THE CAVERN ABANDONMENT ISSUE

40 Years of In-Situ Tests

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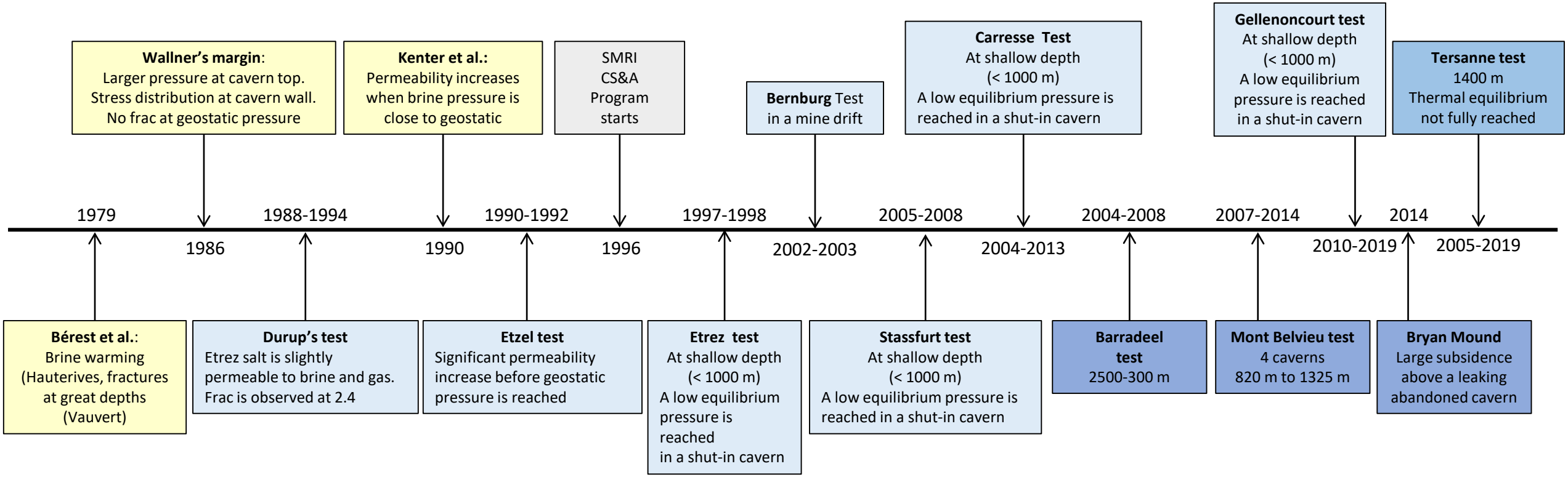
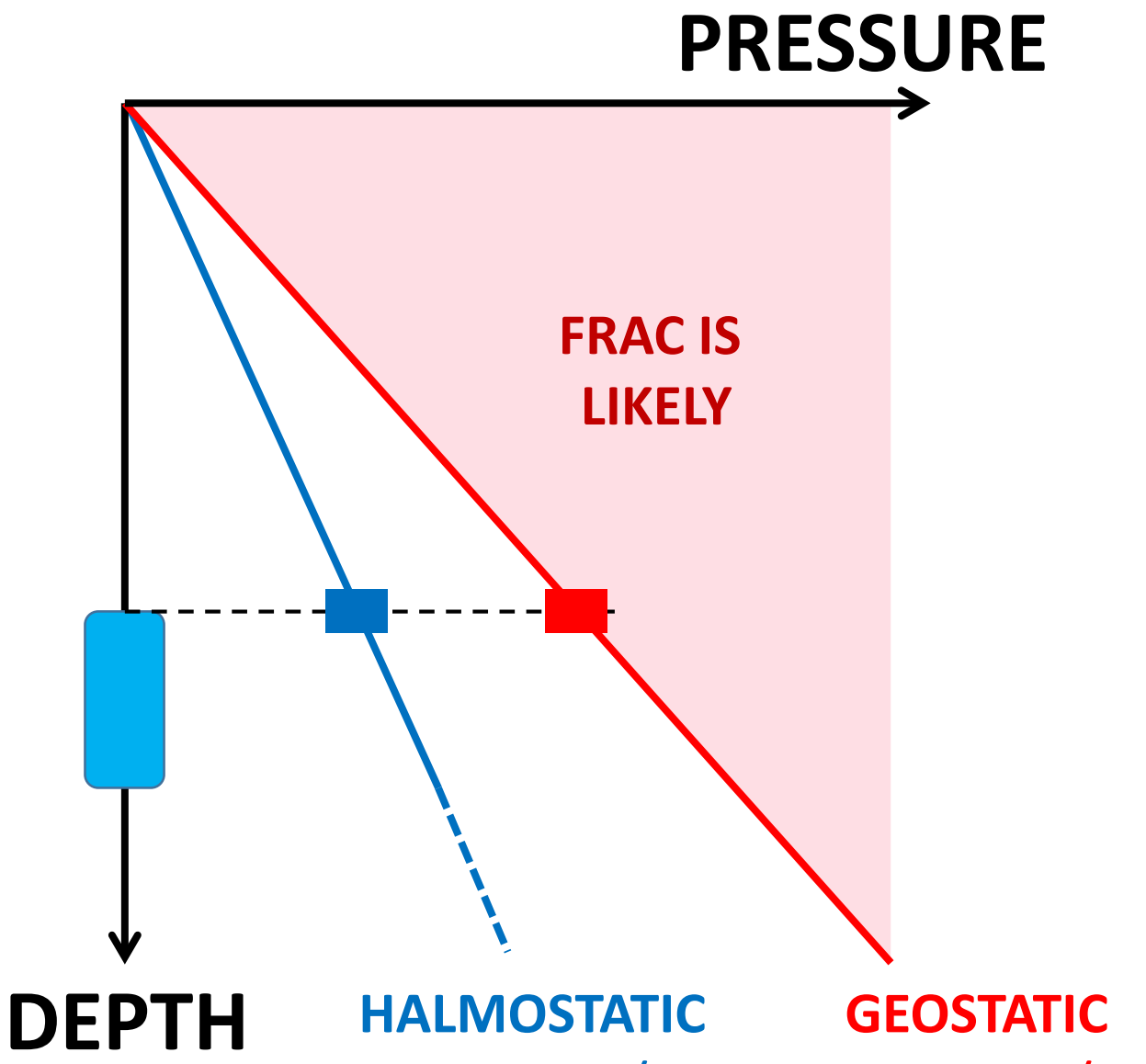
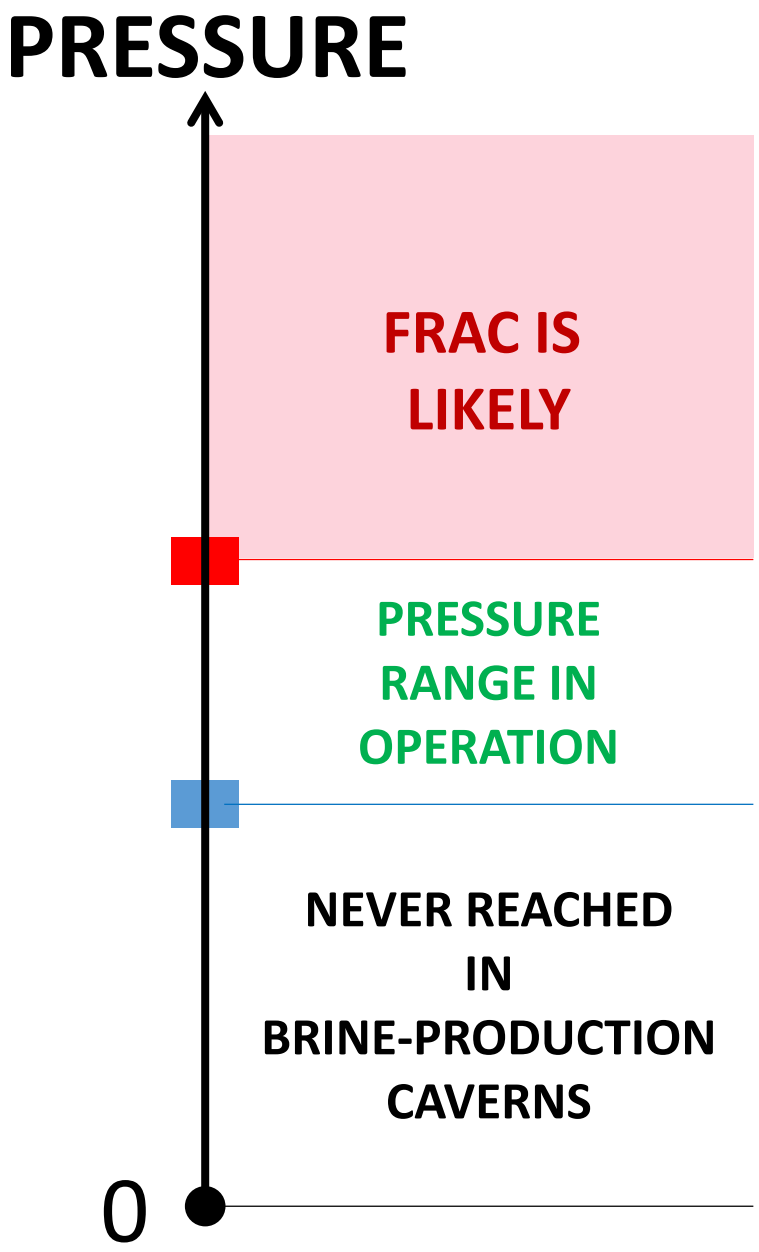
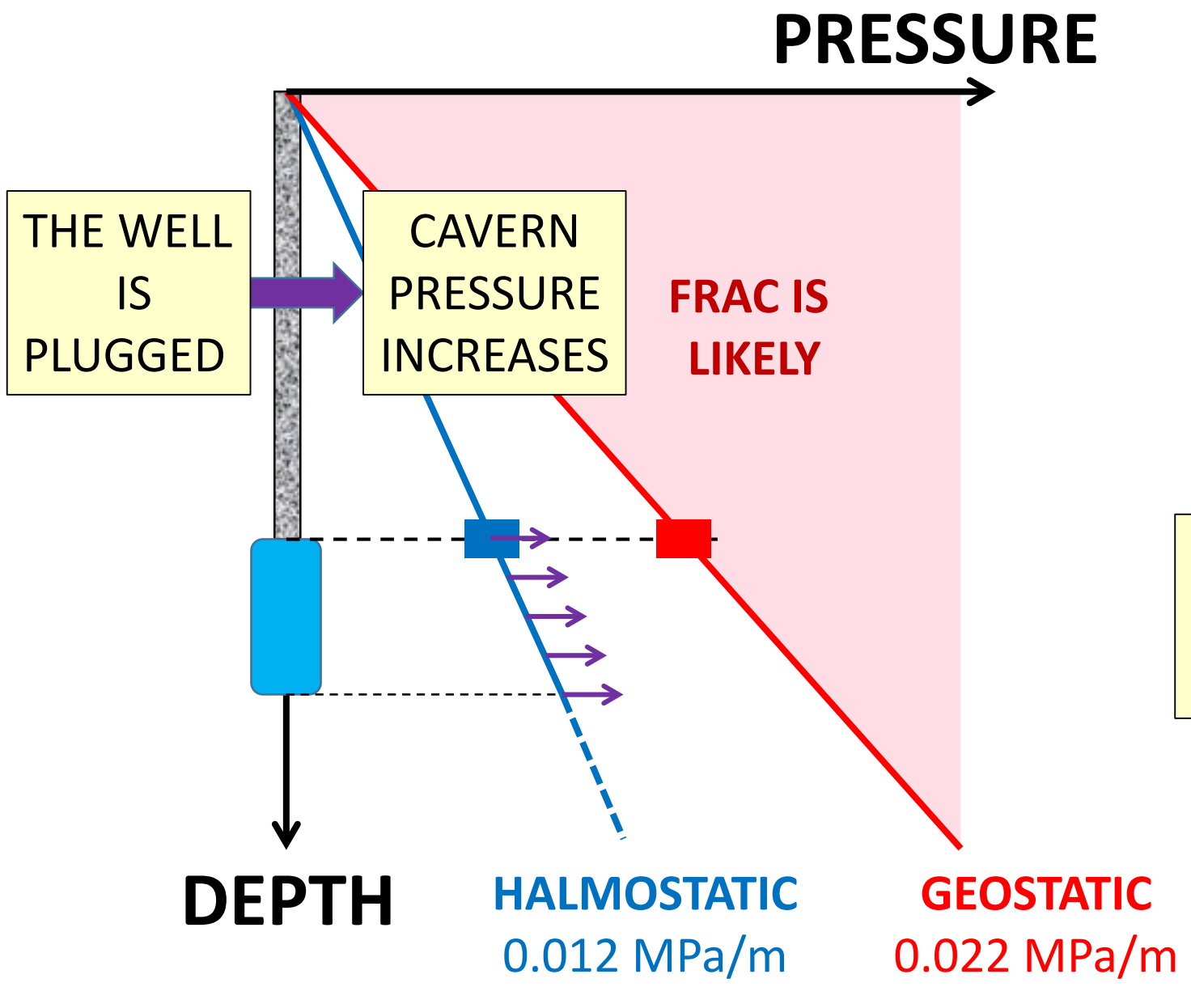
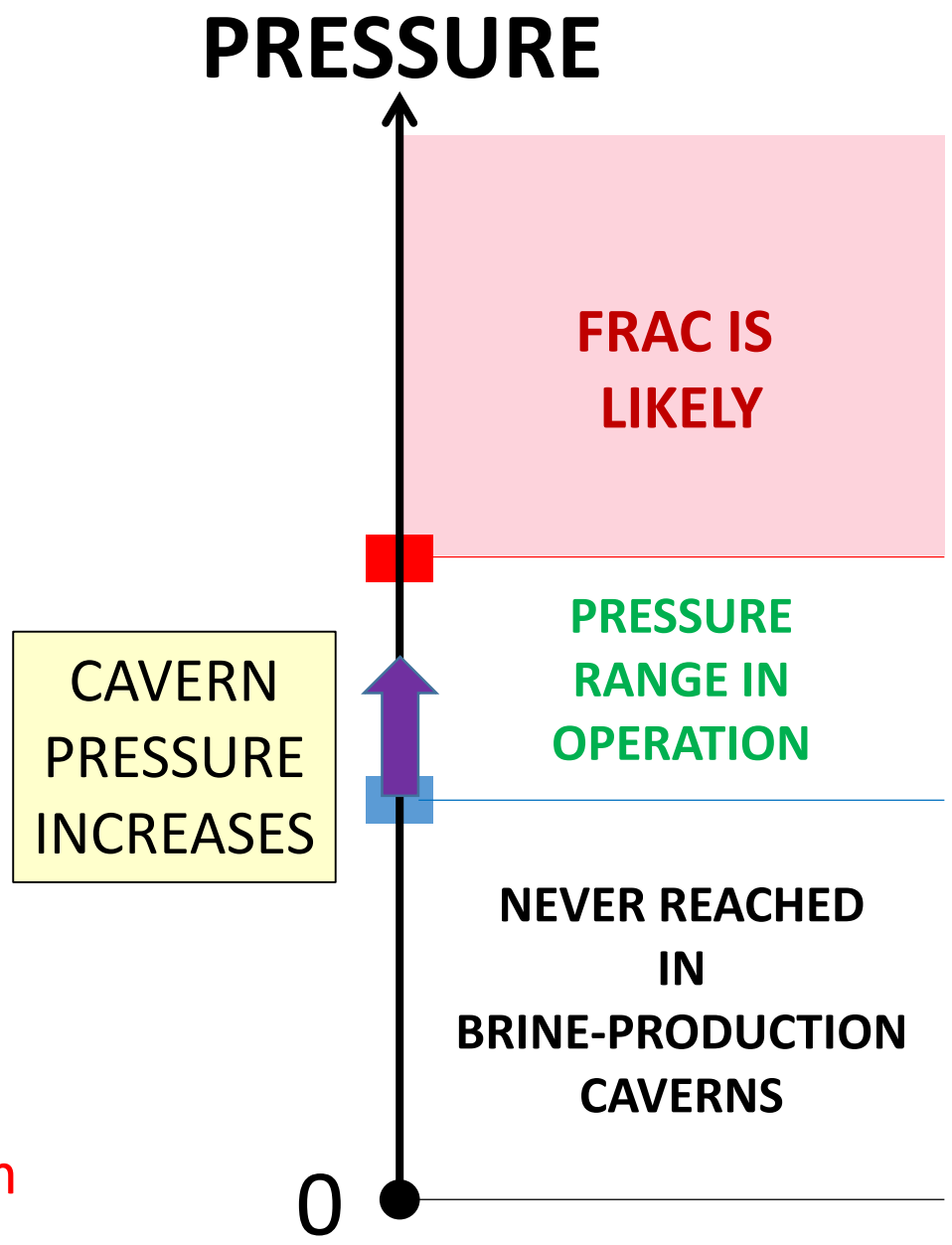
THIS STUDY IS A PART OF THE KEM PROGRAM, SUPPORTED BY THE DUTCH SodM


Wallner's margin:
Larger pressure at cavern top.
Stress distribution at cavern wall.
No frac at geostatic pressure
Kenter et al.:
Permeability increases when brine pressure is close to geostatic
SMRI
CS&A
Program
starts
Bernburg Test
in a mine drift
Carresse Test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached in a shut-in cavern
Gellenoncourt test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached in a shut-in cavern
Tersanne test
1400 m
Thermal equilibrium not fully reached
1979
1986
1988-1994
1990
1990-1992
1996
1997-1998
2002-2003
2005-2008
2004-2013
2004-2008
2007-2014
2010-2019
2014
2005-2019
Bérest et al.:
Brine warming
(Hauterives, fractures at great depths
(Vauvert)
Durup's test
Etrez salt is slightly permeable to brine and gas.
Frac is observed at 2.4
Etzel test
Significant permeability increase before geostatic pressure is reached
Etrez test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached
in a shut-in cavern
Stassfurt test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached in a shut-in cavern
Barradeel test
2500-300 m
Mont Belvieu test
4 caverns
820 m to 1325 m
Bryan Mound
Large subsidence above a leaking abandoned cavern


PRESSURE
FRAC IS LIKELY
DEPTH
HALMOSTATIC
0.012 MPa/m
GEOSTATIC
0.022 MPa/m


PRESSURE
FRAC IS LIKELY
PRESSURE RANGE IN OPERATION
NEVER REACHED IN BRINE-PRODUCTION CAVERNS
0


PRESSURE
THE WELL IS PLUGGED
CAVERN PRESSURE INCREASES
FRAC IS LIKELY
DEPTH
HALMOSTATIC
0.012 MPa/m
GEOSTATIC
0.022 MPa/m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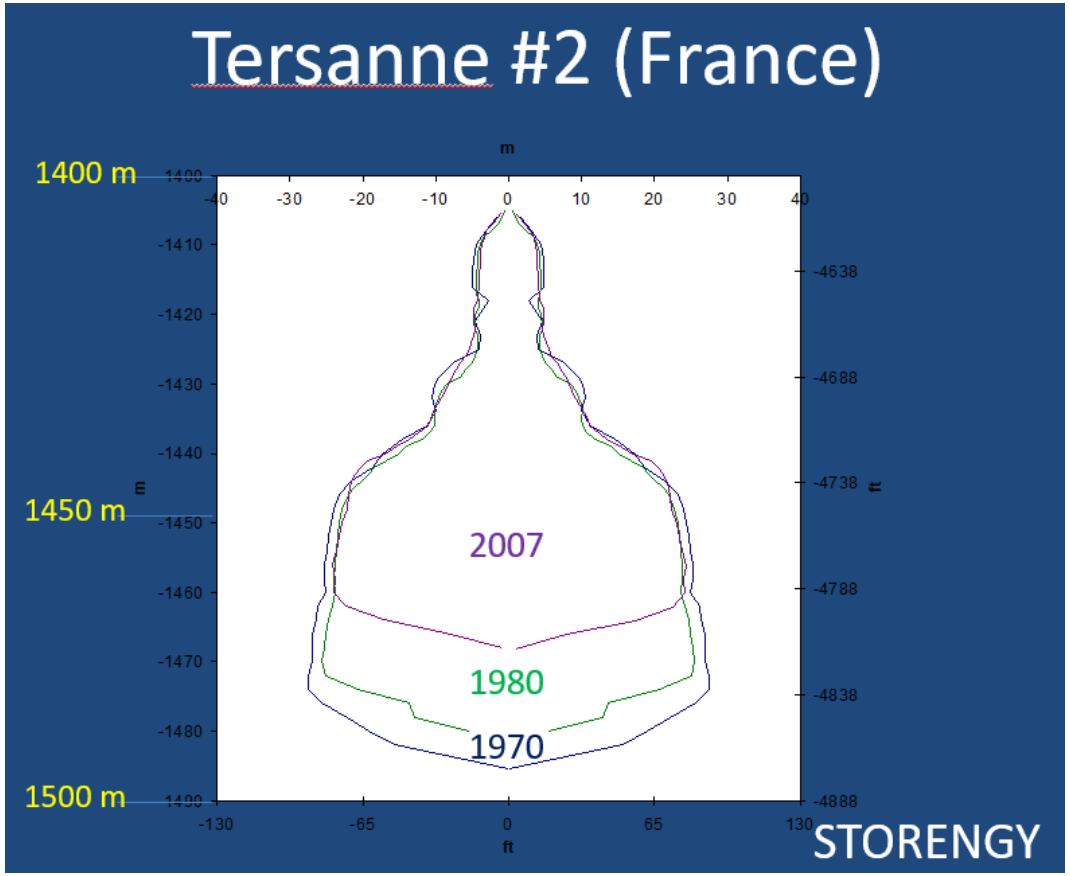
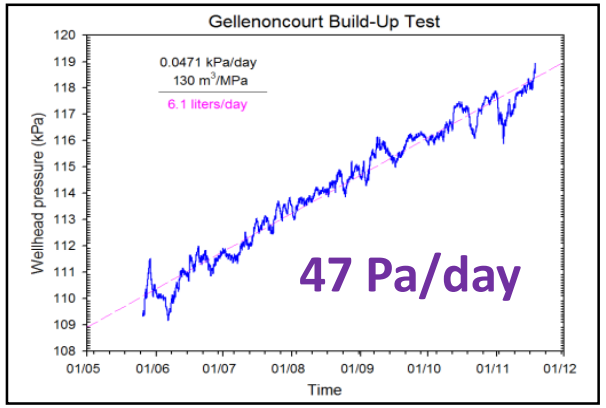
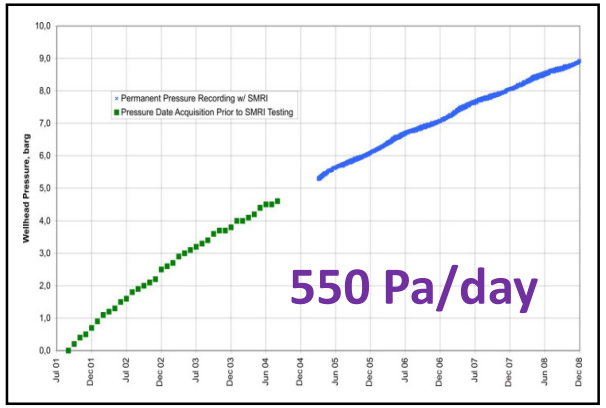


”CREEP CLOSURE”: A 60% VOLUME LOSS IN 37 YEARS (One of the factors explaining pressure increase)

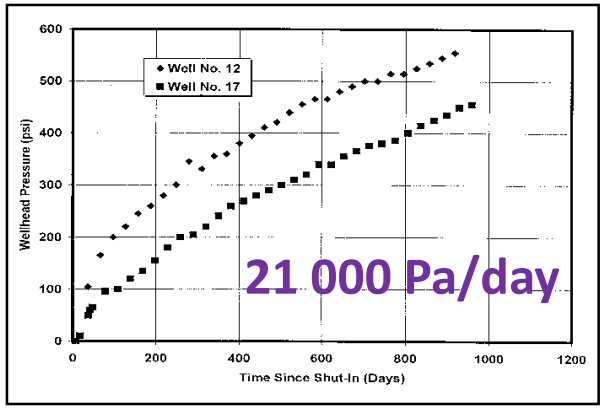
Gellenoncourt
300 m

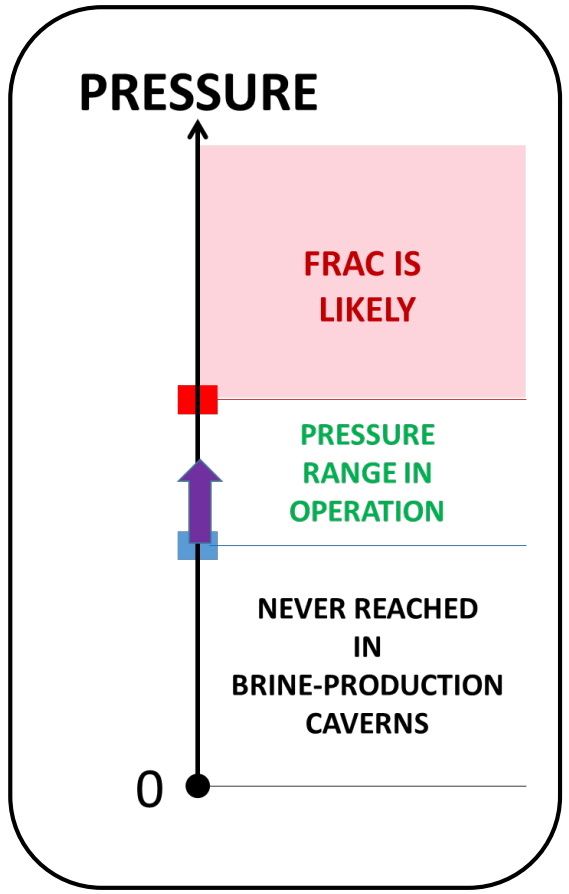


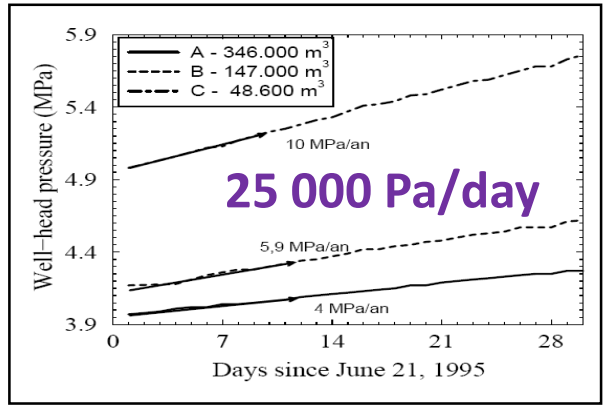
Stassfurt
600 m



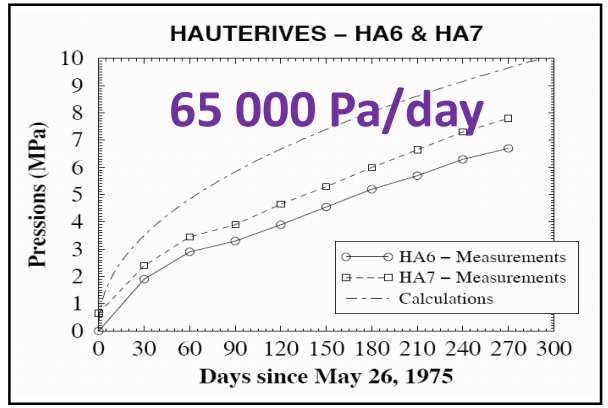
Mont Belvieu
1200 m



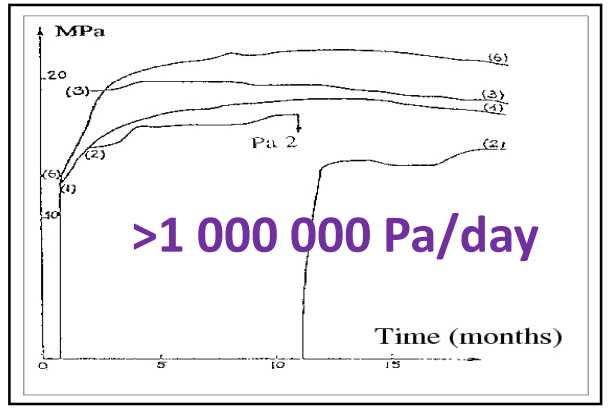




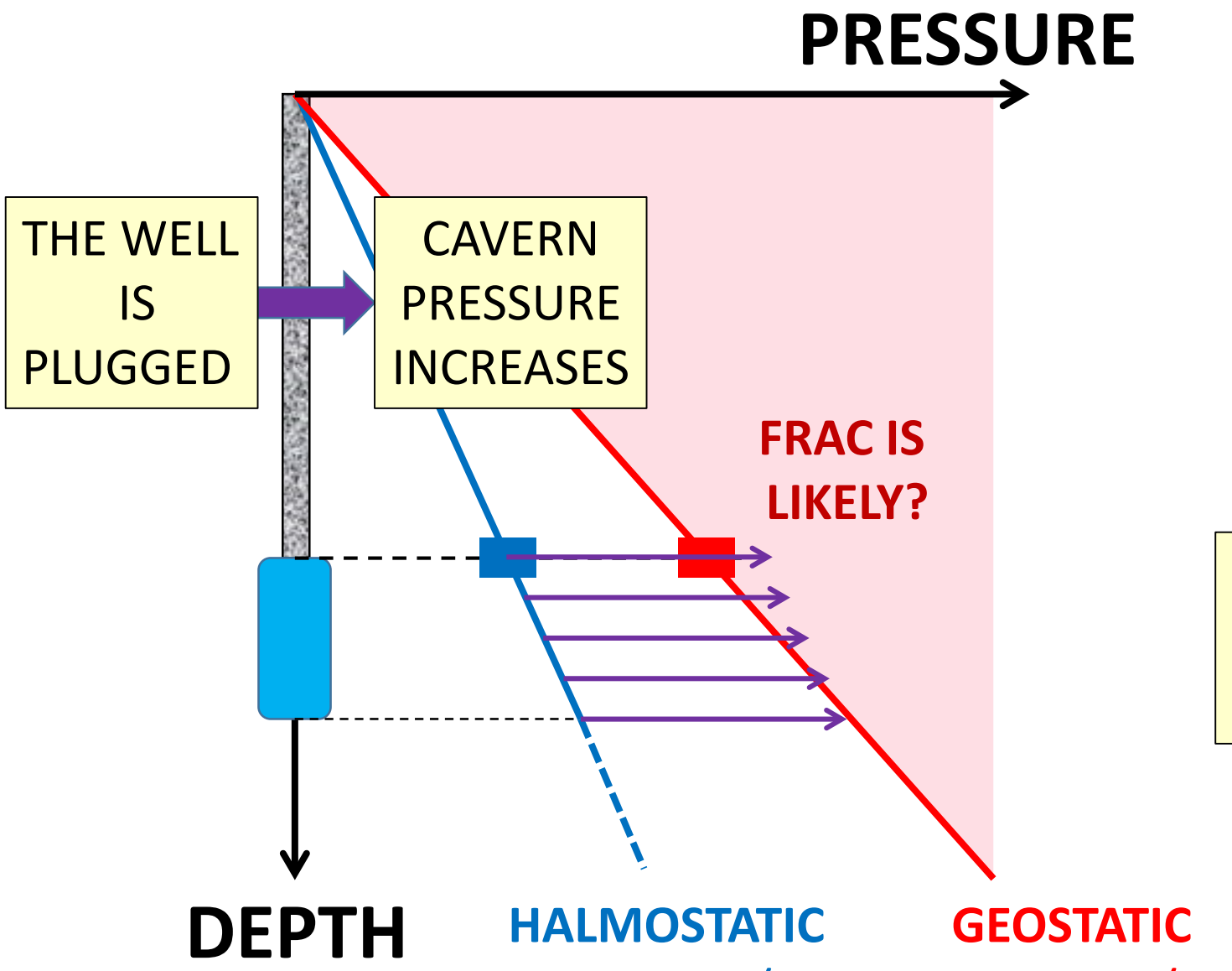
Etrez
1350 m



Hauterives
1500 m



Vauvert
2000 m


PRESSURE
THE WELL IS PLUGGED
CAVERN PRESSURE INCREASES
FRAC IS LIKELY?
DEPTH
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0.012 MPa/m
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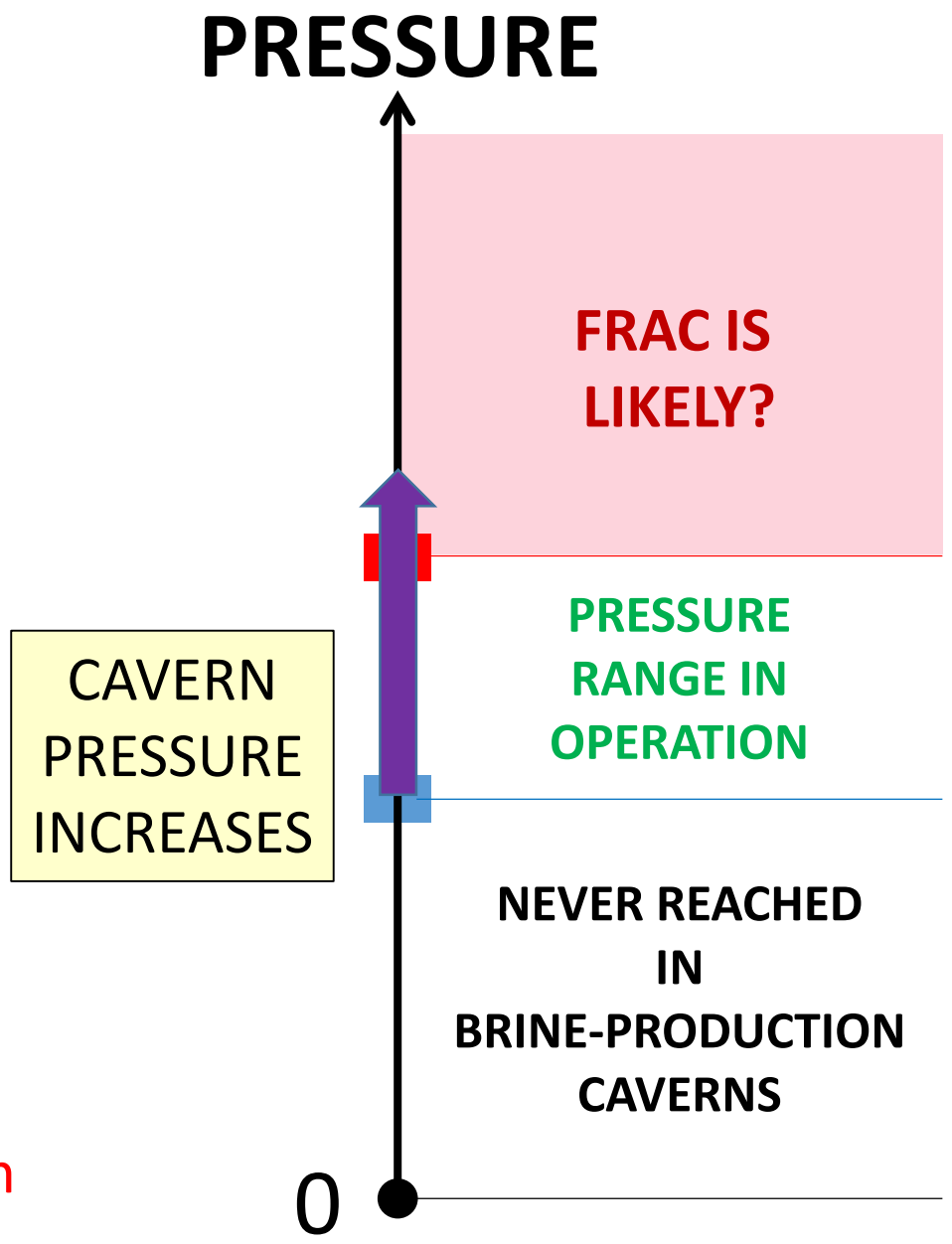
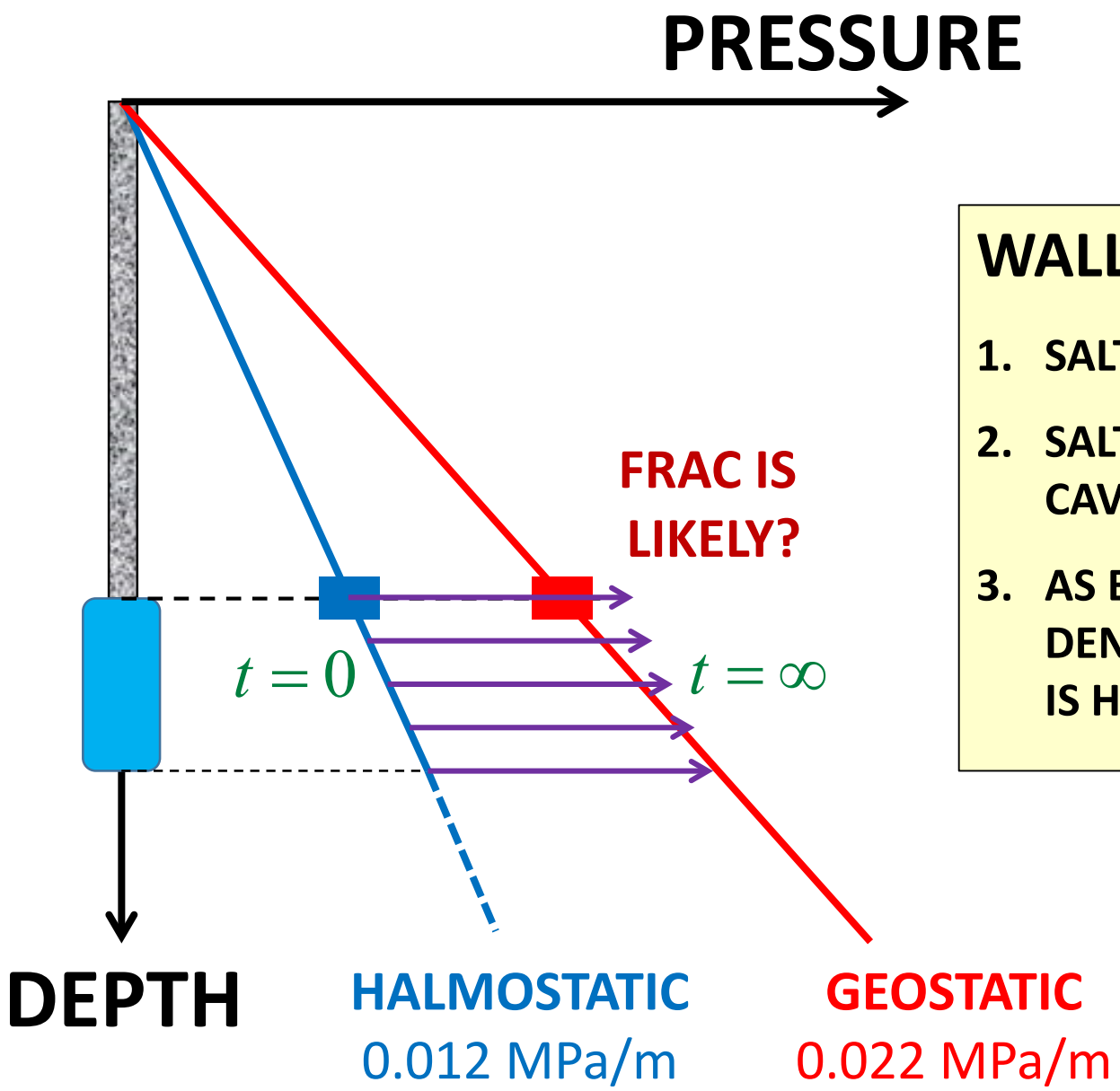
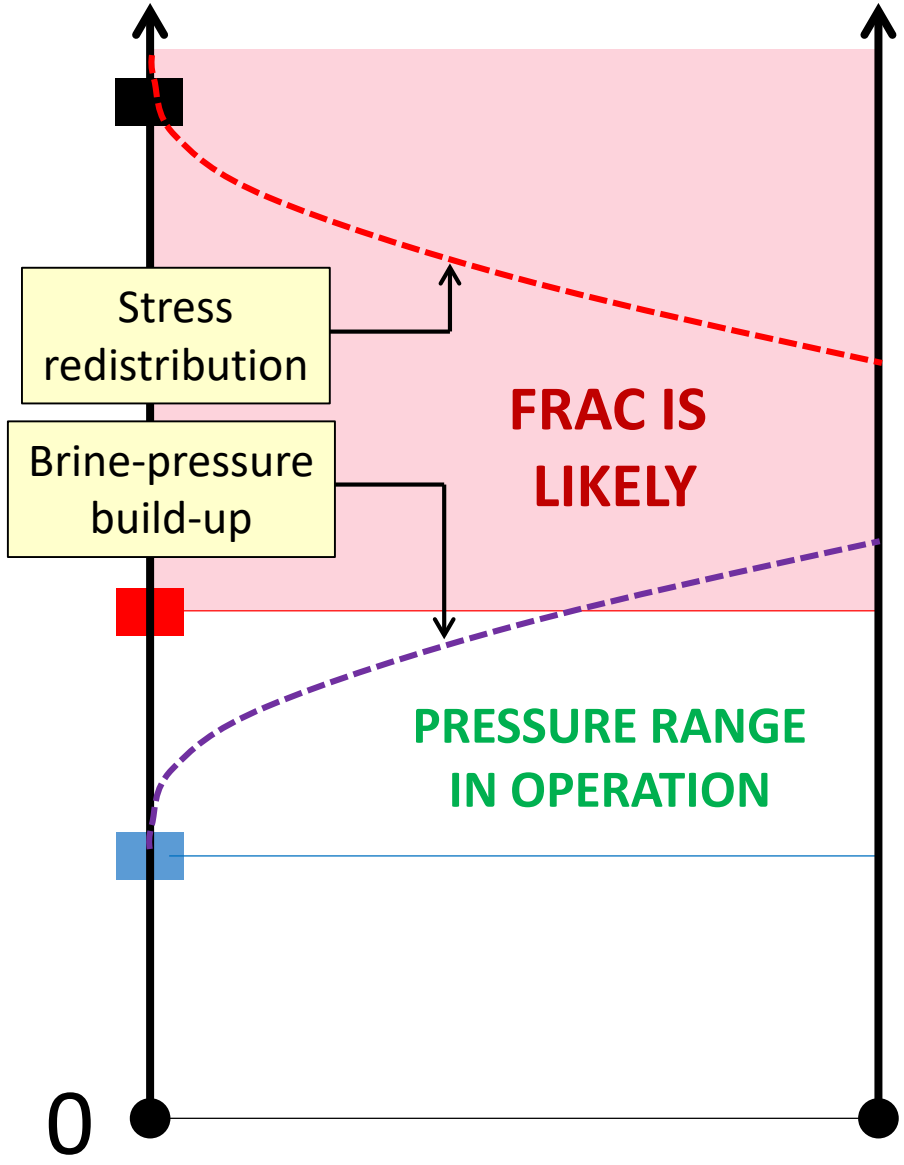

PRESSURE
FRAC IS LIKELY?
CAVERN PRESSURE INCREASES
PRESSURE RANGE IN OPERATION
NEVER REACHED IN BRINE-PRODUCTION CAVERNS
0

THE GERMAN APPROACH, 1986-1992



WALLNER-1 (1986)

1. SALT IS PERFECTLY IMPERMEABLE.
2. SALT IS VISCOPLASTIC, AND CAVERN CLOSES UNTIL CAVERN PRESSURE REACHES GEOSTATIC PRESSURE.
3. AS BRINE DENSITY (1.2) IS SMALLER THAN ROCK DENSITY (2.2), AT FINAL EQUILIBRIUM, BRINE PRESSURE IS HIGHER THAN ROCK STRESS AT CAVERN ROOF.



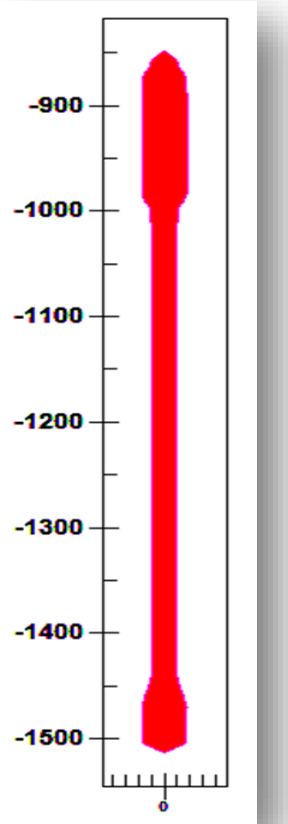
WALLNER-2 (1986)

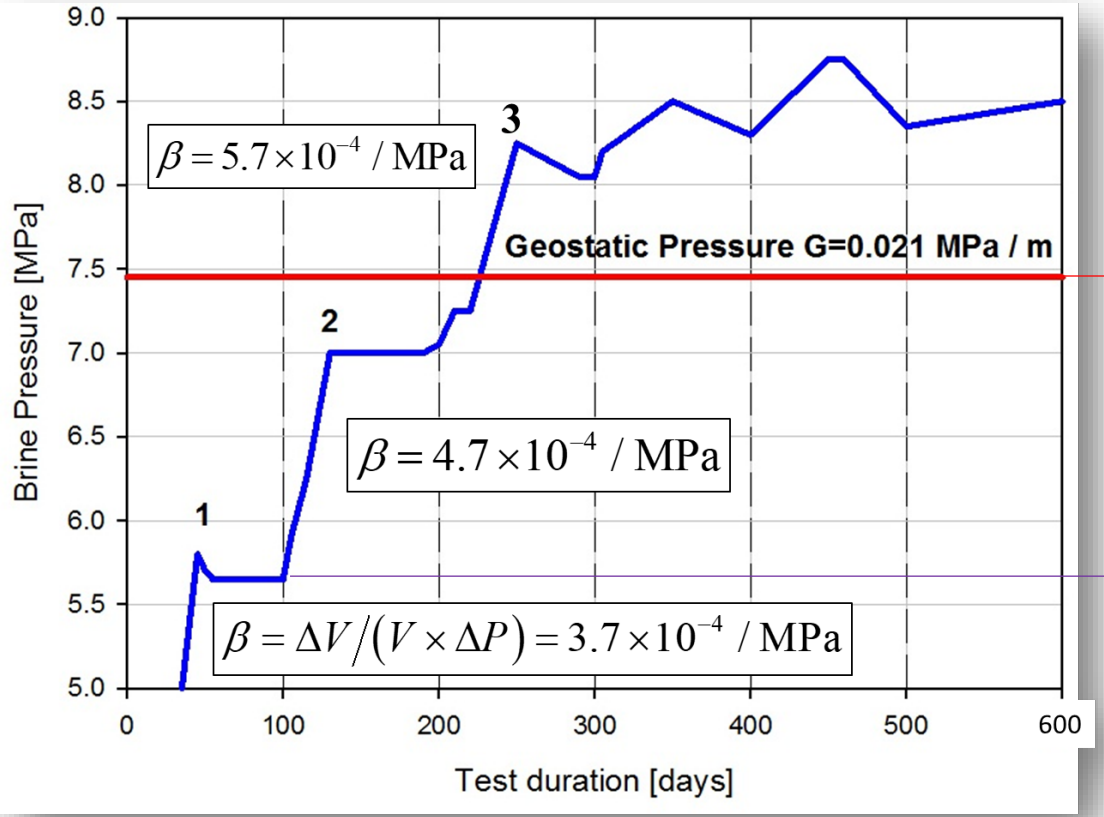
1. SALT IS PERFECTLY IMPERMEABLE.
2. IN A PERFECTLY IMPERMEABLE AND ELASTIC ROCK FORMATION, CAVERN PRESSURE CAN INCREASE TO TWICE THE GEOSTATIC PRESSURE BEFORE FRACKING.
3. SALT IS VISCOPLASTIC RATHER THAN ELASTIC; WHEN CAVERN PRESSURE INCREASES SLOWLY, SLOW STRESS REDISTRIBUTION TAKES PLACE, AND PRESSURE CAN INCREASE TO A VALUE LARGER THAN GEOSTATIC BEFORE FRACKING.

1. AND 2. PROVED TO BE INCORRECT. THE SIGNIFICANCE OF STRESS REDISTRIBUTION (3) PROVED TO BE PERFECTLY CORRECT.

THE ETZEL TEST (1990-1992)

TO PROVE THESE NOTIONS, A 2-YEAR TEST WAS PERFORMED IN AN ETZEL CAVERN PRESSURE SHOULD HAVE INCREASE TO A 0.027 MPa/m PRESSURE GRADIENT. IN FACT, CAVERN COMPRESIBILITY (THE AMOUNT OF BRINE TO BE INJECTED TO INCREASE CAVERN PRESSURE BY 1 MPa) DRASTICALLY INCREASED WHEN GRADIENT WAS HIGHER THAN 0.019 MPa/m



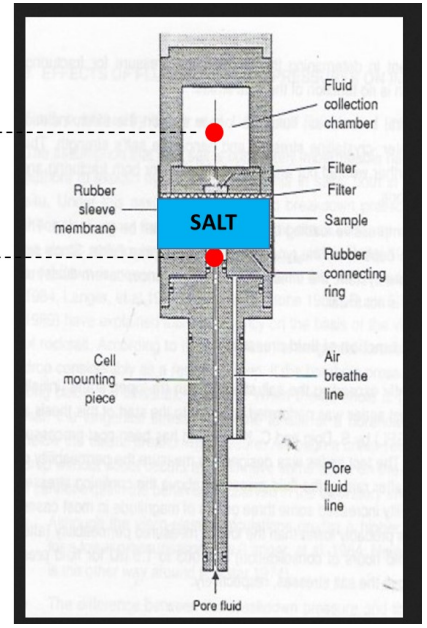


PRESSURE GRADIENT (MPa/m)

0.021

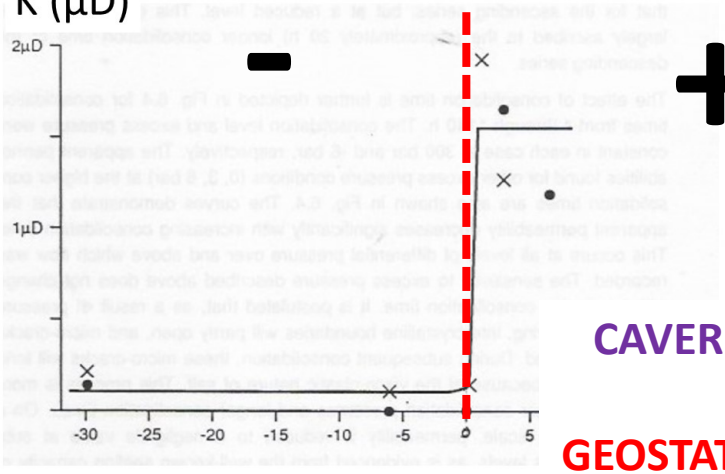
0.019

A DUTCH POINT, 1985-1990



PERMEABILITY

K (μD)



−

+

CAVERN PRESSURE

−

GEOSTATIC PRESSURE

PRESSURE

ROCK SALT PERMEABILITY (K) DRASTICALLY INCREASES

FRAC IS LIKELY

PRESSURE RANGE IN OPERATION

0

KENTER AND FOKKER (1990,1995) PERFORMED LAB TESTS IN A MOCK-UP CAVERN.

THEY PROVED THAT, OPPOSITE TO WALLNER'S VIEW, PERMEABILITY DRASTICALY INCREASES WHEN CAVERN PRESSURE IS CLOSE TO (Δp=0) GEOSTATIC PRESSURE.

THE FRENCH APPROACH, 1979-1998

A SHUT-IN TEST IN A 1300-M DEEP DOUBLE CAVERN AT HAUTERIVES, FRANCE

IN ADDITION TO CREEP CLOSURE, BRINE WARMING IS A MAJOR FACTOR EXPLAINING PRESSURE INCREASE IN A SHUT-IN CAVERN

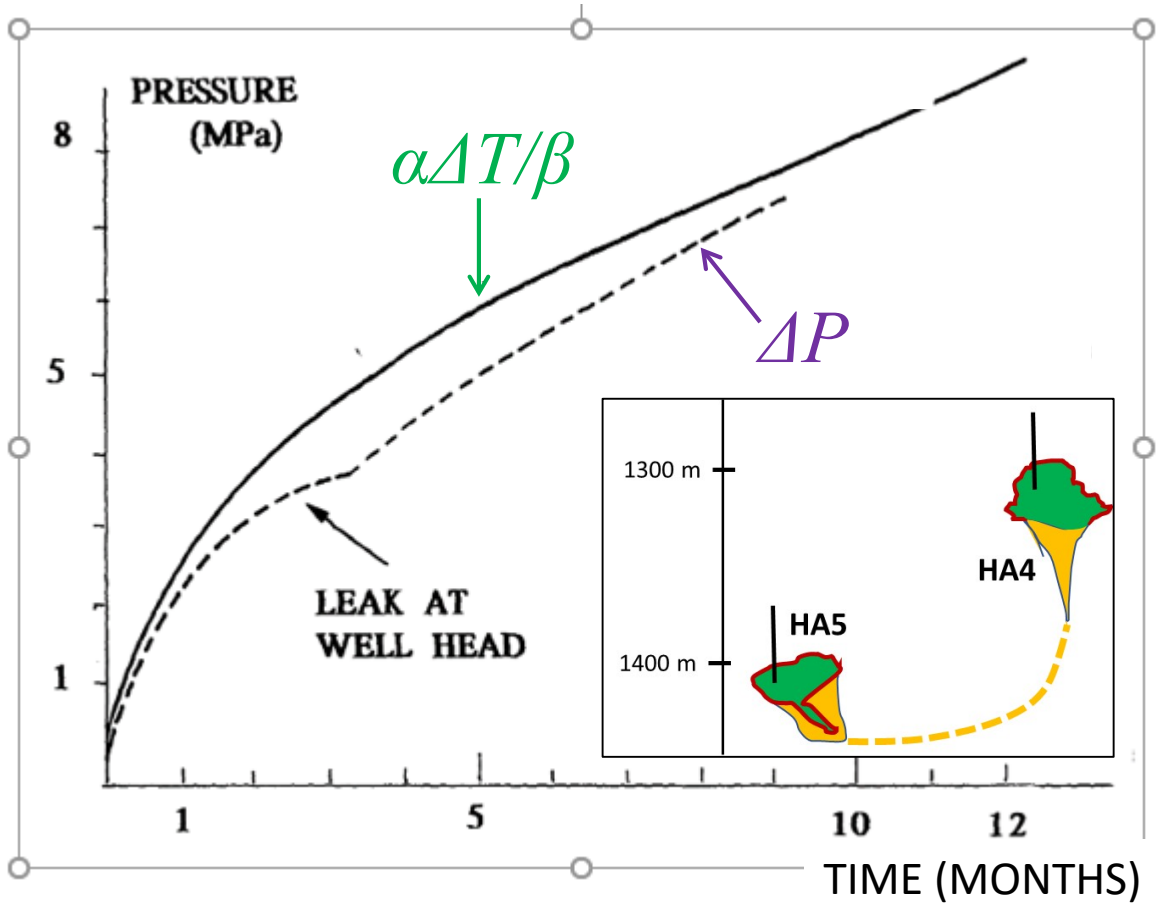
$$M = \rho V$$

$$\Delta\rho = \rho\left(\beta_b \Delta P - \alpha \Delta T\right)$$

$$\Delta V = V \beta_c \Delta P$$

$$\Delta P = \alpha \Delta T / \beta$$

$$\alpha/\beta = 1 \text{ MPa/°C}$$



THERE IS A MAJOR FRAC RISK WHEN THERMAL EQUILIBRIUM HAS NOT BEEN REACHED

BRINE WARMING IS A SLOW PROCESS

THE CHARACTERISTIC TIME IS:

$$t_c\,(\text{years}) = V^{2/3}\,(\text{m}^2) / 400$$

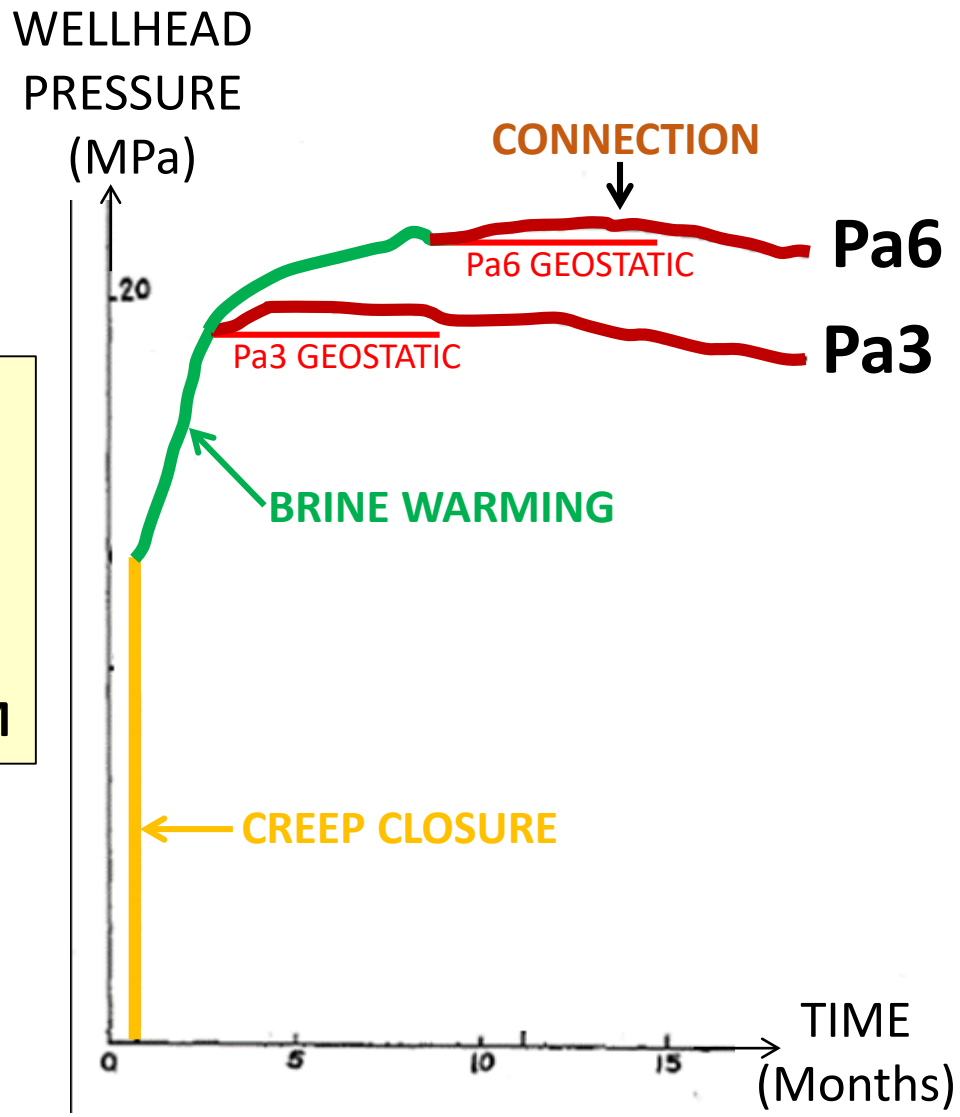
(12 yr when V = 329 000 m³)

Bérest P., Ledoux E., Legait P., de Marsily G. (1979) Thermal effects in Cavities in Salt Rock], 4th Cong. SIMR, Montreux, Switzerland, Vol.1, 31-35.

A SHUT-IN TEST IN A 1800-M DEEP CAVERN AT VAUVERT, FRANCE (1979)

Pa6 AND Pa3 ARE TWO NEIGHBORING CAVERNS OF THE VAUVERT BRINE FIELD.

THEIR DEPTH IS 1800 M



CAVERN PRESSURE IS FIRST GOVERNED BY:

CREEP CLOSURE

FOLLOWED BY

BRINE WARMING

BECAUSE CREEP CLOSURE EXTINGUISHES ITSELF

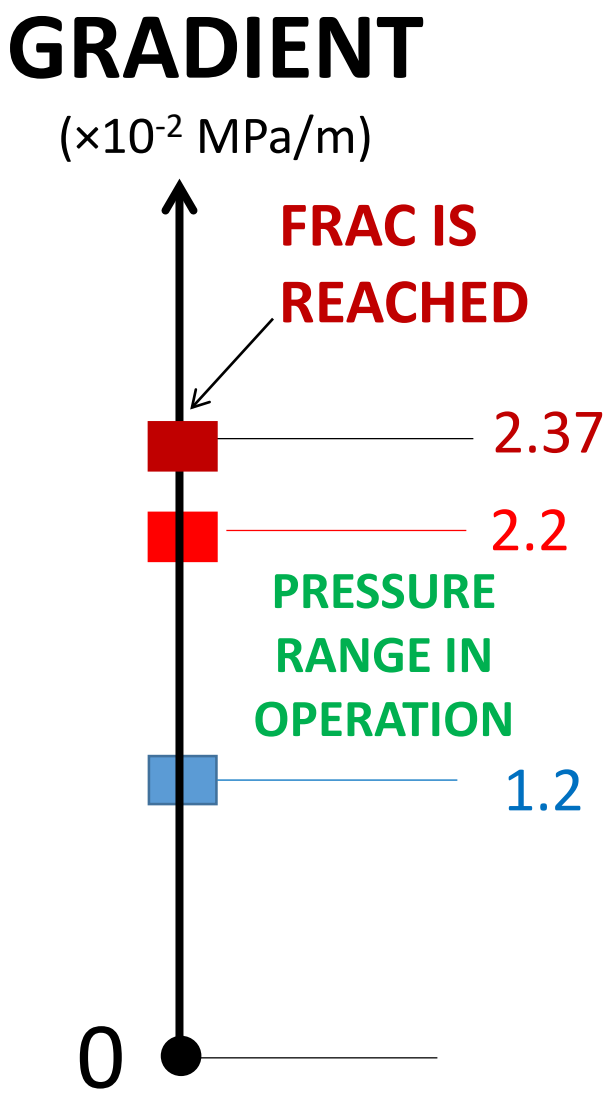
FOLLOWED BY

FRACTURE REOPENING

↓

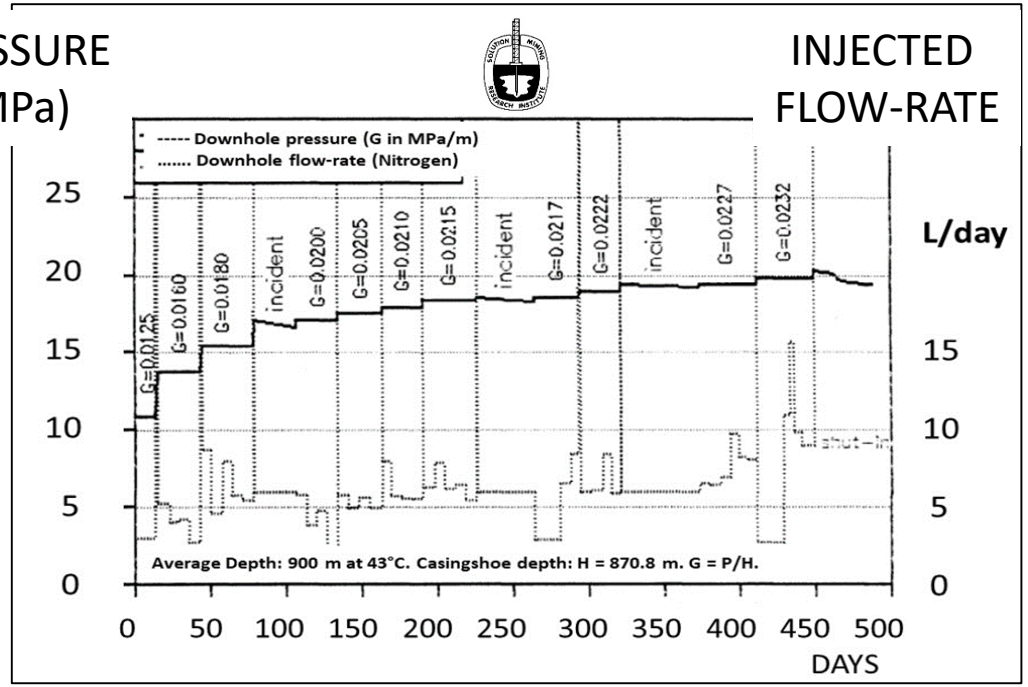
HYDRAULIC CONNECTION

AN INJECTION TEST IN A 900-M DEEP BOREHOLE AT ETREZ, FRANCE



DURUP MEASURED THE AMOUNT OF NITROGEN NEEDED TO INCREASE BOREHOLE PRESSURE FROM HALMOSTATIC TO GEOSTATIC AND TO FRAC. DURUP FOUND:

1. SALT FORMATION IS MICRO-PERMEABLE (6×10^{-20} m²).
2. FRAC IS REACHED AT A 0.0237 MPa/m GRADIENT.



Durup J.G. (1994) *Long term tests for tightness evaluations with brine and gas in salt (Field test n°2 with gas)* - Research Project Report n°94-002-S.

THE ETREZ TEST, 1997-1998

1. PRESSURE EVOLUTION IN AN ABANDONED CAVERN RESULTS FROM THREE MAIN PHENOMENA:

- CREEP CLOSURE
- BRINE THERMAL EXPANSION
- MICRO-PERMEATION THROUGH CAVERN WALLS

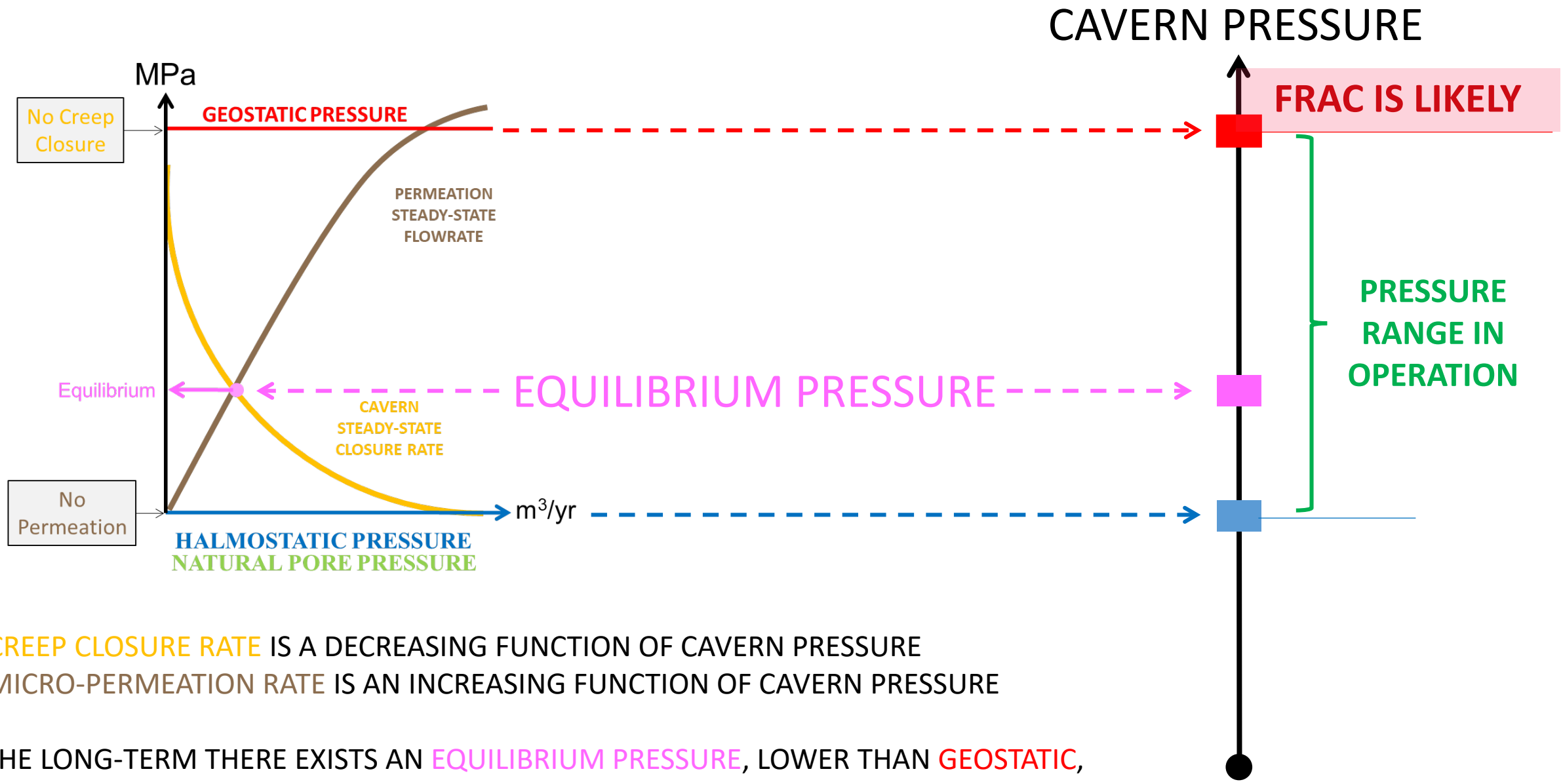
2. HOWEVER

- CREEP CLOSURE RATE IS A DECREASING FUNCTION OF CAVERN PRESSURE
- BRINE THERMAL EXPANSION VANISHES AFTER A (LONG) PERIOD
- MICRO-PERMEATION RATE IS AN INCREASING FUNCTION OF CAVERN PRESSURE

3. THE LONG-TERM, THERMAL EXPANSION VANISHES
THERE EXISTS AN EQUILIBRIUM PRESSURE, LOWER THAN GEOSTATIC, SUCH THAT:

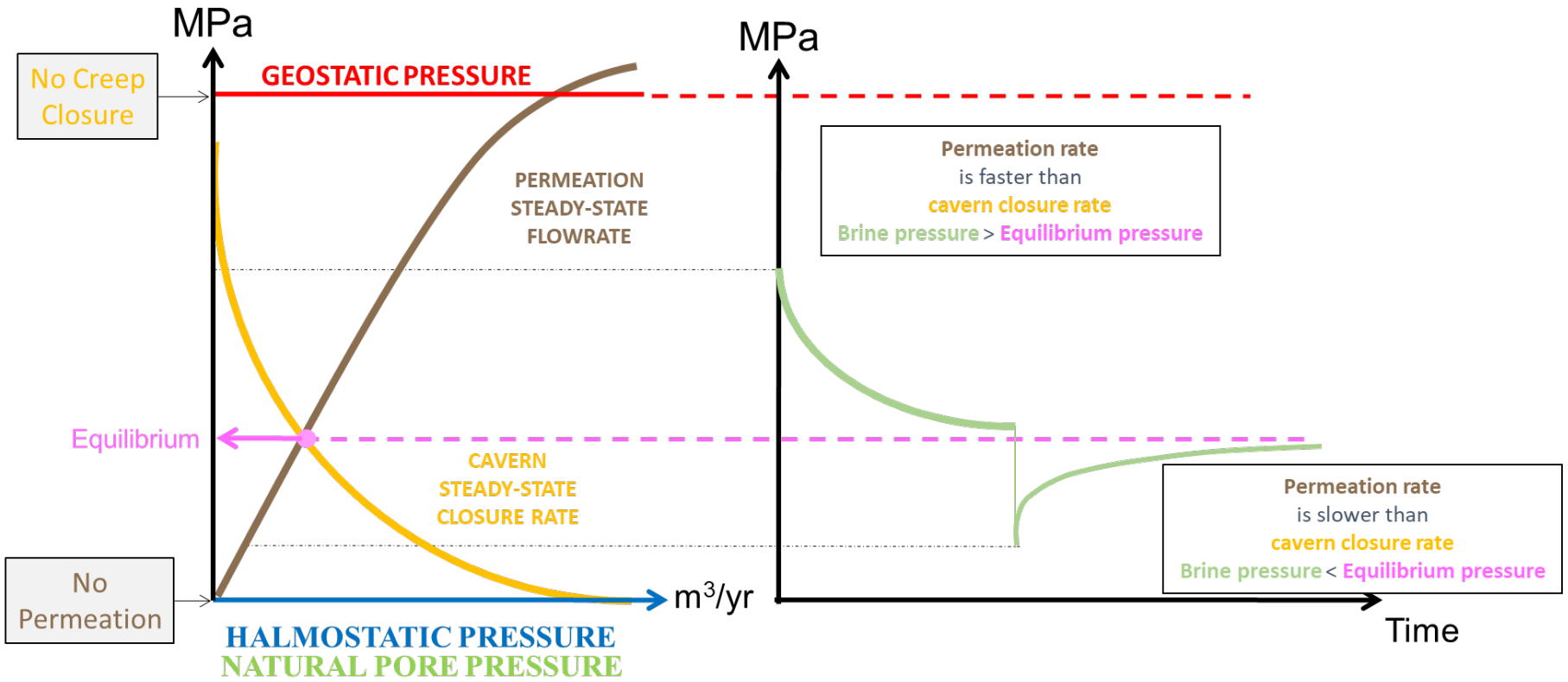
> CREEP CLOSURE RATE EXACTLY EQUALS MICRO-PERMEATION RATE

4. IN 1986, THIS NOTION REMAINED TO BE PROVED



- CREEP CLOSURE RATE IS A DECREASING FUNCTION OF CAVERN PRESSURE
- MICRO-PERMEATION RATE IS AN INCREASING FUNCTION OF CAVERN PRESSURE

IN THE LONG-TERM THERE EXISTS AN EQUILIBRIUM PRESSURE, LOWER THAN GEOSTATIC, SUCH THAT CREEP CLOSURE RATE EXACTLY EQUALS MICRO-PERMEATION RATE



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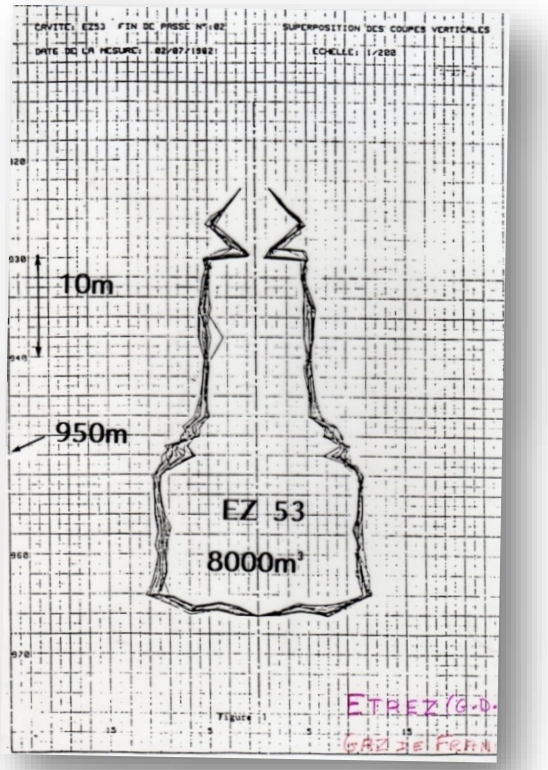
IN THE LONG-TERM THERE EXISTS AN EQUILIBRIUM PRESSURE, LOWER THAN GEOSTATIC, SUCH THAT CREEP CLOSURE RATE EXACTLY EQUALS MICRO-PERMEATION RATE

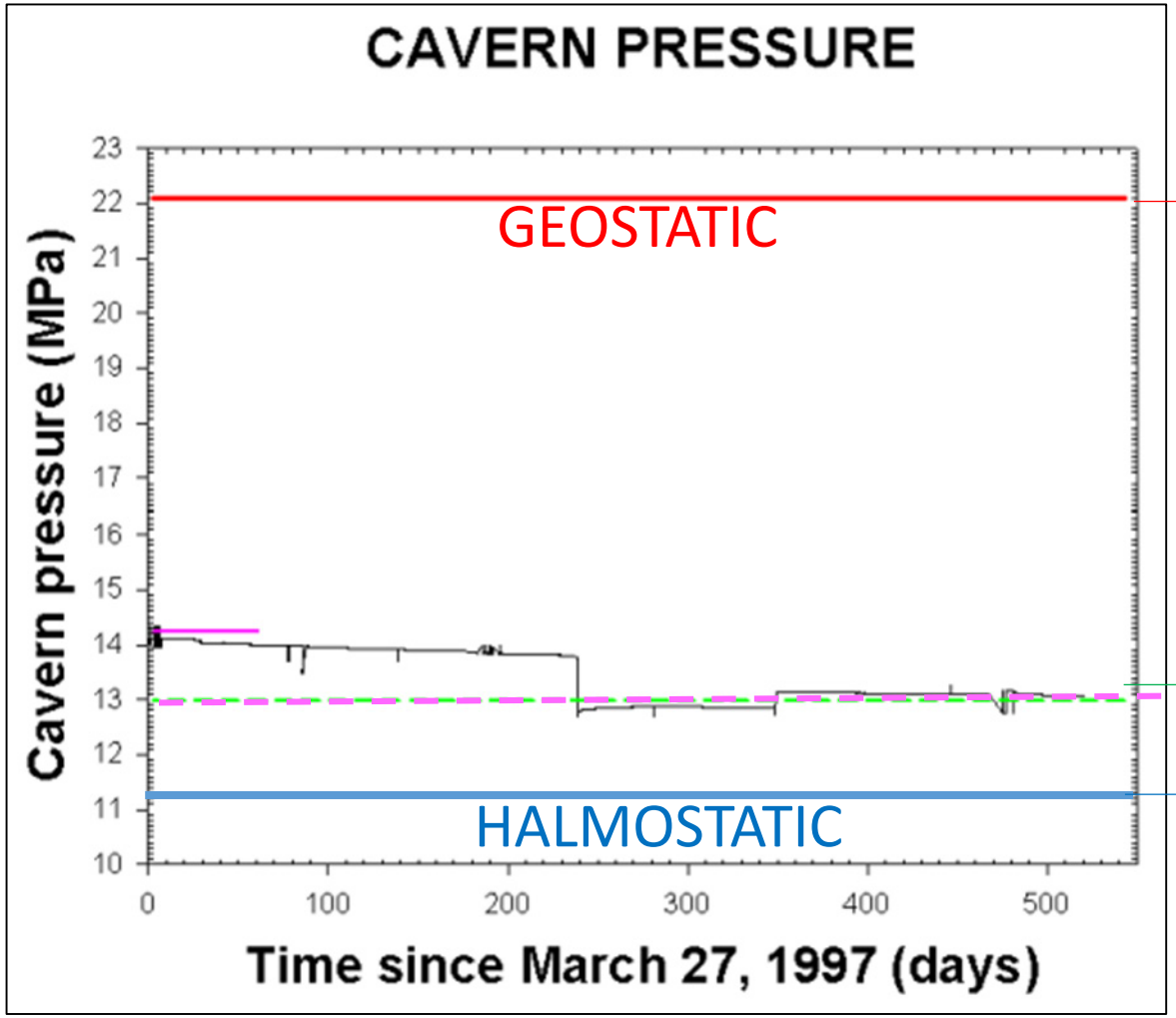
THE FINAL EQUILIBRIUM PRESSURE CAN BE APPROACHED BY A TRIAL-AND-ERROR METHOD:

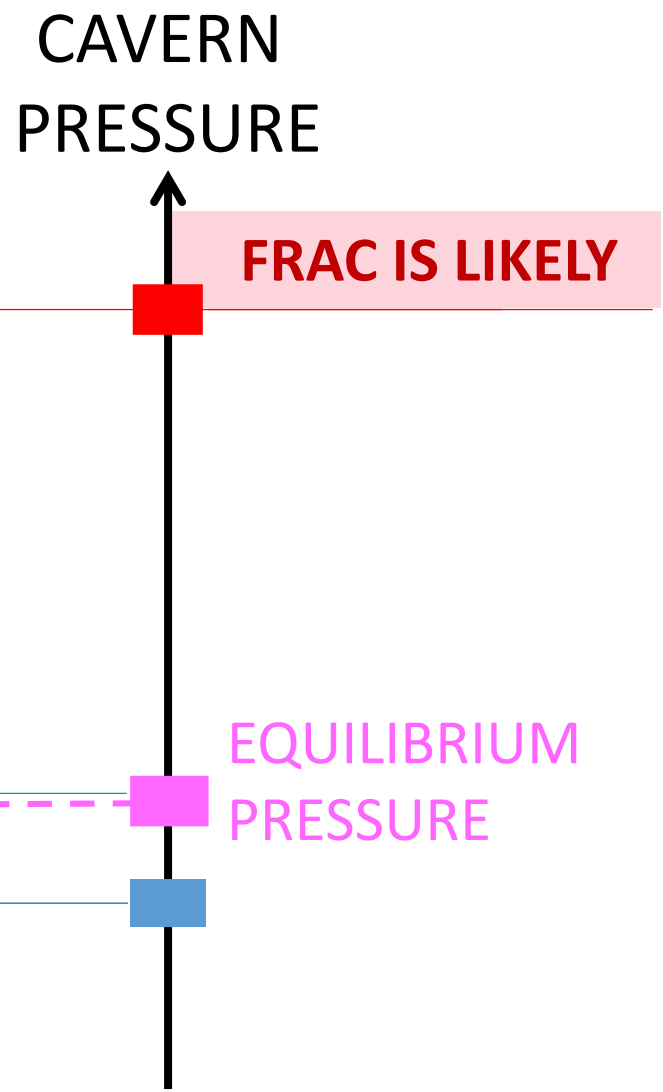
DIFFERENT CAVERN PRESSURE VALUES ARE TESTED PROVIDING AN UPPER BOUND AND A LOWER BOUND

A 500-DAY TEST WAS PERFORMED IN A 950-M DEEP CAVERN AT ETREZ, FRANCE



EZ53

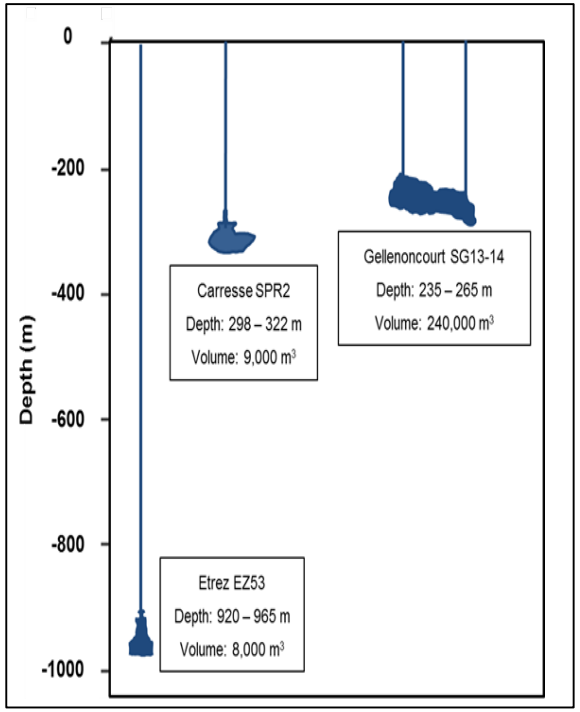


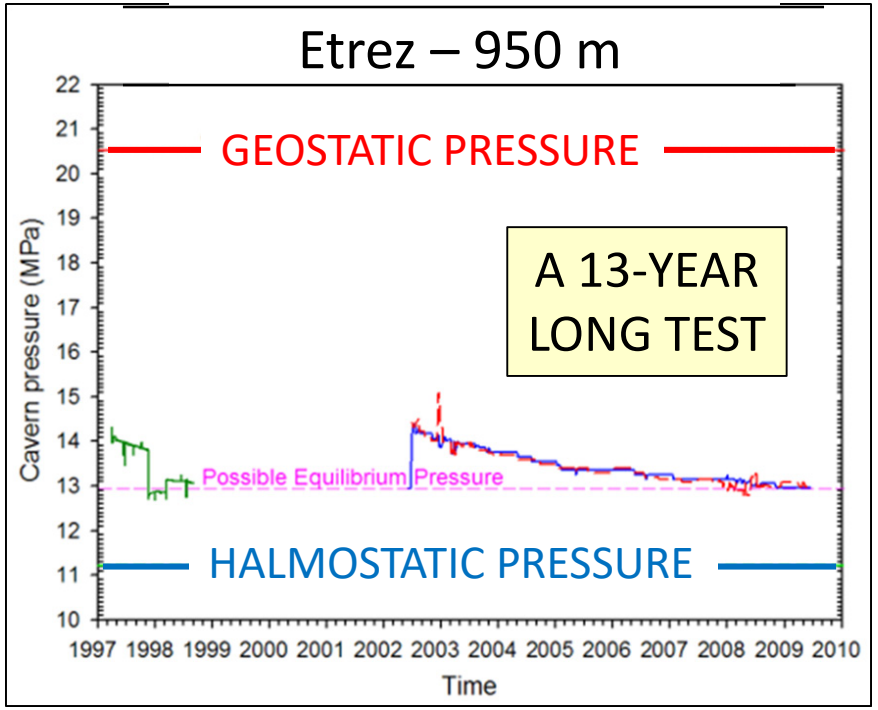


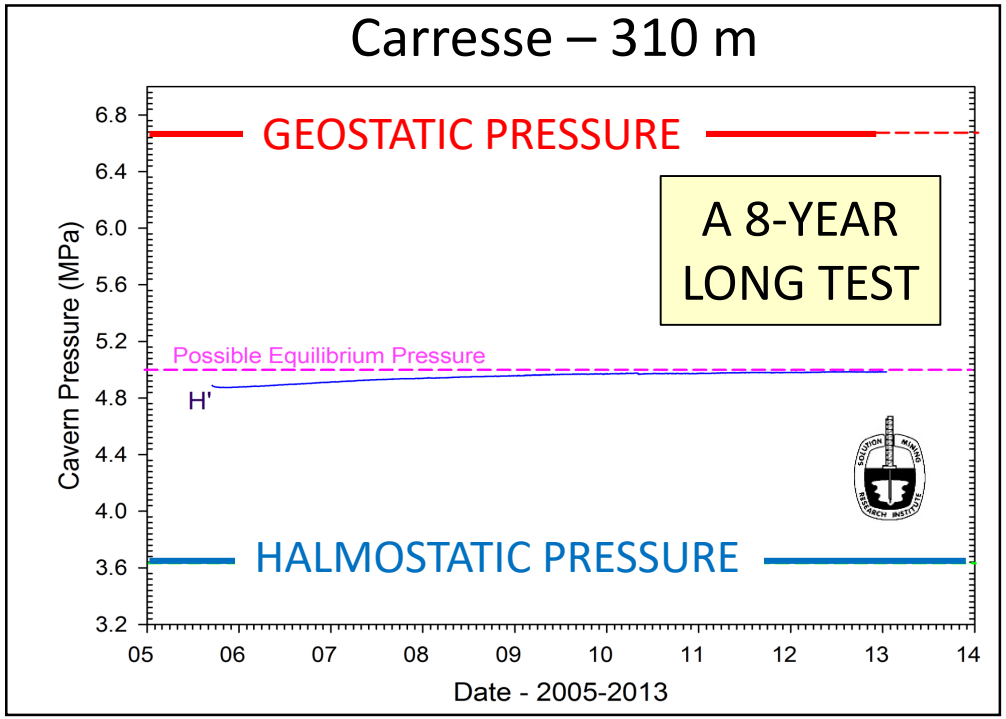
Bérest et al. (1998) Long-Term Evolution of a Sealed Cavern, SMRI Project Report No. 98-0004.

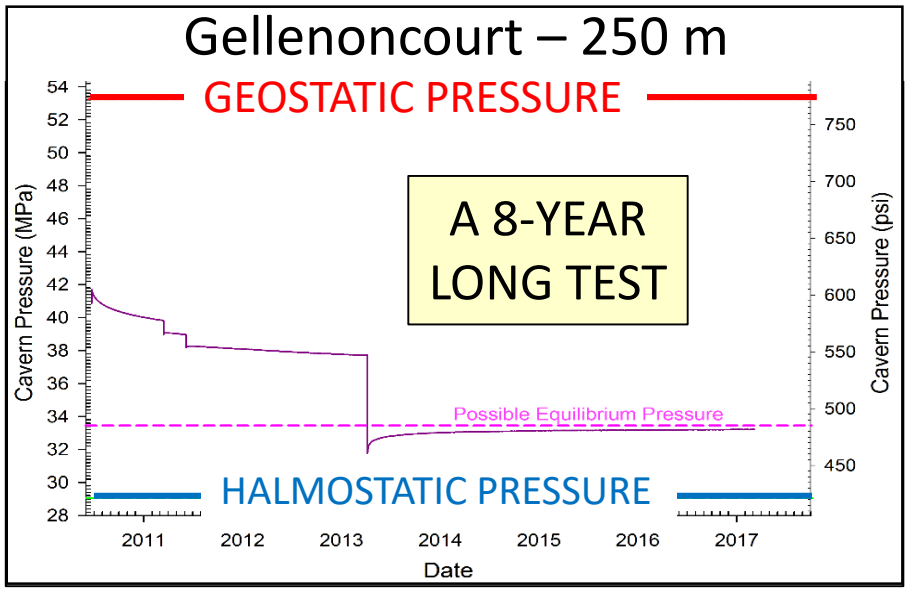
THE SMRI PROGRAM (1997-2014)

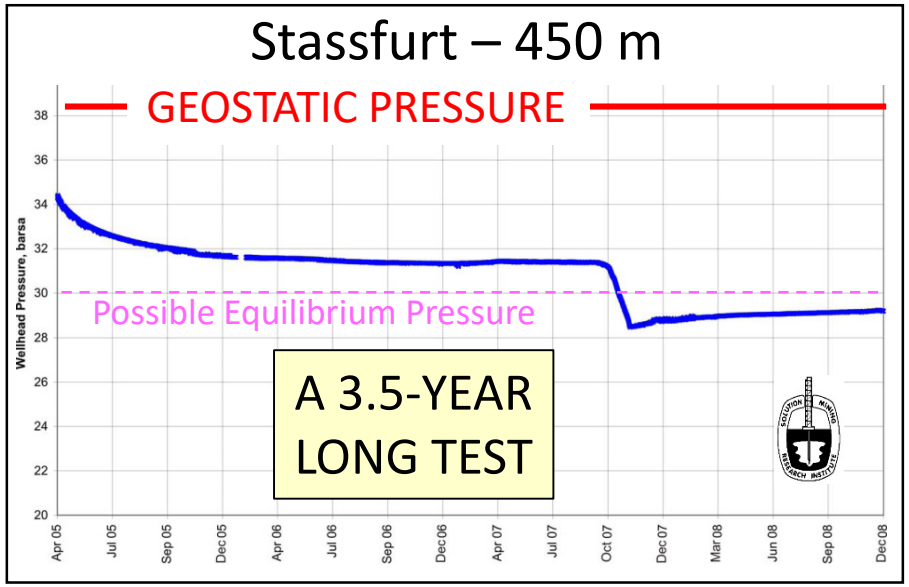
"following three succinct field tests performed in the late 1980s and early 1990s by Gaz de France and partially supported by the SMRI [Gaz de France, 1990, 1994; Bérest et al., 1998]… the SMRI initiated a multi-project program focused on addressing the complex issues of sealing and abandonment of solution-mined cavern wells" (Ratigan, 2003, p. 1).

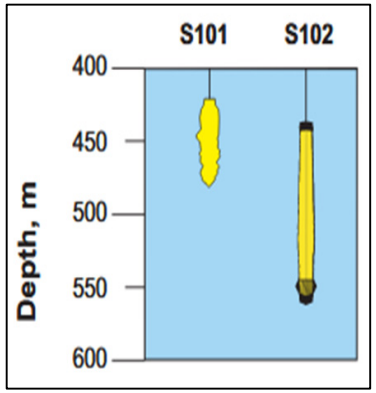

0
-200
-400
-600
-800
-1000
Depth (m)
Carresse SPR2
Depth: 298 – 322 m
Volume: 9,000 m³
Gellenoncourt SG13-14
Depth: 235 – 265 m
Volume: 240,000 m³
Etrez EZ53
Depth: 920 – 965 m
Volume: 8,000 m³


Etrez – 950 m
GEOSTATIC PRESSURE
A 13-YEAR LONG TEST
Possible Equilibrium Pressure
HALMOSTATIC PRESSURE
Cavern pressure (MPa)
Time
22
21
20
19
18
17
16
15
14
13
12
11
10
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

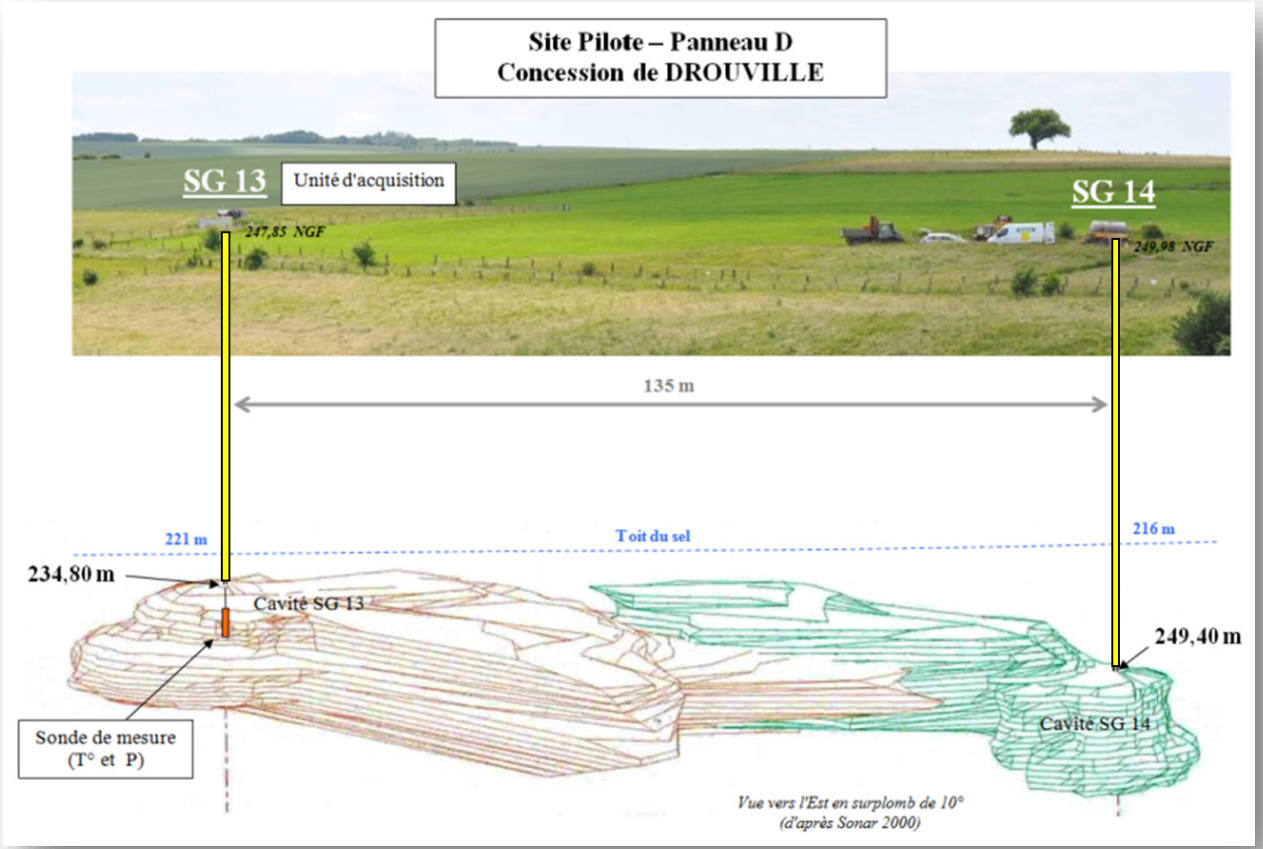

Carresse – 310 m
GEOSTATIC PRESSURE
A 8-YEAR LONG TEST
Possible Equilibrium Pressure
H'
HALMOSTATIC PRESSURE
Cavern Pressure (MPa)
Date - 2005-2013
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
05 06 07 08 09 10 11 12 13 14

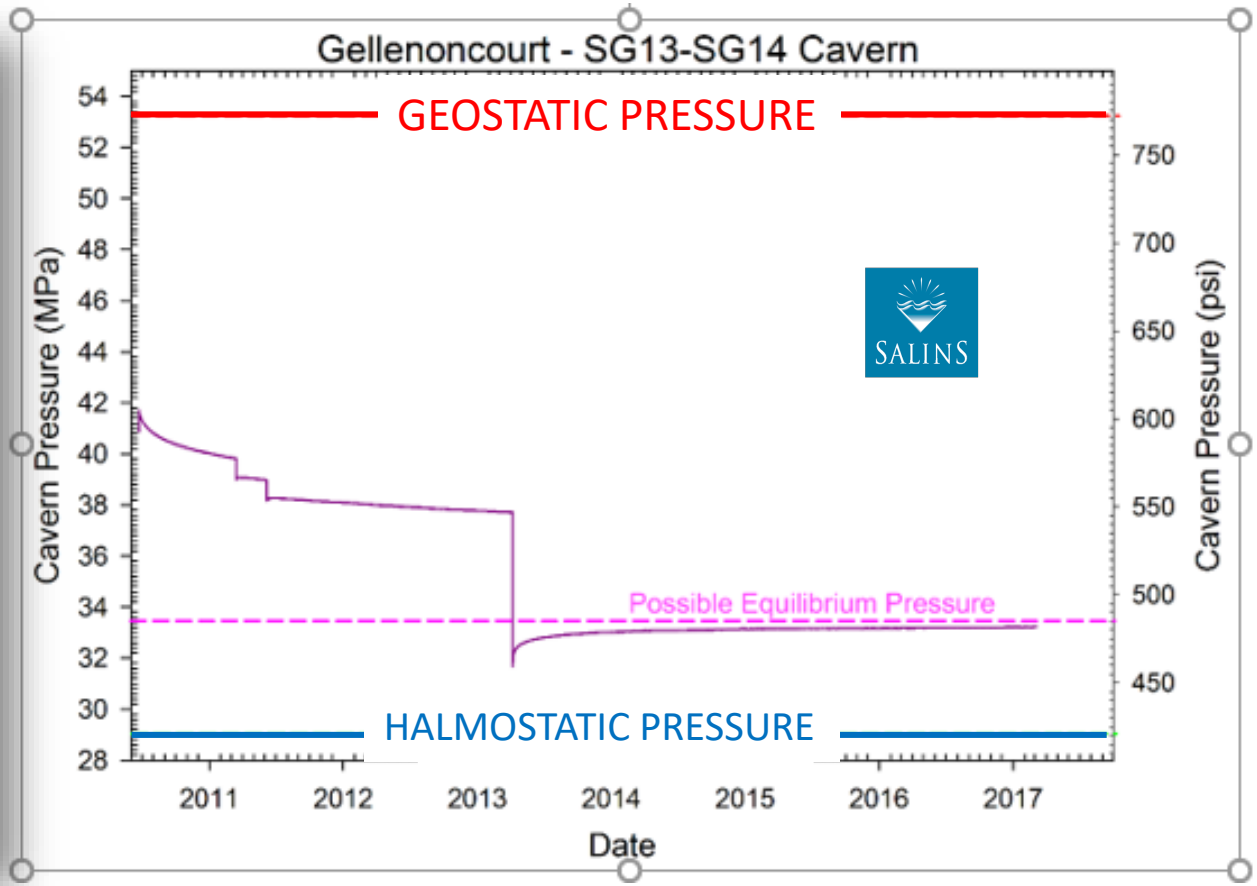

Gellenoncourt – 250 m
GEOSTATIC PRESSURE
A 8-YEAR LONG TEST
Possible Equilibrium Pressure
HALMOSTATIC PRESSURE
Cavern Pressure (MPa)
Cavern Pressure (psi)
Date
54
52
50
48
46
44
42
40
38
36
34
32
30
28
750
700
650
600
550
500
450
2011 2012 2013 2014 2015 2016 2017


Stassfurt – 450 m
GEOSTATIC PRESSURE
Possible Equilibrium Pressure
A 3.5-YEAR LONG TEST
Wellhead Pressure, barsa
38
36
34
32
30
28
26
24
22
20
Apr 05 Jul 05 Sep 05 Dec 05 Apr 06 Jul 06 Sep 06 Dec 06 Apr 07 Jul 07 Oct 07 Dec 07 Mar 08 Jun 08 Sep 08 Dec 08


S101
S102
Depth, m
400
450
500
550
600

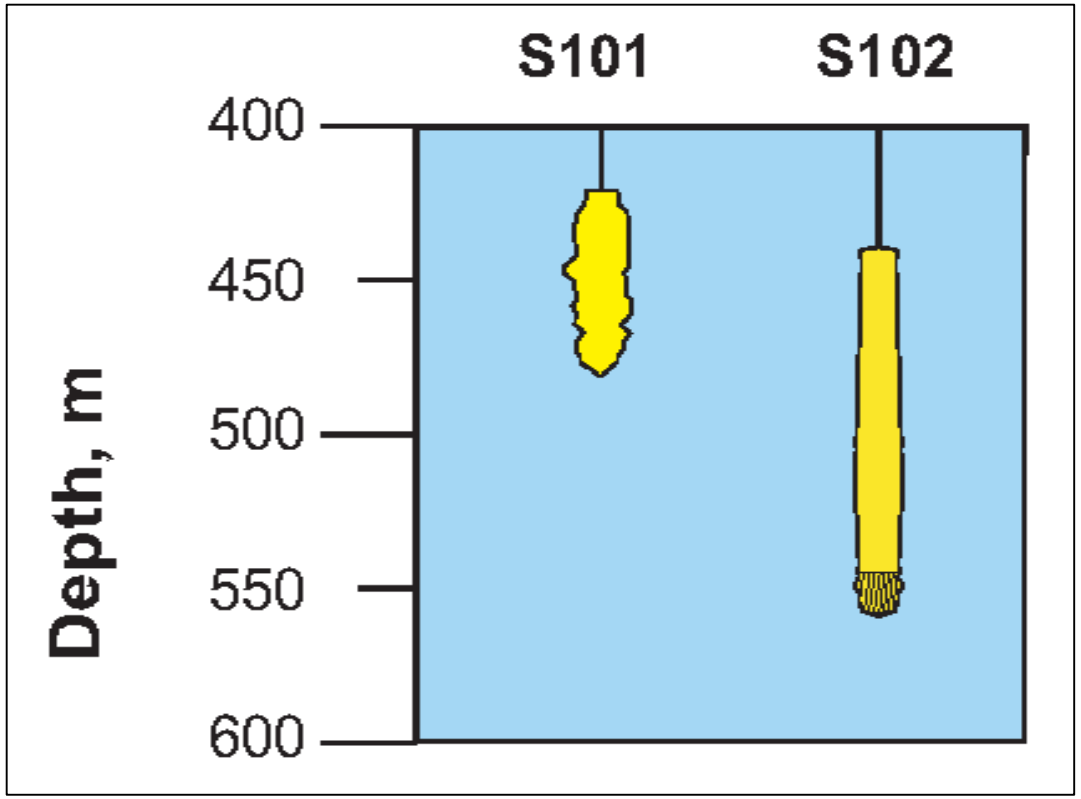
A 8-YEAR ABANDONMENT TEST IN A 250-M DEEP CAVERN AT GELLENONCOURT, FRANCE

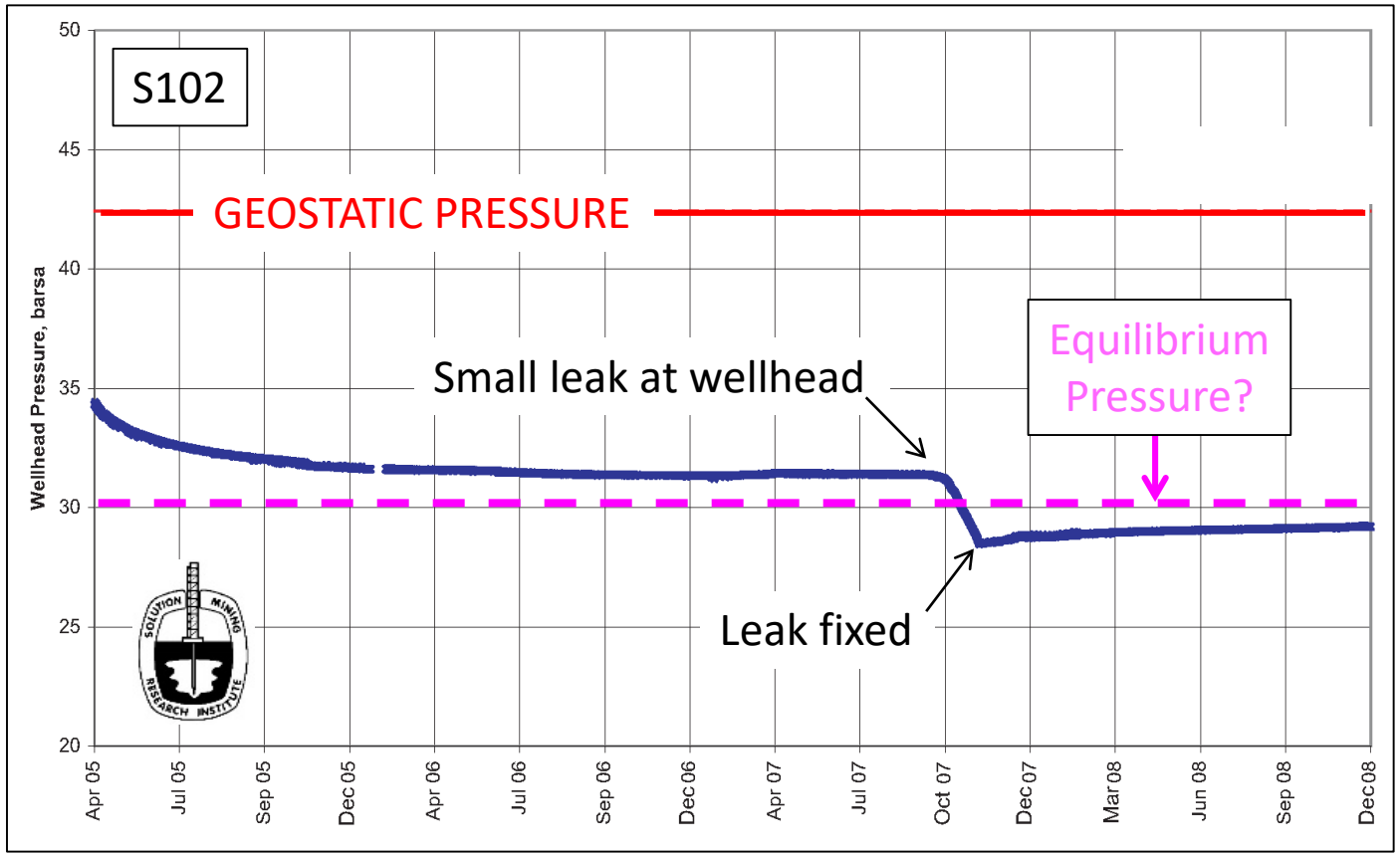




Brouard B., Bérest P., de Greef V. Beraud, J.F., Lheur C. and Hertz E. (2013) *Creep closure rate of a shallow salt cavern at Gellenoncourt, France*. Int. J. Rock Mech. Min. Sc., 2013.

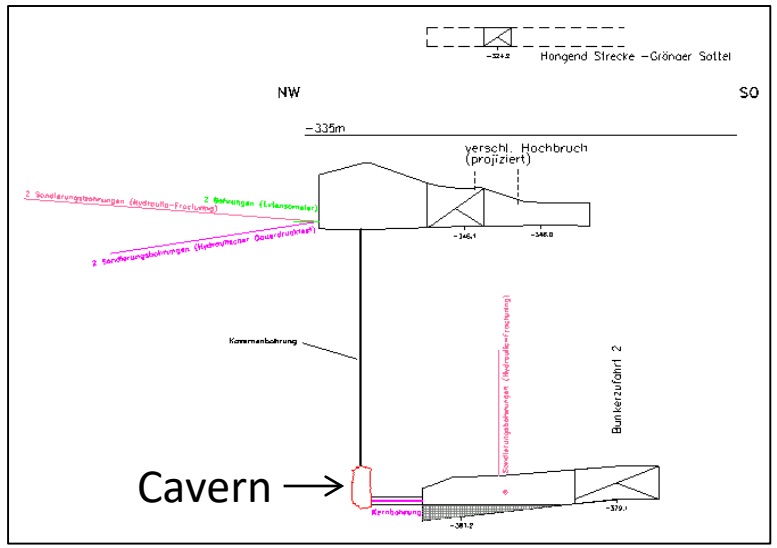
A 3-YEAR ABANDONMENT TEST IN A 500-M DEEP CAVERN AT STASSFURT, GERMANY

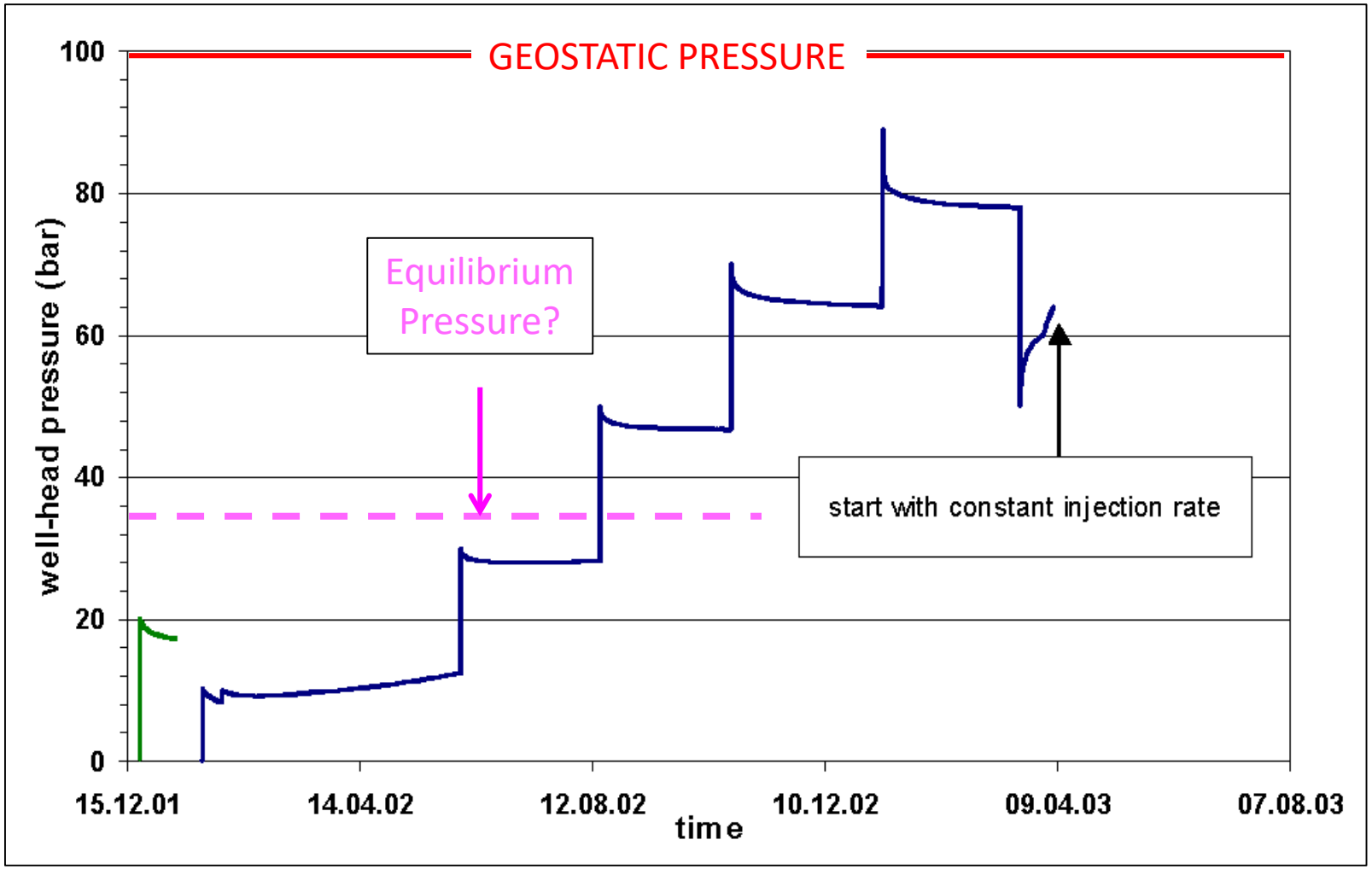




Banach A. and Klafki M. (2009) *Stassfurt Shallow Cavern Abandonment Field Tests*. SMRI Research Report RR 2009-01.

A 40-MONTH SHUT-IN TEST IN A 448-M DEEP SMALL (22 M^3) CAVERN LEACHED OUT FROM A MINE DRIFT AT BERNBURG, GERMANY





Brückner et al. (2003). *The Bernburg Test Cavern – A Model Study of Cavern Abandonment*. Proc. SMRI Fall Meeting, 5 – 8 October Chester, UK.

THE PROBLEM WITH DEEP CAVERNS (2007-2019)

WHY TESTING DEEP CAVERNS RAISE DIFFICULT PROBLEMS?

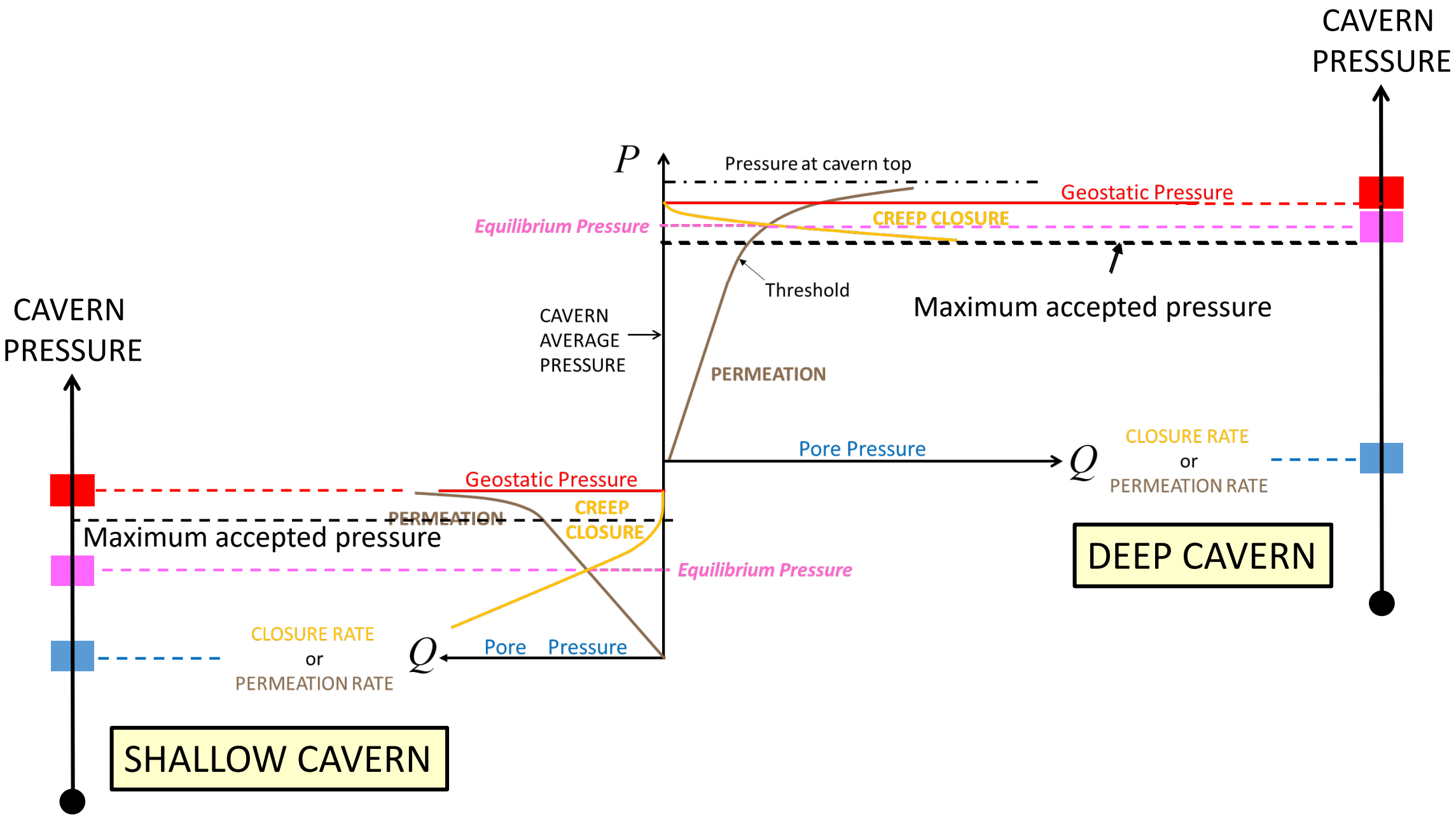
- **BRINE WARMING BECOMES NEGLIGIBLE AFTER A LONGER PERIOD.**
- **EQUILIBRIUM PRESSURE IS CLOSE TO GEOSTATIC PRESSURE (G = 0.022 MPa/m) AND REGULATORY AUTHORITIES ARE RELUCTANT TO ACCEPT TESTING PRESSURES HIGHER THAN MAXIMUM PRESSURES DURING OPERATION (G = 0.018 MPa/m).**
- **LONGER TESTS AND FREQUENT VENTINGS ARE NEEDED.**

THE MAXIMUM ACCEPTABLE PRESSURE IN A CAVERN IS

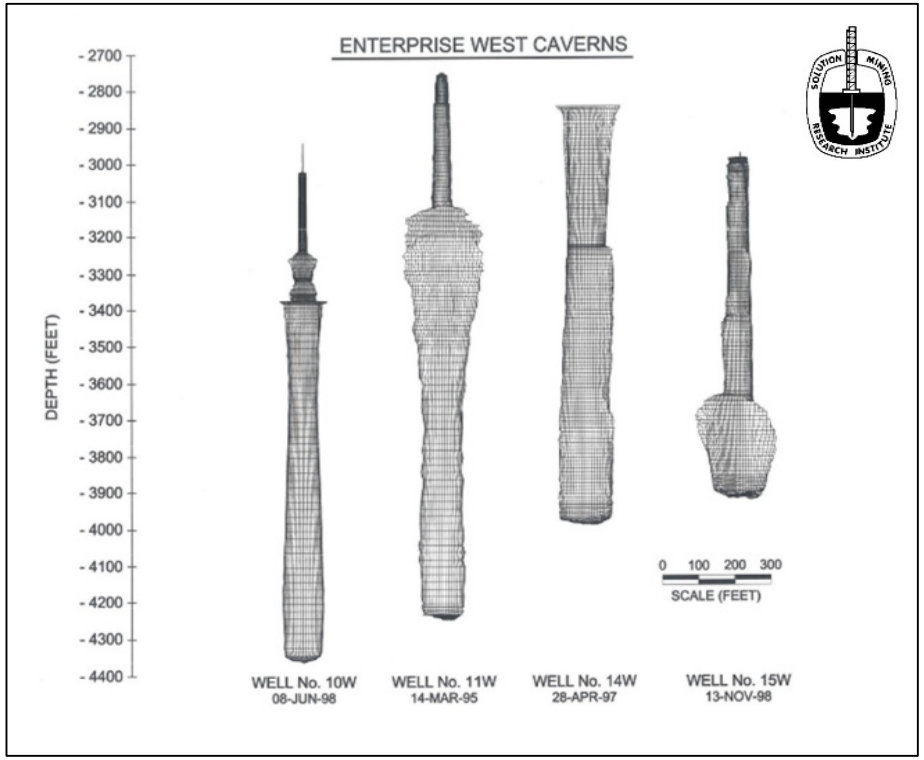
0.018 MPa/m

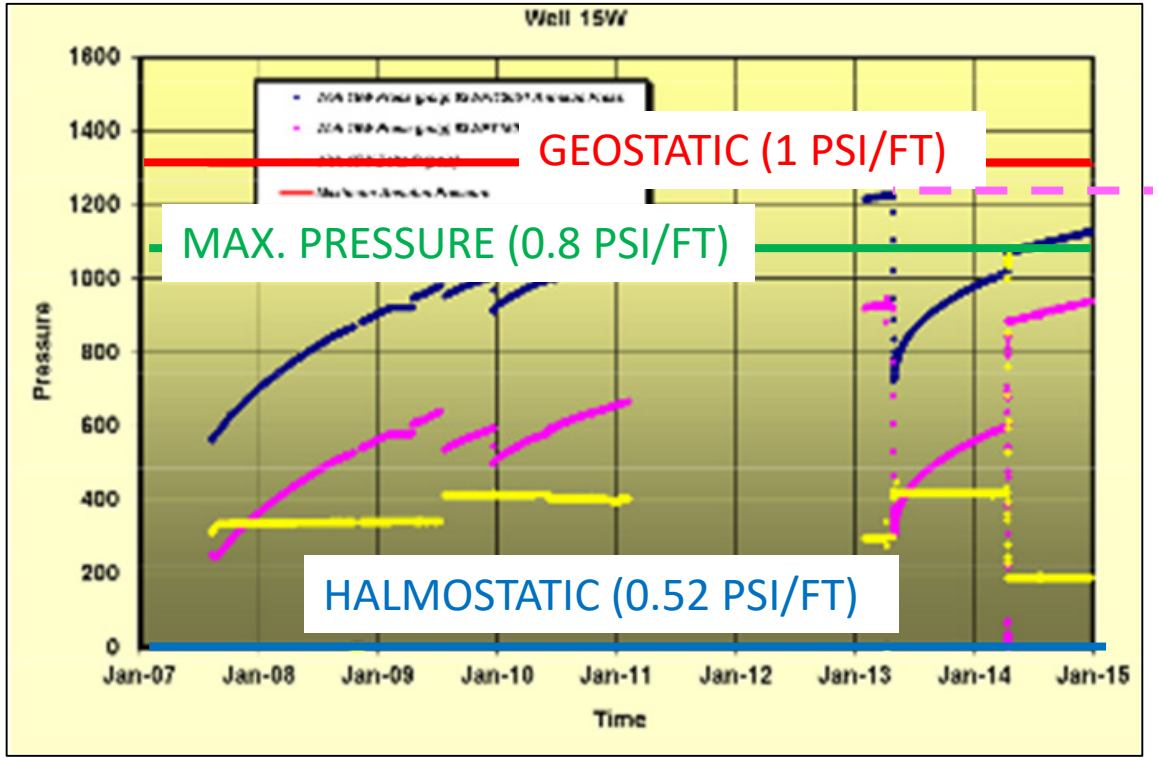
IN MOST CASES

Gas storage	Authors	CCS depth (m)	Pmax (MPa)	Maximum gradient (MPa/m)	Maximum gradient (psi/ft)
Aldbrough	Slingsby et al., 2011	1800	27	0.015	0.66
Carriço	Colcombet et al., 2008	1000	18	0.018	0.8
Etzel	Schweinsburg et al., 2010	1150	20	0.017	0.76
Holford	Fawthrop et al., 2013	≈ 550	10	0.018	0.8
Krummhörn	Rummel et al., 1996	≈1500	27	0.018	0.8
Nuttermoor	Bernhardt et al., 2013	≈ 1000	17	0.017	0.76
Teesside	Mullaly, 1982	≈ 350	4.5	0.013	0.58
Zuidwending	Hoelen et al., 2010	1000	18	0.018	0.8
Manosque	de Laguérie & Durup, 1994	1000	18	0.018	0.8
Stublach	Pellizzaro et al., 2011	≈ 550	10	0.018	0.8
Egan	Chabannes, 2005	1125	23	0.0204	0.9
Kansas	Itsvan, 1998	NA	12		
China	Fansheng et al., 2010	≈ 2000	17	0.016-0.017	0.72
Aldbrough	McLeod et al., 2011	≈1500	27	0.0155	0.66
Nüttermoor	Bernhardt et al., 2013	≈ 1020	17	0.017	0.8
Germany	Wagler et al., 2013	≈ 648	12.2	0.0188	0.83
Torup	Johansen, 2010			0.0184	0.81
Huai'an	Zhao et al., 2013	1493	26.0	0.0175	0.77
Jintan (Xi-2#)	Yang et al., 2015	937	13.5 15.0	0.144 0.0160	0.64 0.7
Jintan (PetroChina)	Hongling Ma, Institute of Soil and Rock Mechanics, Wuhan, pers.com. (May 2018)	≈1000	17.0 18.0	0.0170 0.0180	0.76 0.8
Jintan (Sinopec)		900	17.0	0.0188	0.83
Qianjiang		1980	32.0	0.0160	0.7


CAVERN PRESSURE
P
Pressure at cavern top
Geostatic Pressure
CREEP CLOSURE
Equilibrium Pressure
Threshold
Maximum accepted pressure
CAVERN AVERAGE PRESSURE
PERMEATION
Pore Pressure
Q
CLOSURE RATE or PERMEATION RATE
DEEP CAVERN
CAVERN PRESSURE
Geostatic Pressure
PERMEATION
CREEP CLOSURE
Maximum accepted pressure
Equilibrium Pressure
CLOSURE RATE or PERMEATION RATE
Q
Pore Pressure
SHALLOW CAVERN

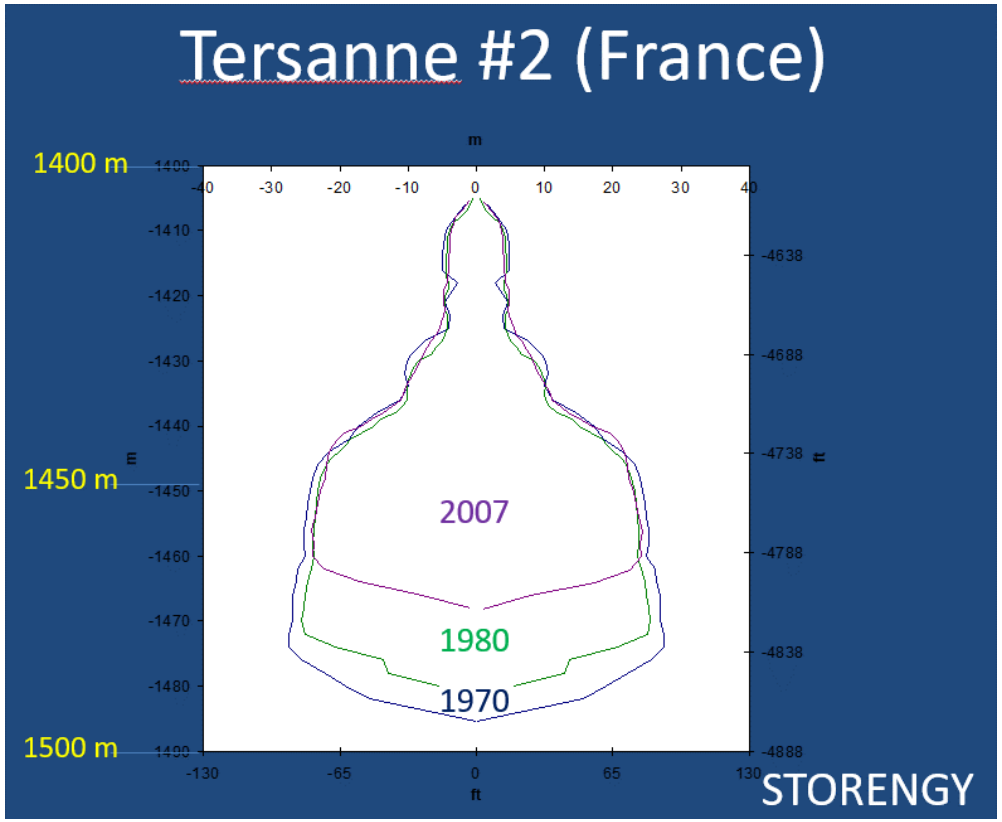
SHUT-IN 8-YEAR LONG TESTS IN FOUR 1000-M DEEP CAVERN AT MONT BELVIEU, TEXAS

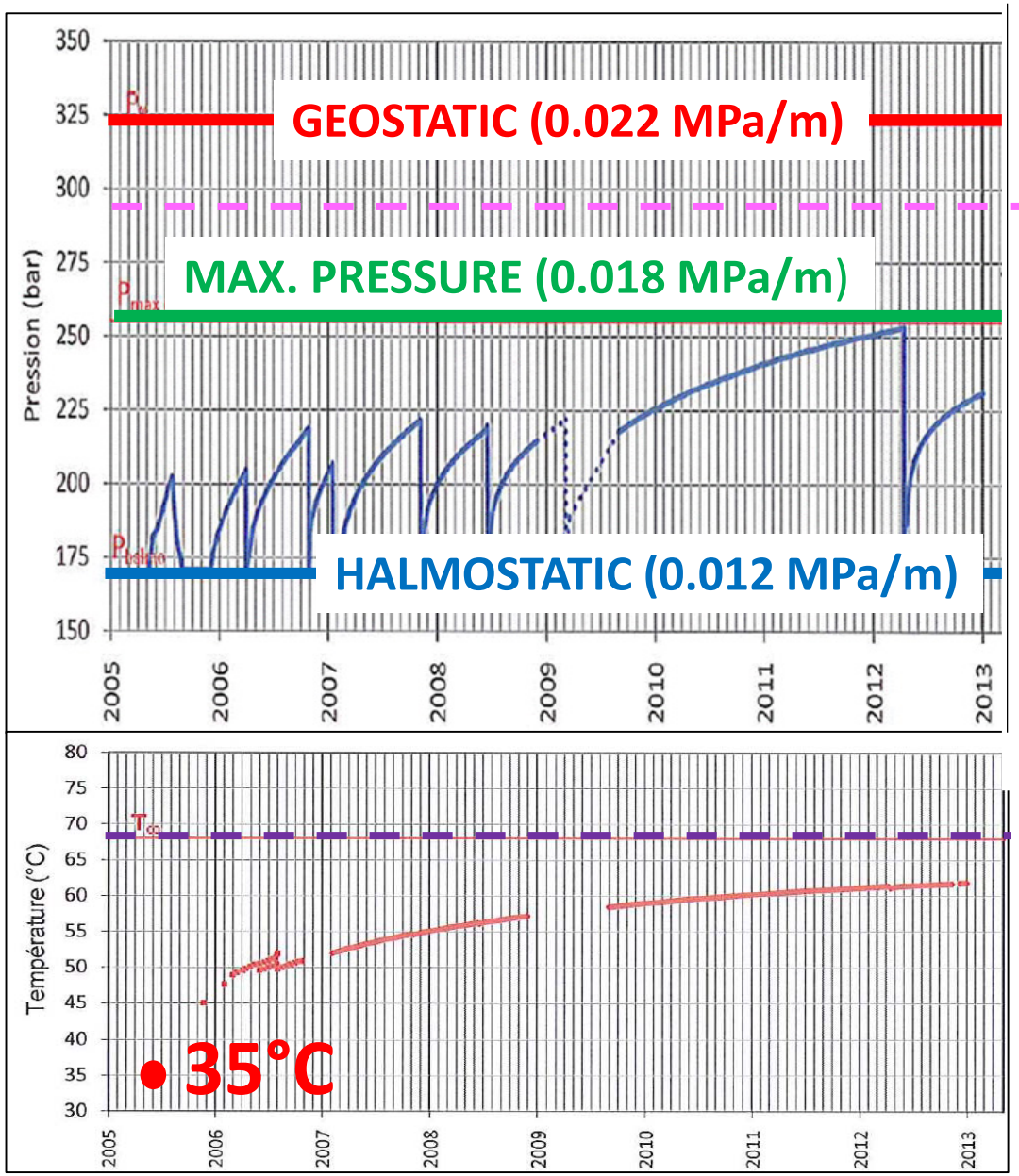




Enterprise Products Operating L.L.C., PB Energy Storage Services, RESPEC 3824. (2015) *SMRI Cavern abandonment field tests in deep caverns*. August 2015. SMRI Research Report RR2015-02.

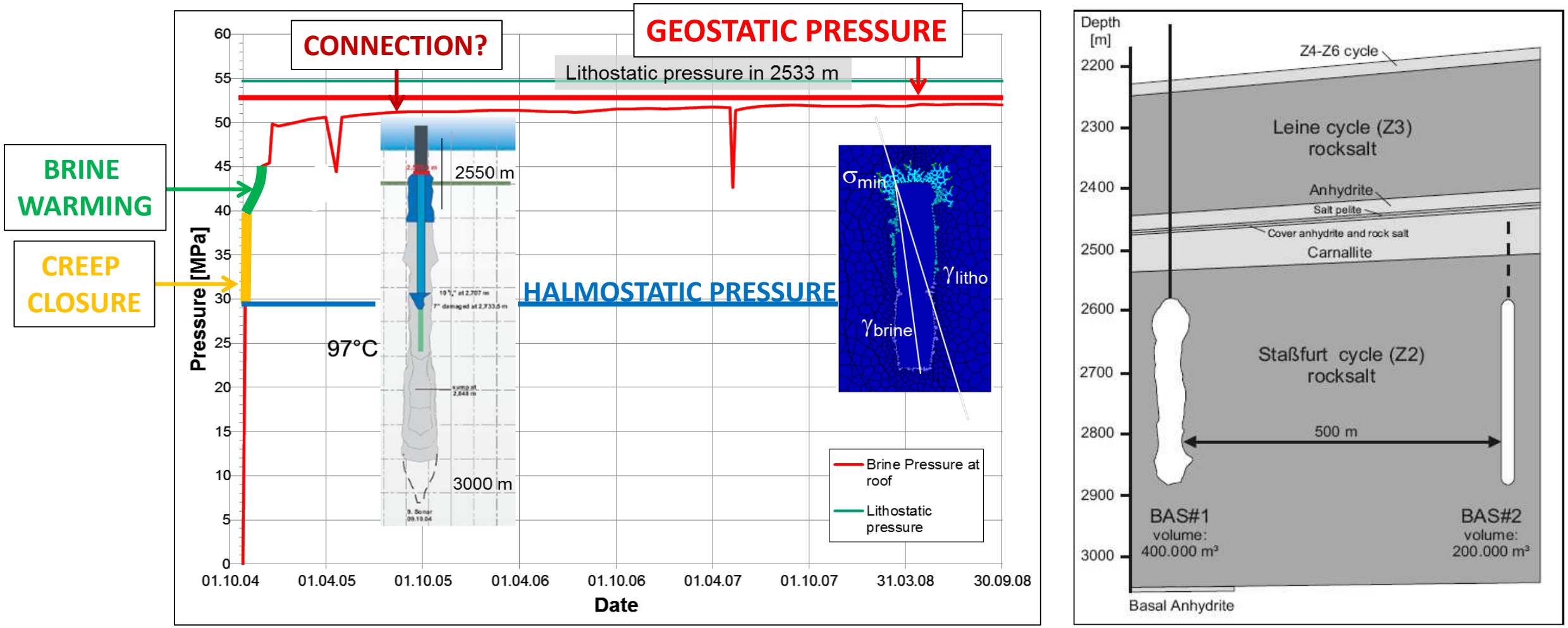
A SHUT-IN TEST, 14-YEAR LONG, IN A 1450-M DEEP CAVERN AT TERSANNE, FRANCE





Hévin G. and Rousset E. (2013*) Te02 salt cavern. 8 years of abandonment test*. Proc. SMRI Fall Meeting, Avignon, France.

A SHUT-IN TEST, 3-YEAR LONG, IN A 2000-M DEEP CAVERN AT BARRADEEL, THE NETHERLANDS



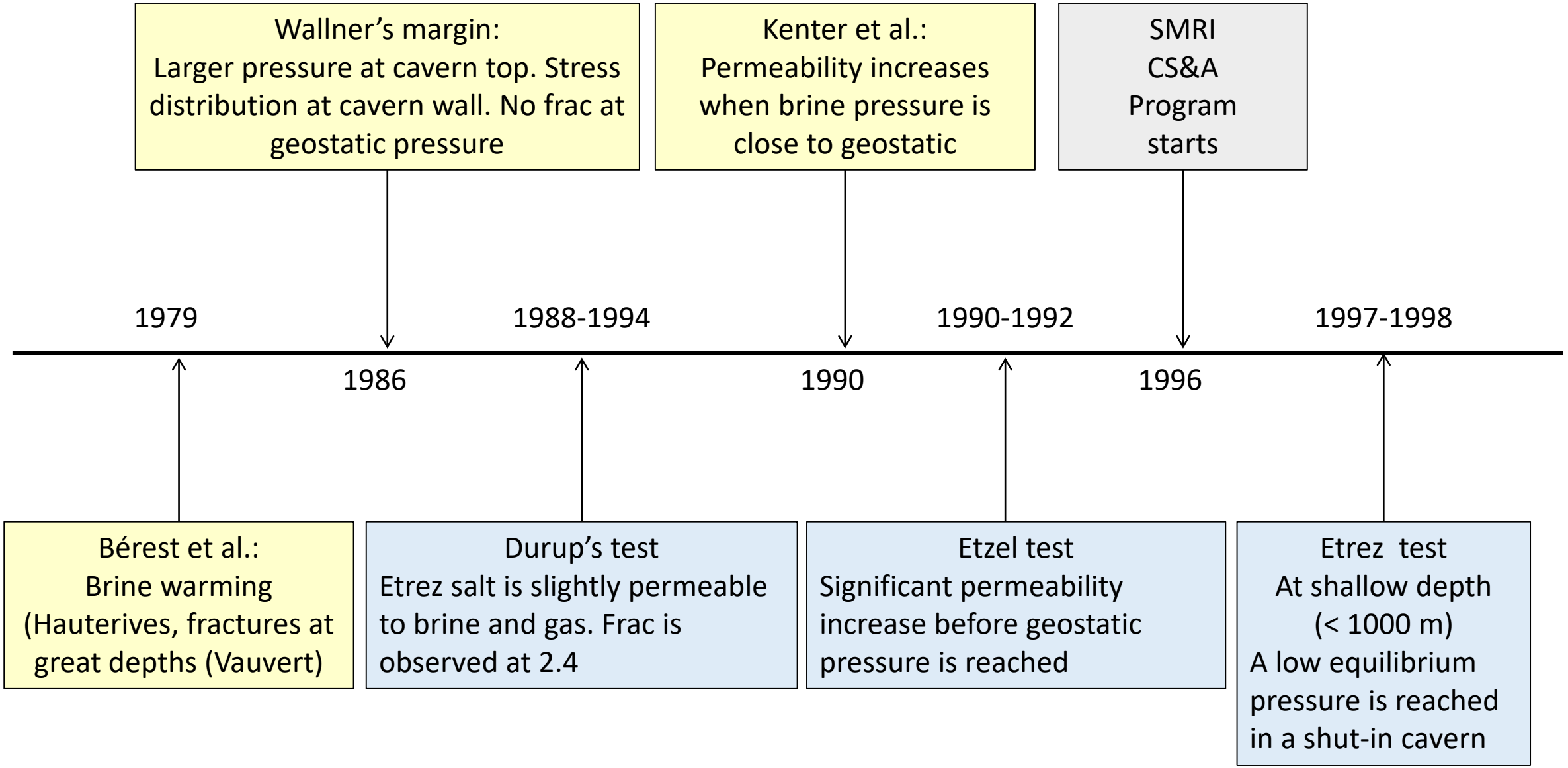
(After Minkley et al., 2018b)

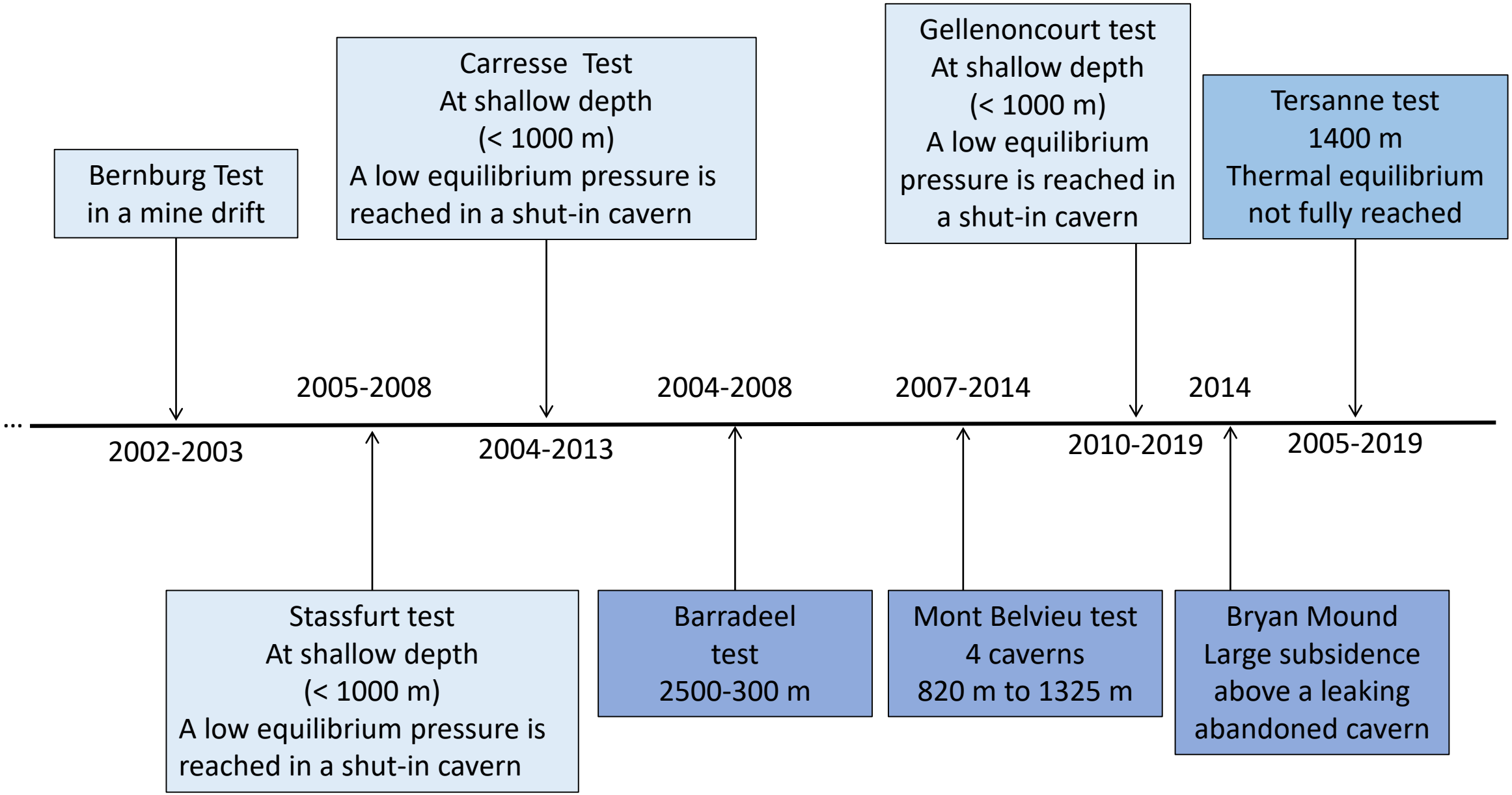
Van Heekeren H., Bakker T., Duquesnoy T., de Ruiter V. and Mulder L. (2009) *Abandonment of an extremely deep Cavern at Frisia Salt*. Proc. SMRI Fall Meeting, 27-28 April 2009, Krakow, Poland.

CONCLUSIONS

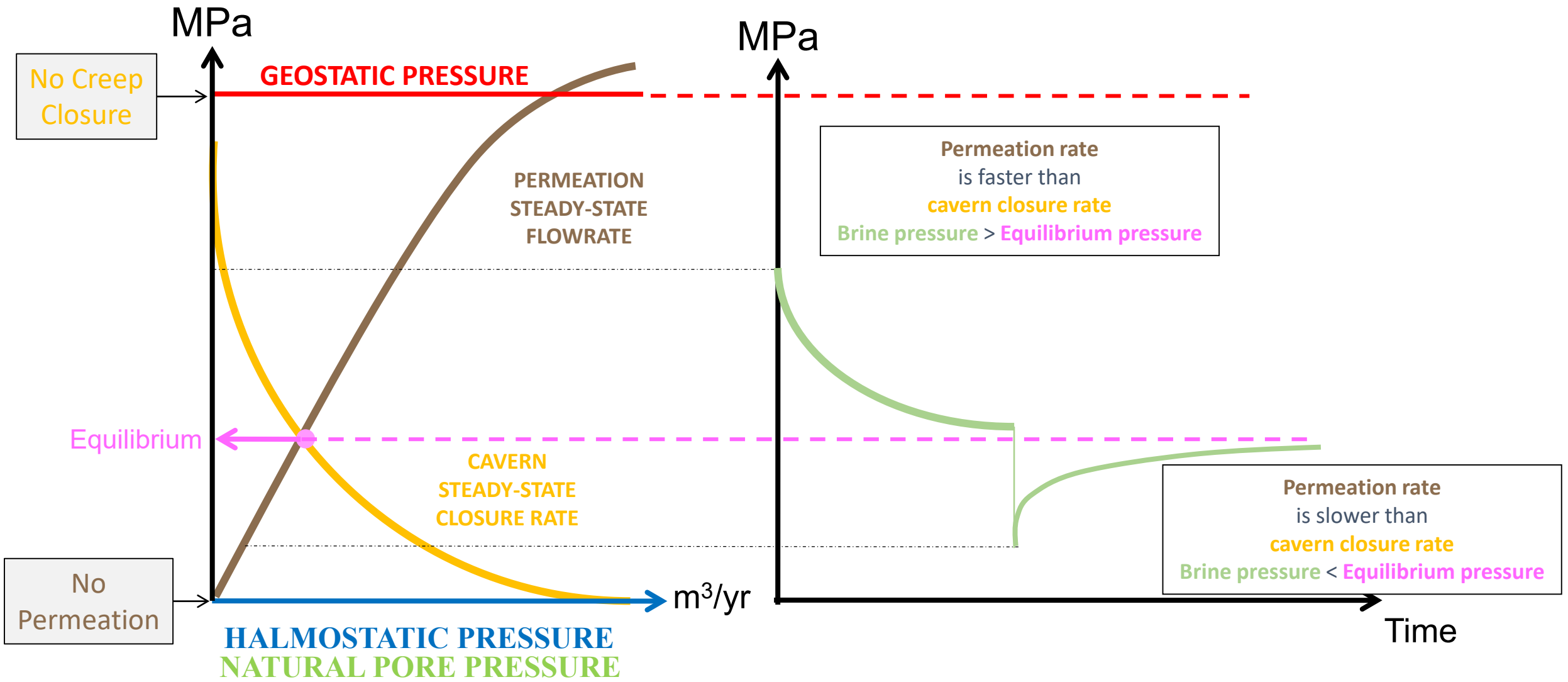
- ✓ 12 IN-SITU TESTS WERE DESCRIBED (Hauterives, Vauvert, Etzel, Etrez 58, Etrez 53, Carresse, Stassfurt, Gellenoncourt, Bernburg, Mont Belvieu, Tersanne, Barradeel).
- ✓ PRESSURE EVOLUTION IN AN SHUT-IN CAVERN RESULTS FROM:
  - BRINE WARMING
  - CAVERN CREEP CLOSURE
  - BRINE MICRO-PERMEATION THROUGH THE CAVERN WALLS
- ✓ AFTER BRINE WARMING HAS VANISHED (OFTEN A LONG PROCESS) AN EQUILIBRIUM PRESSURE IS REACHED.
- ✓ IN SHALLOW CAVERNS (<1000 m): THIS EQUILIBRIUM PRESSURE IS SIGNIFICANTLY SMALLER THAN GEOSTATIC; A SAFE ABANDONMENT CAN BE CONSIDERED.
- ✓ IN DEEP CAVERNS (>1000 m), THE EQUILIBRIUM PRESSURE IS CLOSER TO GEOSTATIC, RAISING A MORE DIFFICULT PROBLEM.

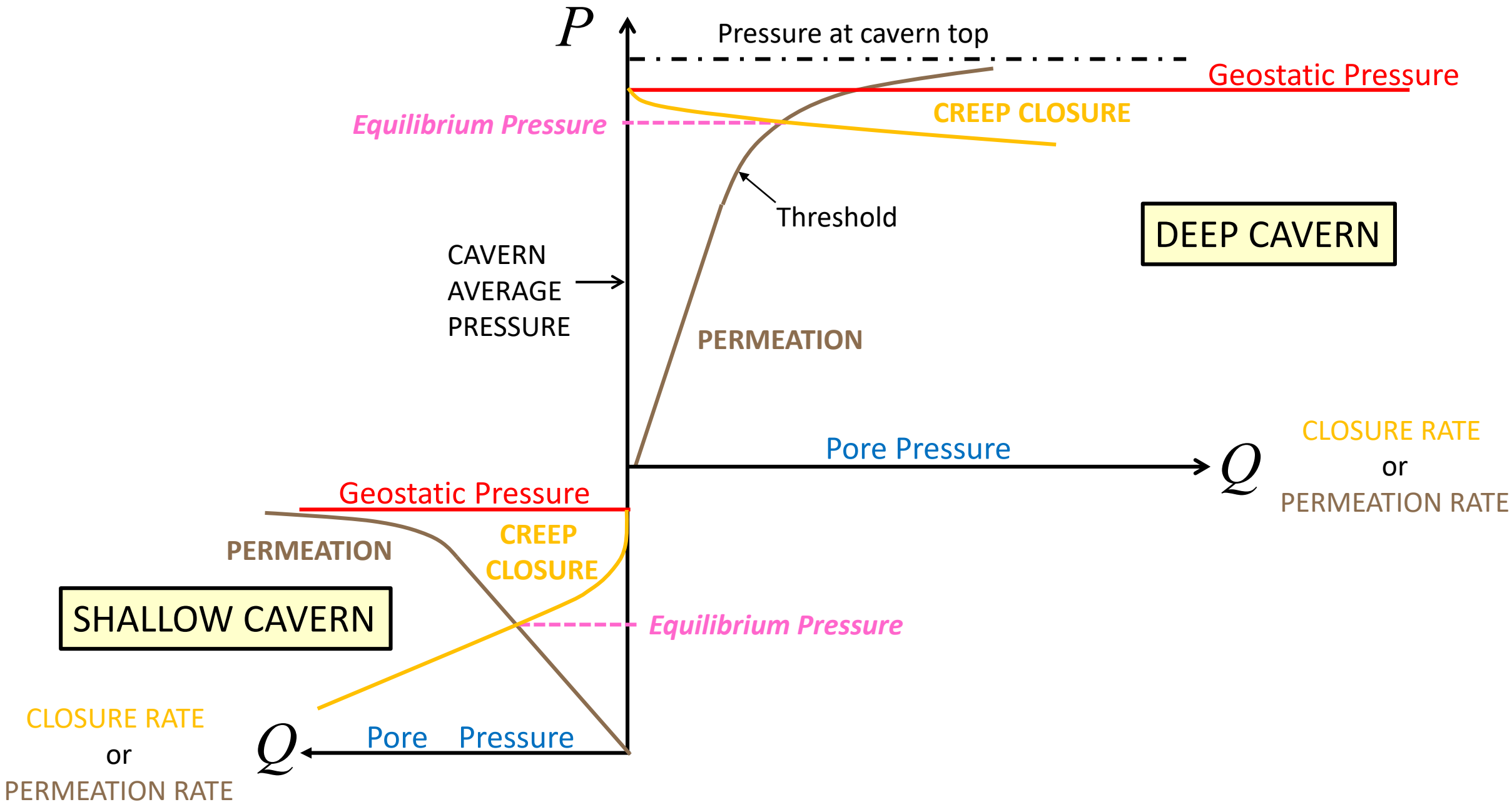
QUESTIONS?


Wallner's margin:
Larger pressure at cavern top. Stress distribution at cavern wall. No frac at geostatic pressure
Kenter et al.:
Permeability increases when brine pressure is close to geostatic
SMRI
CS&A
Program
starts
1979
1988-1994
1990-1992
1997-1998
1986
1990
1996
Bérest et al.:
Brine warming
(Hauterives, fractures at great depths (Vauvert)
Durup's test
Etrez salt is slightly permeable to brine and gas. Frac is observed at 2.4
Etzel test
Significant permeability increase before geostatic pressure is reached
Etrez test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached in a shut-in cavern


Bernburg Test
in a mine drift
Carresse Test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached in a shut-in cavern
Gellenoncourt test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached in a shut-in cavern
Tersanne test
1400 m
Thermal equilibrium not fully reached
...
2002-2003
2005-2008
2004-2013
2004-2008
2007-2014
2010-2019
2014
2005-2019
Stassfurt test
At shallow depth
(< 1000 m)
A low equilibrium pressure is reached in a shut-in cavern
Barradeel
test
2500-300 m
Mont Belvieu test
4 caverns
820 m to 1325 m
Bryan Mound
Large subsidence above a leaking abandoned cavern

BACK-UP


MPa
No Creep Closure
GEOSTATIC PRESSURE
PERMEATION STEADY-STATE FLOWRATE
Equilibrium
CAVERN STEADY-STATE CLOSURE RATE
No Permeation
m³/yr
HALMOSTATIC PRESSURE
NATURAL PORE PRESSURE
MPa
Permeation rate is faster than cavern closure rate
Brine pressure > Equilibrium pressure
Permeation rate is slower than cavern closure rate
Brine pressure < Equilibrium pressure
Time


P
Pressure at cavern top
Geostatic Pressure
CREEP CLOSURE
Equilibrium Pressure
Threshold
DEEP CAVERN
CAVERN
AVERAGE
PRESSURE
PERMEATION
Pore Pressure
Q
CLOSURE RATE
or
PERMEATION RATE
Geostatic Pressure
PERMEATION
CREEP
CLOSURE
SHALLOW CAVERN
Equilibrium Pressure
CLOSURE RATE
or
PERMEATION RATE
Q
Pore Pressure

- Appropriate geological knowledge and site characterization
- Site-specific risk assessment and detection of possible leakage pathways
- Preventive measures provided by an appropriate safe design
- Implementation of testing and monitoring procedures that aims at the early detection of any misconstruction or abnormal behaviour of the underground storage.