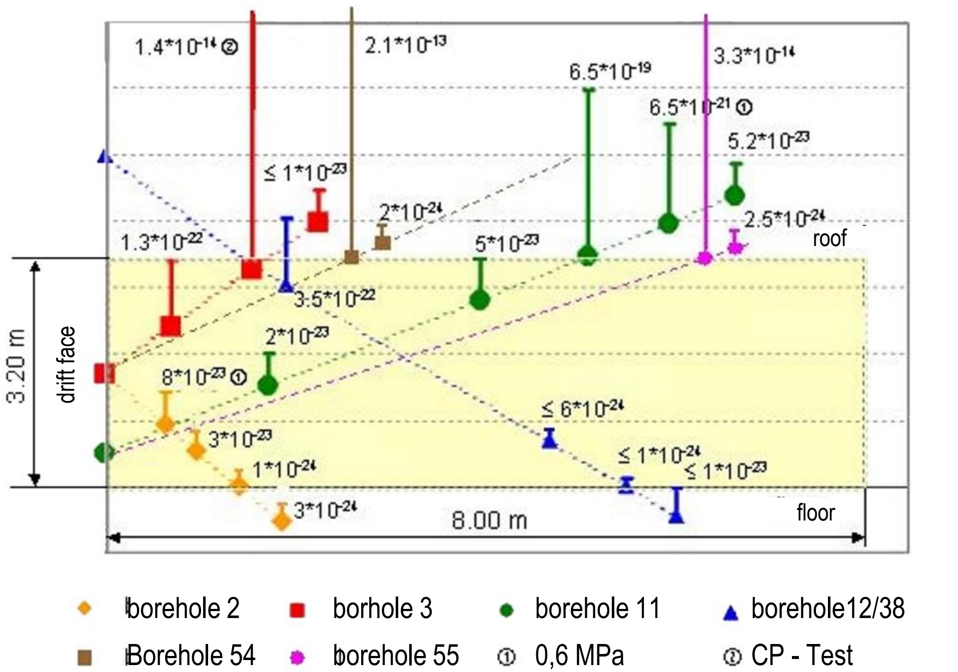
Results of permeability measurements

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Plan view

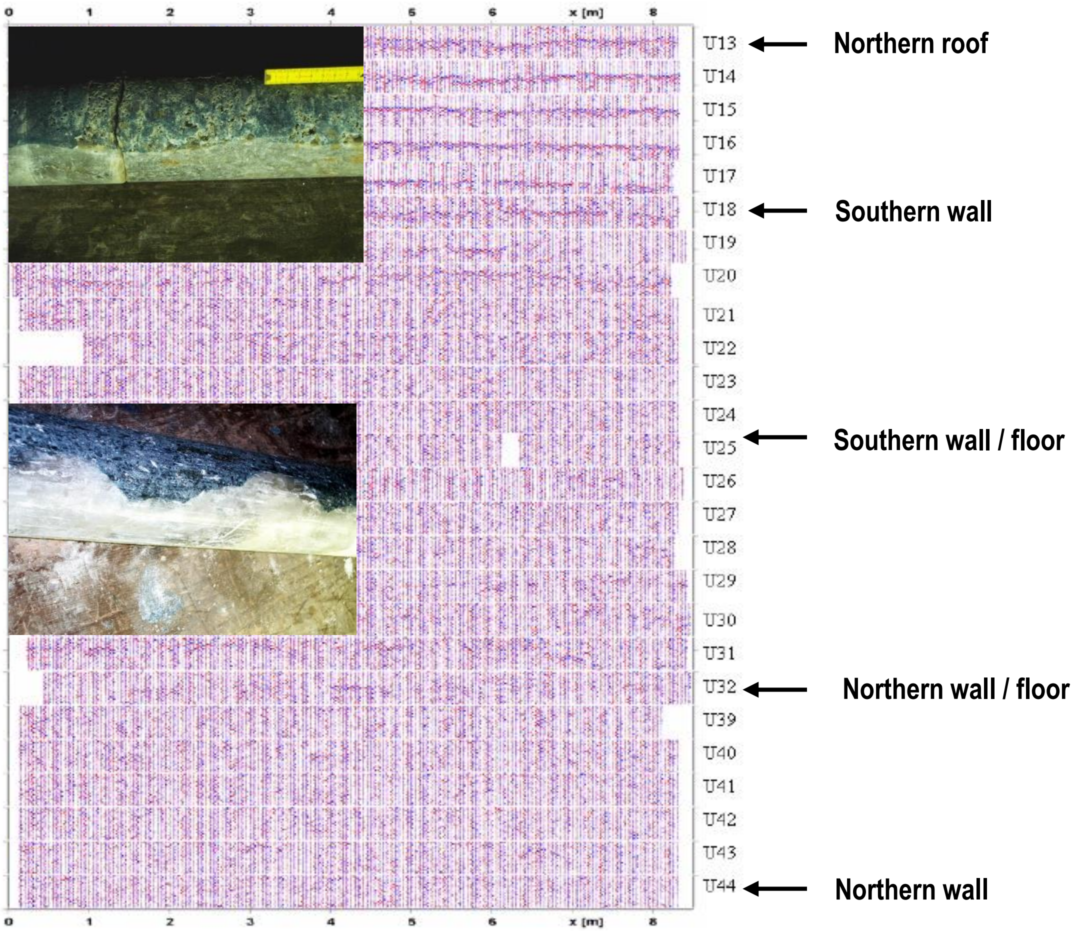


Side view



- For evaluation of the seal´s hydraulic resistance 34 measurements from boreholes were available

Results of ultrasonic measurements



- Photo documentation from the building phase showed that high permeability values in the roof resulted from a hand filled gap → Not representative!

<u>Lesson learnt</u>
Inclining the roof of salt contour in order to improve future drift seal constructions

Evaluation of permeability values using Eurocode „Geotechnical Design“

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

- Derivation of „cautious estimates“ for permeabilities of sealing body, contact zone and, excavation damaged zone/rock salt

Element	5%-Fractile [m²]	Upper confidence limit of mean value [m²]	Direct design value with $p_f < 0.1\%$ [m²]	Mean value [m²]
Sealing body	$3 \cdot 10^{-22}$	$5 \cdot 10^{-23}$	$3 \cdot 10^{-21}$	$3 \cdot 10^{-23}$
Contact zone except roof	$4 \cdot 10^{-22}$	$7 \cdot 10^{-23}$	$1 \cdot 10^{-20}$	$1 \cdot 10^{-23}$
Contact zone roof	$6.2 \cdot 10^{-13}$	$4.7 \cdot 10^{-13}$	$6.3 \cdot 10^{-12}$	$4.6 \cdot 10^{-14}$
Former EDZ	$2 \cdot 10^{-21}$	$1 \cdot 10^{-22}$	$8 \cdot 10^{-20}$	$2 \cdot 10^{-23}$

- This state of knowledge was applied to the pilot seal BW-K2C-750-1 in the Asse mine in order rate the permeability of the sealing body made of Sorel concrete A1.

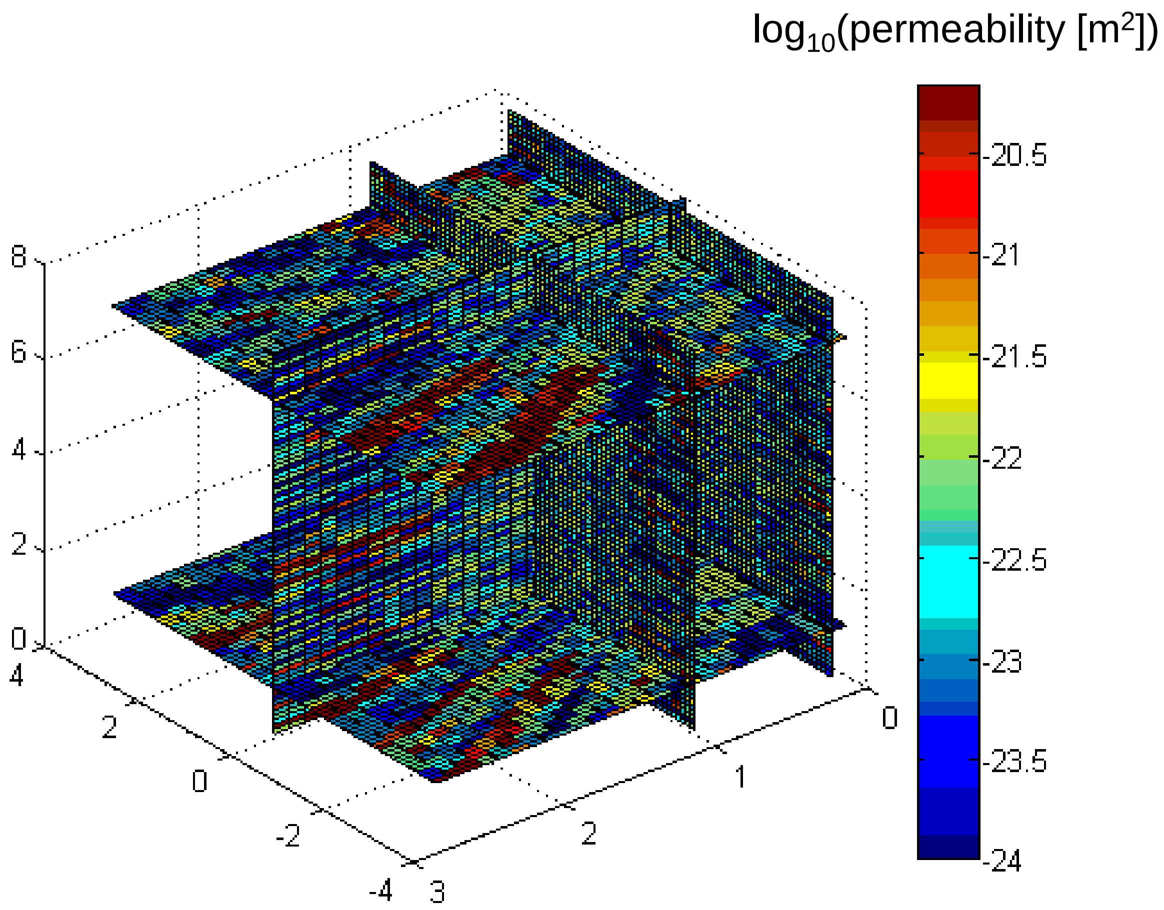
Evaluation of permeability values using a geostatistical approach

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

- Sampling for spatial variability
  - Each sample is assumed as representative for the whole seal structure
  - In reality, though, all samples come from one and the same seal and represent hydraulic conductivity at different locations of this seal
- Question
  - How to „upscale“ these data (packer scale 10 cm) in order to derive conclusions for the whole seal?
- Geostatistical approach
  - Consider „true“ seal (the one the data come from) as one realisation of a location-dependent random variable („random function“)
  - Derive conclusions about pdf and spatial behaviour of the random function from the data („variography“, central: „assumption of stationarity“)
  - Sample realisations of the so described random variable (one realisation corresponds with one „possible seal“)
  - Calculate hydraulic flow (for given pressure gradient) for each realisation and calculate effective conductivity (permeability)
  - Perform statistics for these effective conductivities (permeabilities)

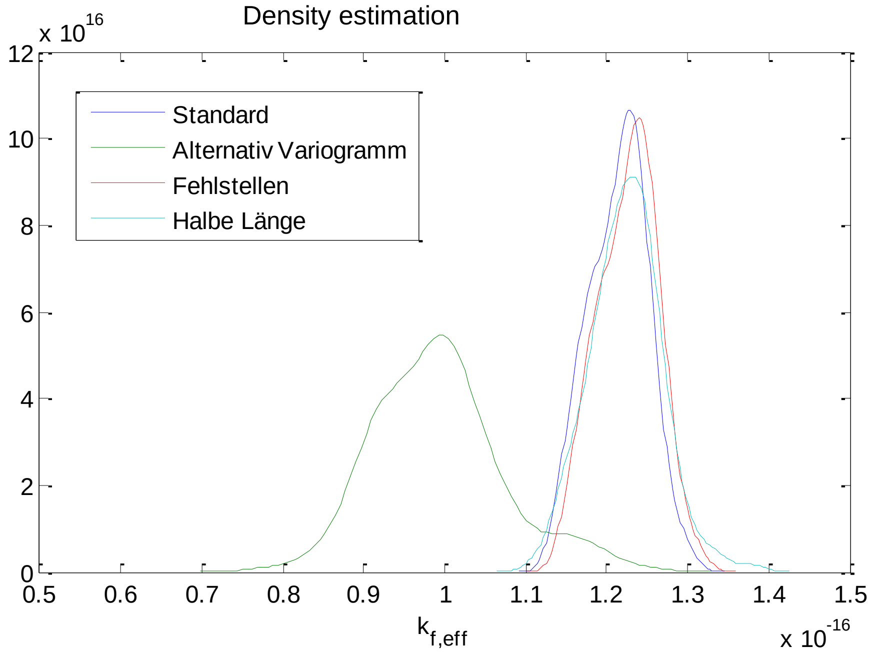
$$Qt = \sum_{i=0}^{n} q_i$$

Example - One realization



Effective conductivity

- Statistics for effective conductivity (different model assumptions)



- Conclusion

- For a seal which is correctly described by the underlying assumptions, the effective conductivity is with a likelihood of 1/10,000 smaller than $1.3 \cdot 10^{-16}$ m/s (permeability $1.3 \cdot 10^{-23}$ m^2, statistical confidence 95 %).

Comparison - Geostatistics vs Eurocode

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

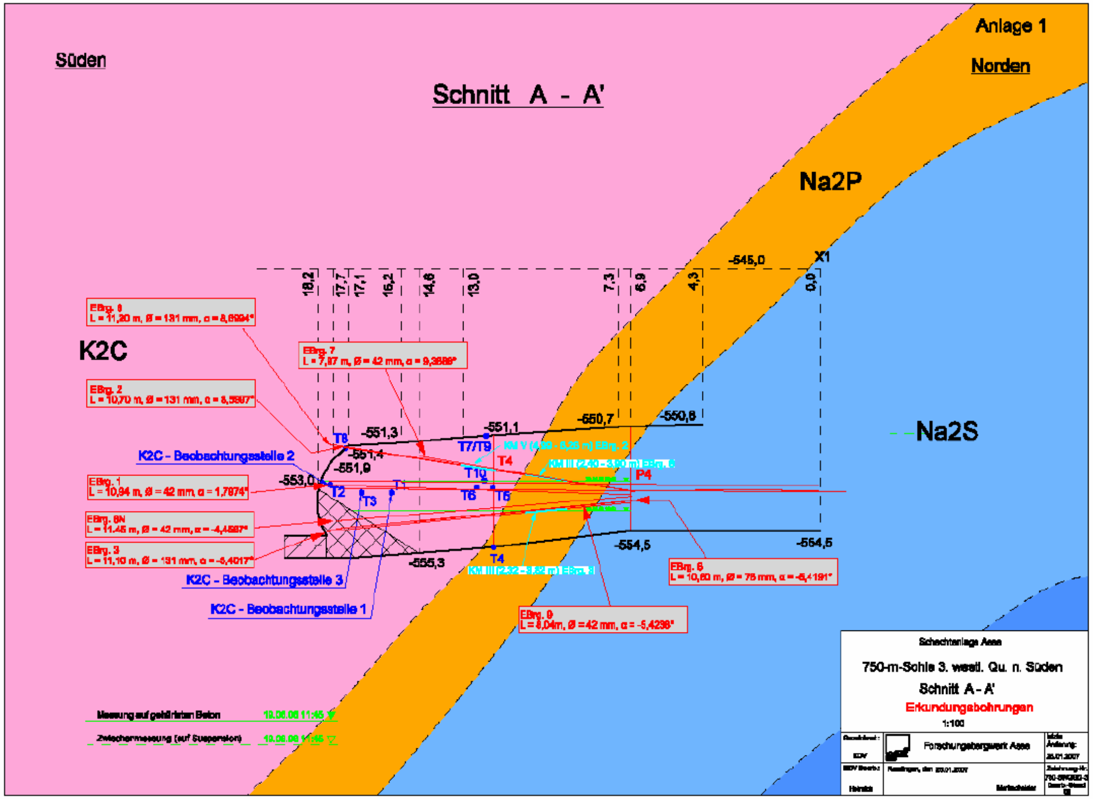
- ➢ Integral permeabilty using geostatstical methods
- For a seal which is correctly described by the underlying assumptions, the effective conductivity is with a likelihood of 1/10.000 smaller than $1{,}3 \cdot 10^{-23}$ m^2 (statistical confidence 95 %).

- ➢ Integral permeability using European Standard of Geotechnical Design (EN 1997)
- Upper confidence limit of integral permeability $6.7 \cdot 10^{-23}$ m^2
- Mean value of integral permeability $2.6 \cdot 10^{-23}$ m^2

- ➢ The upper confidence limit of the mean value (reliable mean value) according European Standard of Geotechnical Design can reliably be applied in practice

Pilot seal BW-K2C-750-1 – Sorel concrete

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG



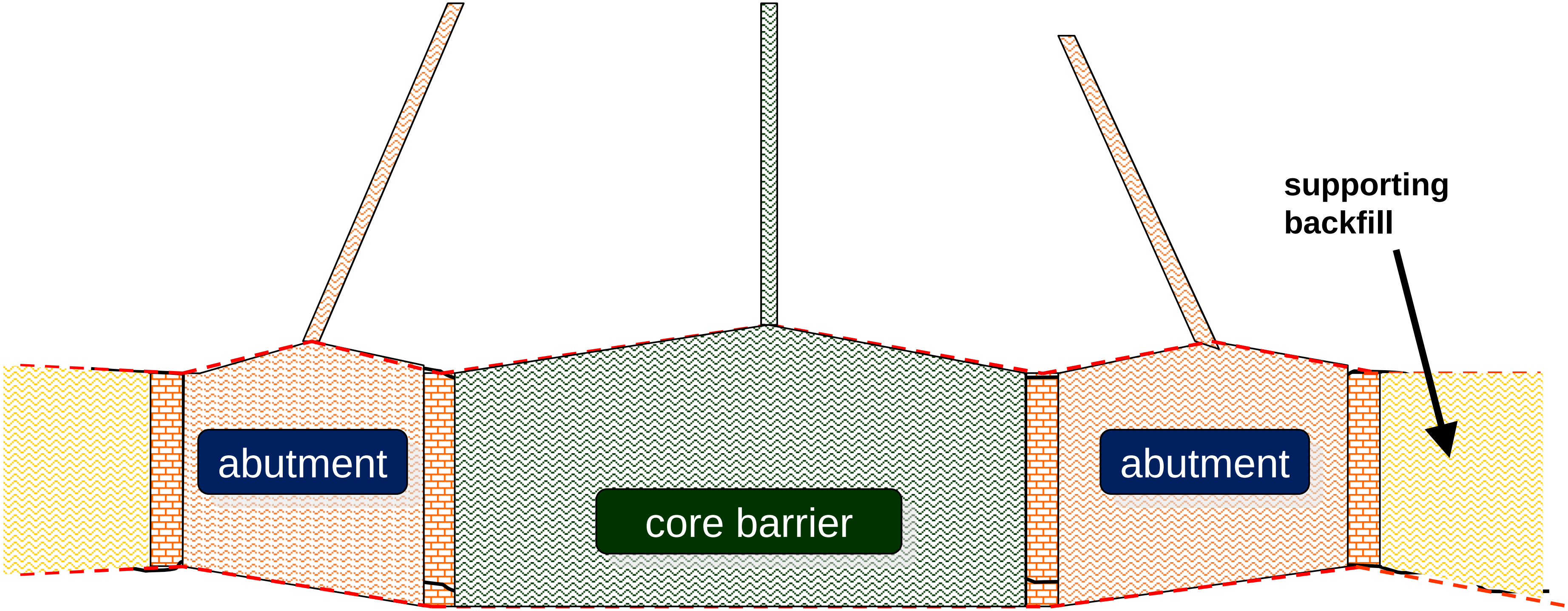
➢ Reliable mean value of sealing body (upper limit) 4.5E-18 m² ~ 5E-18 m²

Sealing body
Measured permeability values [m²]
1.00E-18
1.20E-19
7.00E-18
2.20E-18
1.20E-18
3.00E-18
2.70E-17
1.80E-18
4.00E-18
1.20E-18
3.00E-18

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Tests <u>with</u> hydromechanical loading via pressure chamber

Finally: Concreting of the core barrier (complete)

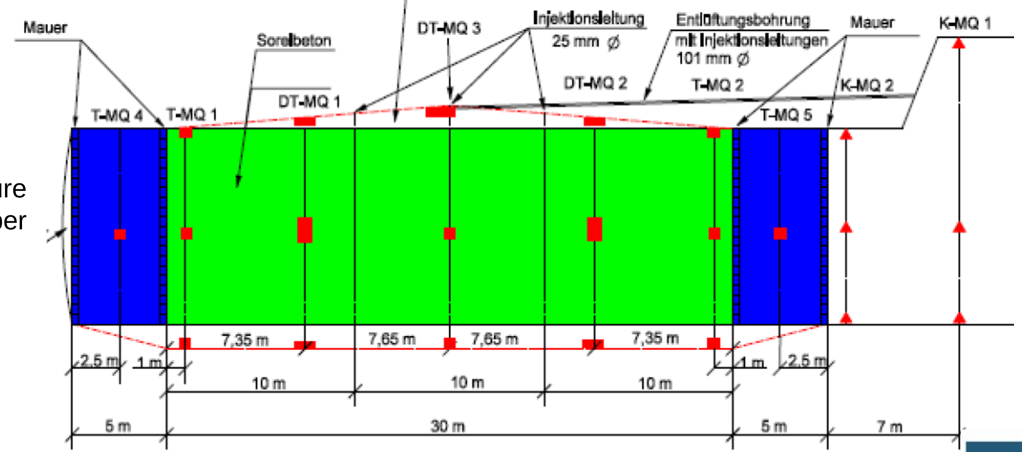


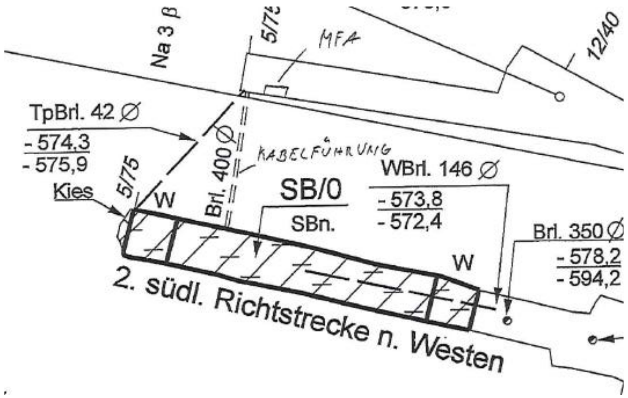
Pilot seal A2 (PSB A2)

- <u>Construction features (2002-2003)</u>
  - Based on mining experience the EDZ was removed shortly before concreting of abutments and core barrier
  - The roof was inclined in order to achieve positive locking to sealing body
  - The sealing body was made of a very low permeable but soft building material (Sorel concrete 29.6 A2) in order to avoid potentially crack-inducing stress peaks
  - Installation of measuring devices – temperature and total pressure

Removal of EDZ (0.2 – 0.5 m)

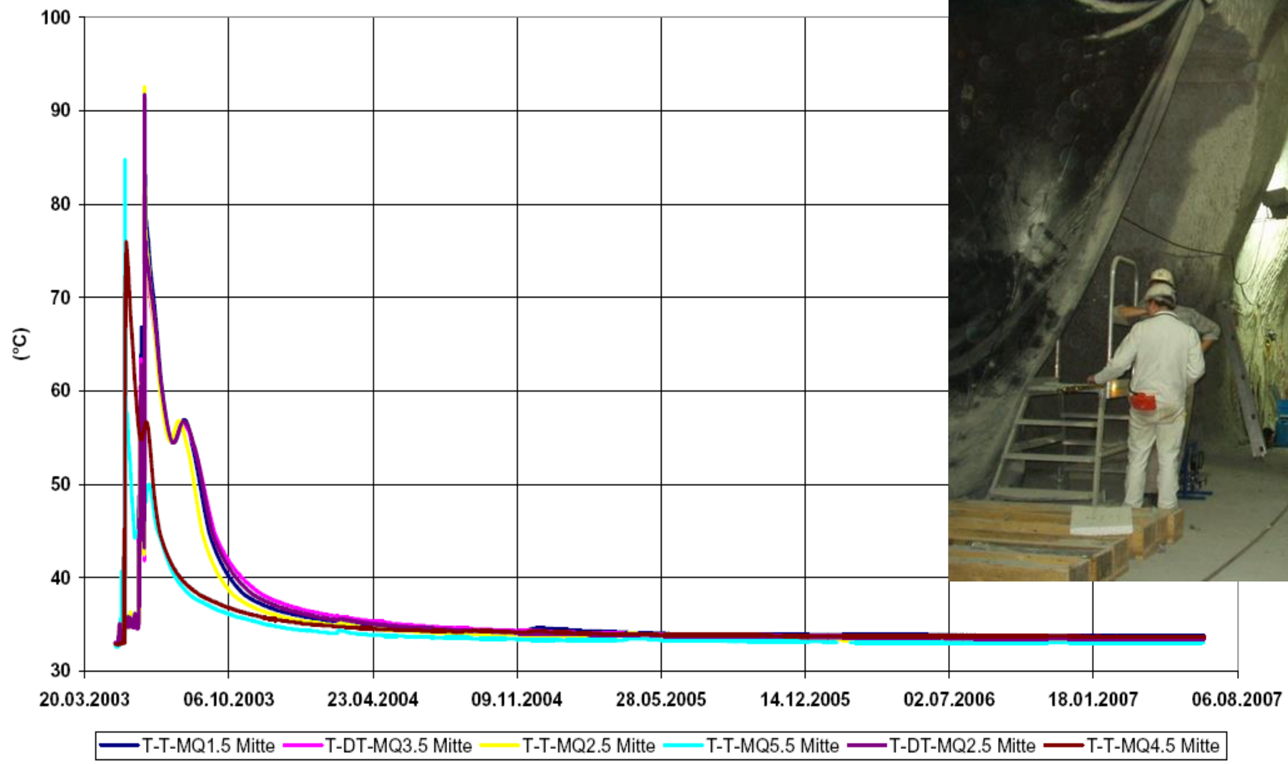
Pressure chamber



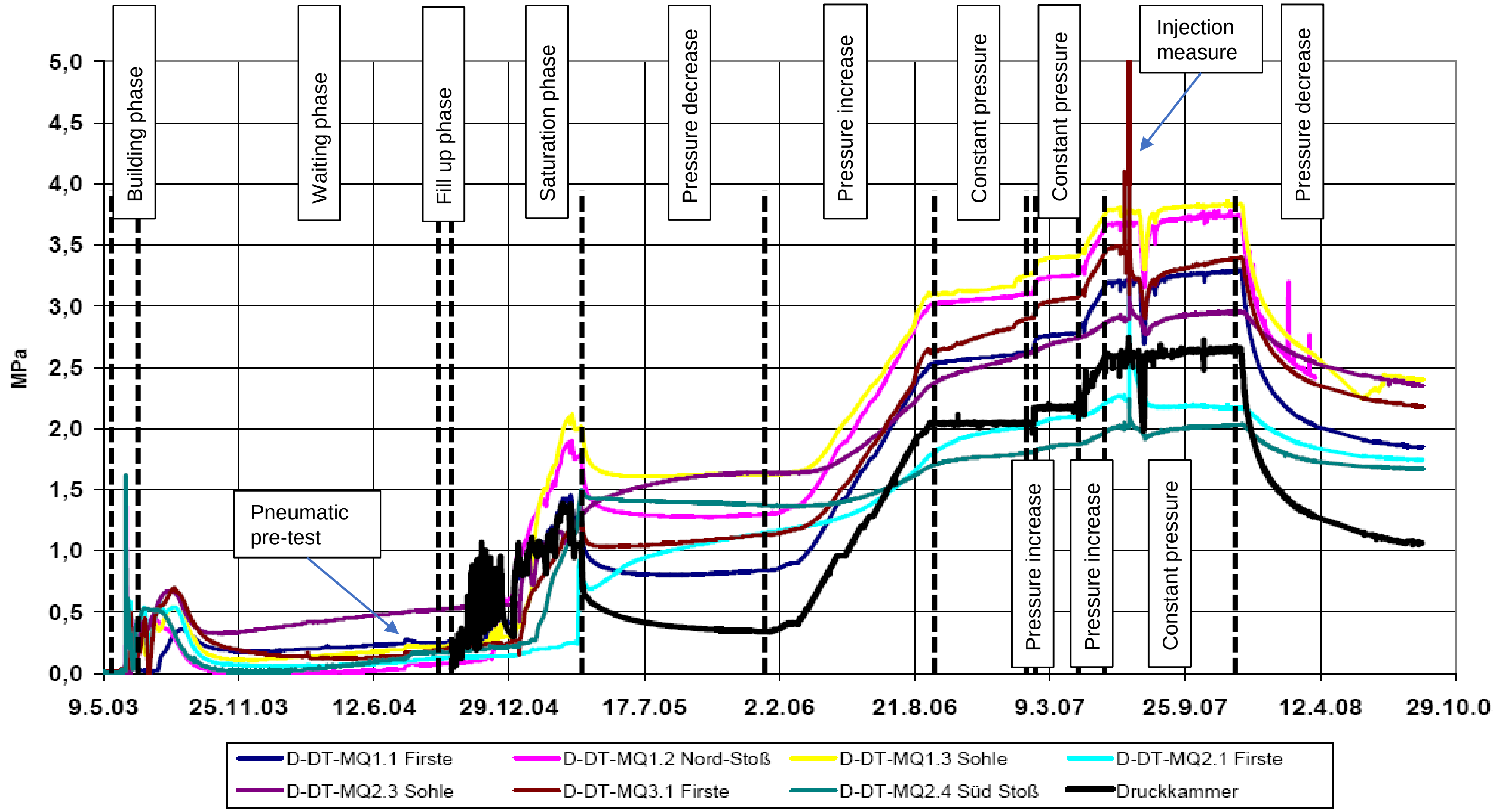


PSB A2 – Construction phase

PSB A2 center – temperatures versus time

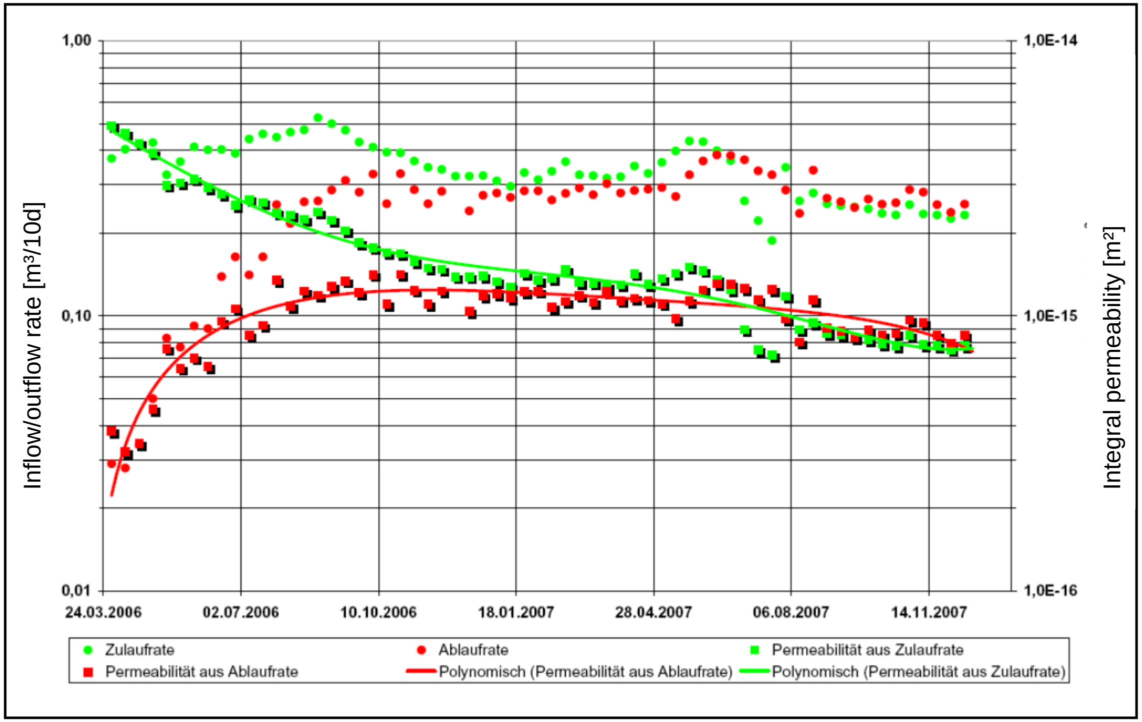


PSB A2 – Pressure build-up phase



PSB A2 – Integral permeability

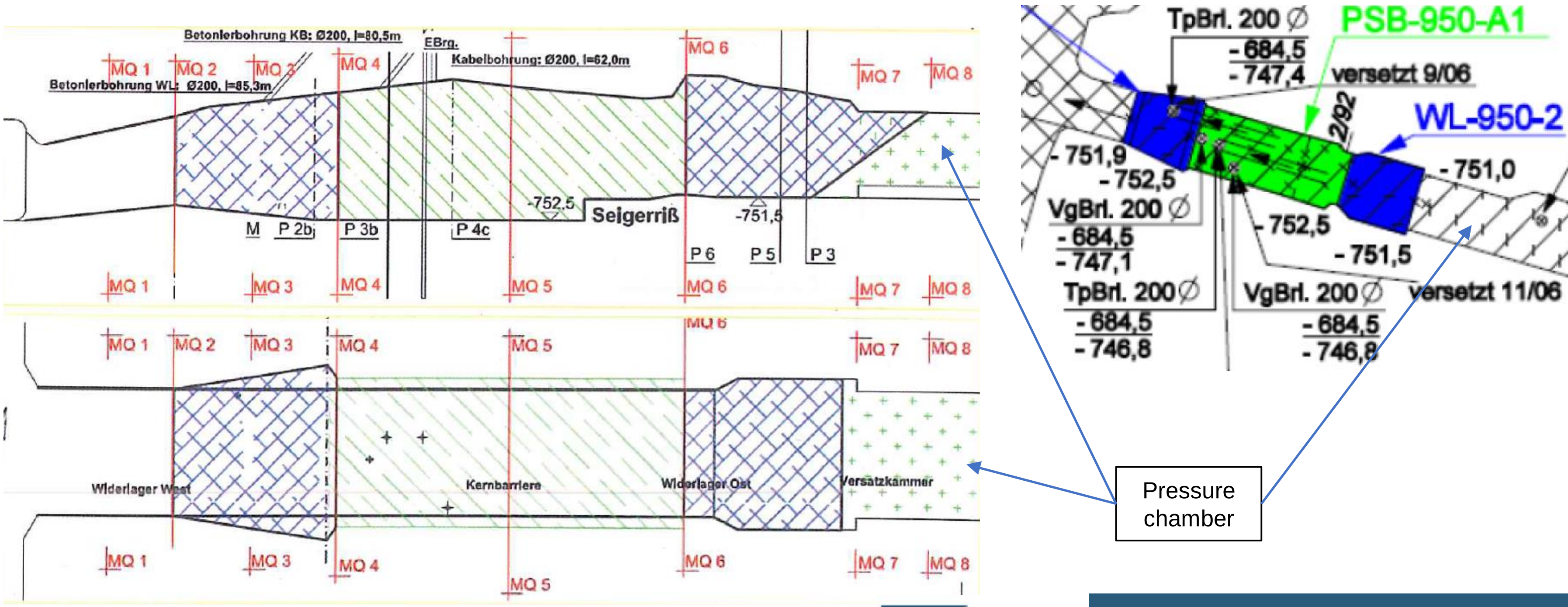
BUNDESGESELLSCHAFT FÜR ENDLAGERUNG



- <u>Lessons learnt from PSB A2</u>
  - Removal of EDZ according to mining experience is not sufficient
  - → Prospective removal of EDZ is based on measured data
  - Selection of „soft“ but low permeable building material is not favourable
  - → EDZ acts as preferential pathway
  - → Use of „stiff“ and low permeable building material

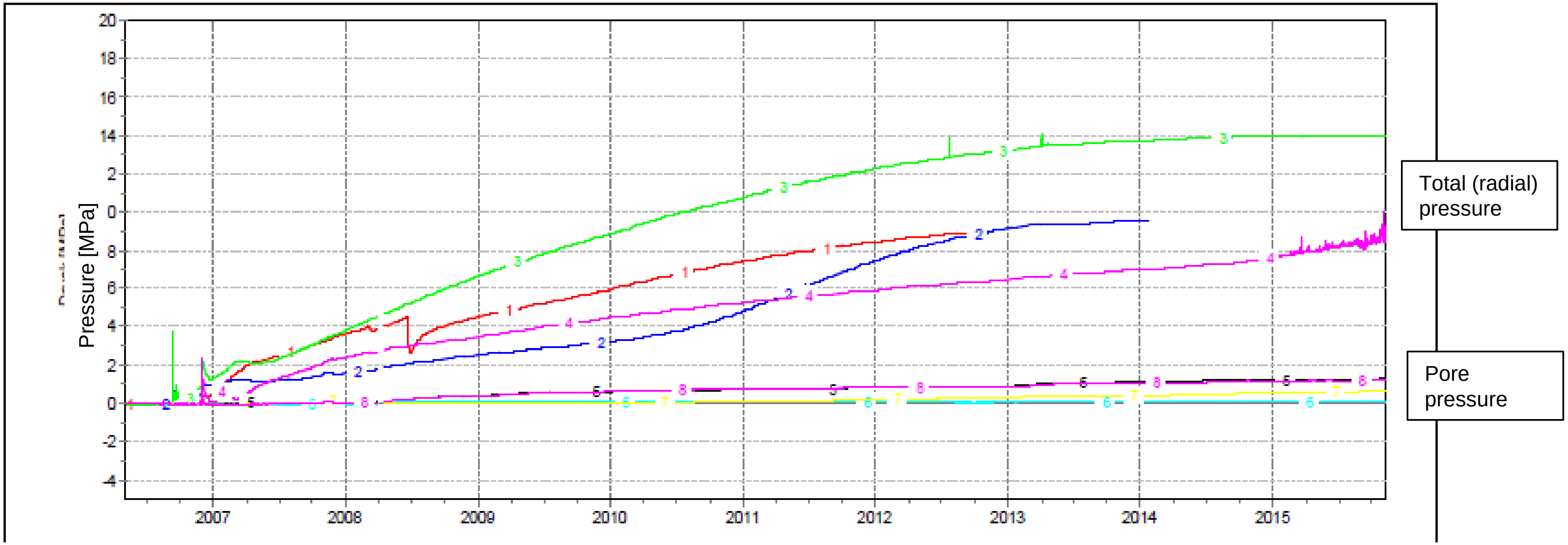
Pilot seal A1 (PSB A1)

➢ Improved construction features (2006)
- Removal of EDZ based on measured values
- Selection of „stiff“ building material for sealing body
- Installation of measuring devices – temperature, total pressure, pore pressure



Pilot seal A1 (PSB A1)

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG



Pore pressure remained well below total pressure

→ No pressure decrease with time

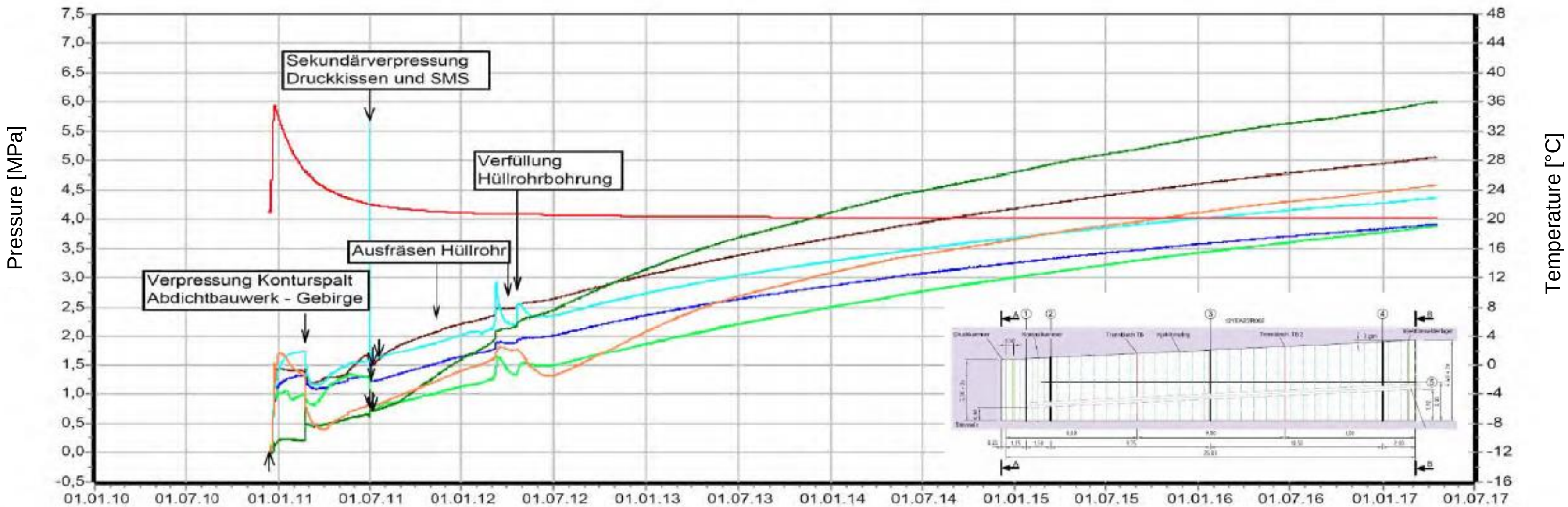
→ PSB A1 is lower permeable than PSB A2

- <u>Lesson learnt from PSB A1</u>
  - Use of „stiff“ building material accelerates rock pressure build-up

  → Total pressure well above pore pressure prevents pathways via EdZ

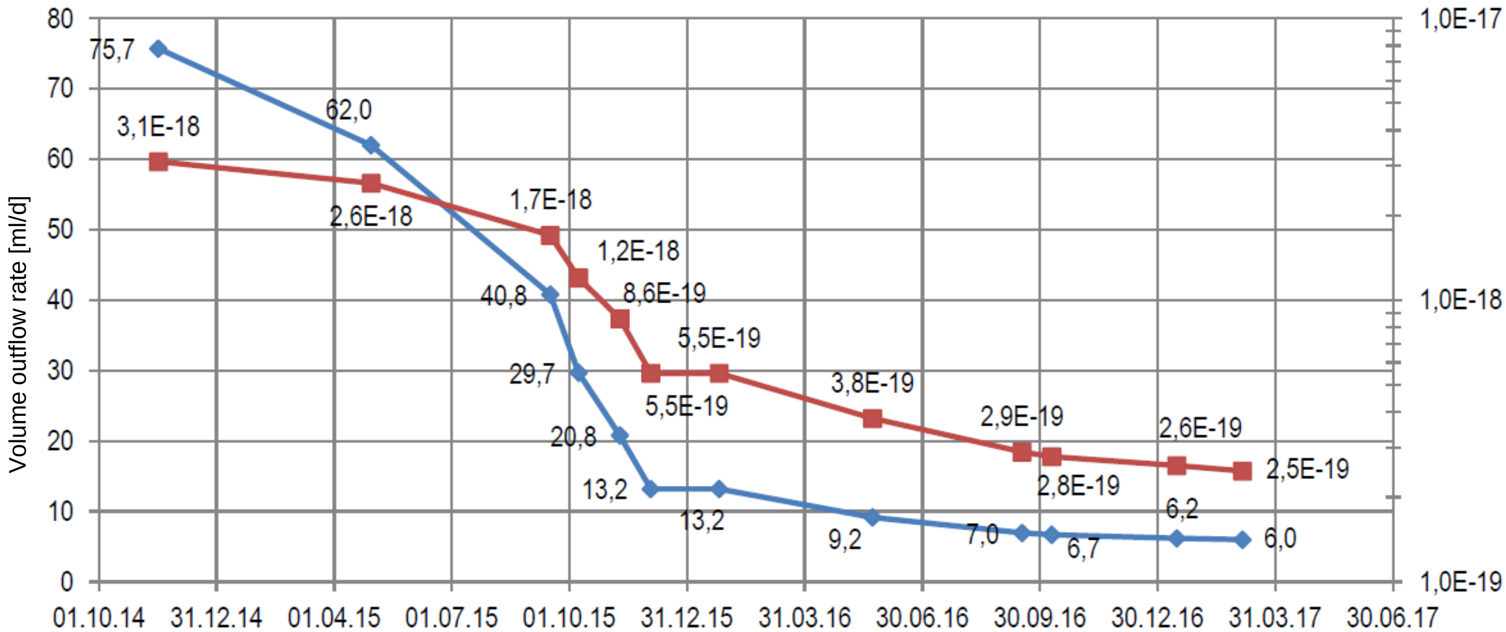
ERAM pilot seal
„Abdichtbauwerk im Steinsalz“ – salt concrete

- <u>Special test specification (2010)</u>
  - Keep brine pressure below total (radial) pressure



Messlokation	Grubenraum	Bohrung	Messstelle	Kurve	Messsystem	Position	Messrichtung [gon]	Messneigung [gon]	Höhe [mNN]	Bezugsmessung
MQ3	12YEA25/R002		12-CP003L-B01		Spannung		367	0	-278,39	15.12.2010
MQ3	12YEA25/R002		12-CP003L-B06		Spannung		368	0	-280,23	15.12.2010
MQ3	12YEA25/R002		12-CP003L-B03		Spannung		170	0	-278,39	15.12.2010
MQ3	12YEA25/R002		12-CP003L-B04		Spannung		170	0	-280,21	15.12.2010
MQ3	12YEA25/R002		12-CP003L-B02		Spannung		270	97	-276,87	15.12.2010
MQ3	12YEA25/R002		12-CP003L-B05		Spannung		0	-100	-281,23	15.12.2010
MQ3	12YEA25/R002		12-CT003L-B01		Temperatur		-	-	-278,39	15.12.2010

Abdichtbauwerk im Steinsalz – Integral permeability



Pore pressure remained below total (radial) pressure
→ No seeping brine detected at drift face of seal
→ Calculation of low integral permeability based on outflow rate

- Conclusion
  - Observing strictly lessons learnt enables to build tight drift seals in rock salt.

Summary and conclusion

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

➢ <u>Summary of lessons learnt</u>

- Removal of EDZ must be based on measuring results
- Inclining the salt contour in the roof to achieve positive fit of salt contour and sealing body
- Adequate „stiffness“ of sealing body accelerates pressure build-up in the EdZ
- For prognosis of rock pressure build-up stress state and convergence rate of drift seal location must be known, reliably
- Selection of high converging drift seal locations accelerates safe confinement of radioactive waste
- Measures (e.g. pore storages within the sealing system) slowing down fluid pressure build-up at drift seal´s location keep pore pressure below rock pressure in EdZ

Conclusion

It is demonstrated that drift seals can be erected as a component of a sealing system that guarantees safe confinement of radioactive waste in rock salt.

ACKNOWLEDGEMENT

BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Many thanks …

to all colleagues from BGE and BGETEC (former GSF, HMGU, Asse GmbH, BfS, DBE, DBETEC) for their collaboration for more than 20 years …

to our partners from TU Clausthal, TU Bergakademie Freiberg, TU Braunschweig for their scientific input …

to our subcontractors IBeWa, KUTEC, GmuG, IfG for their target-oriented professional work and …

to BMBF, BMWi, BMU for their financial support


Many thanks
for your attention!