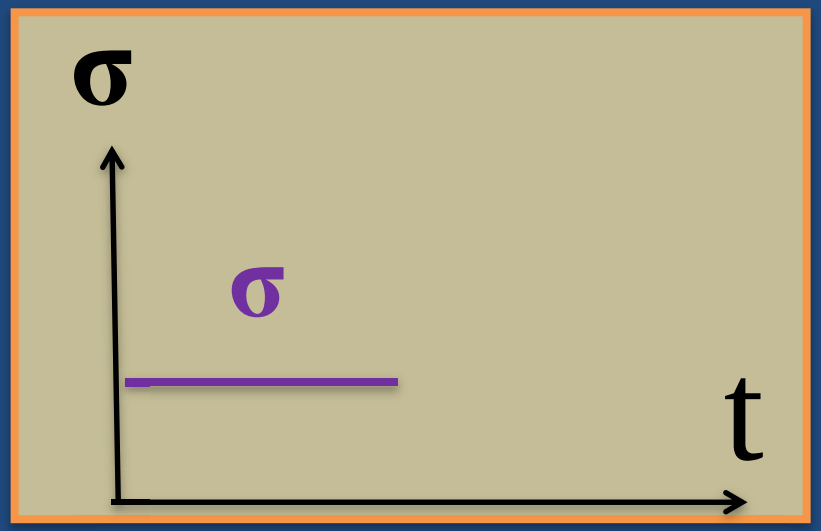
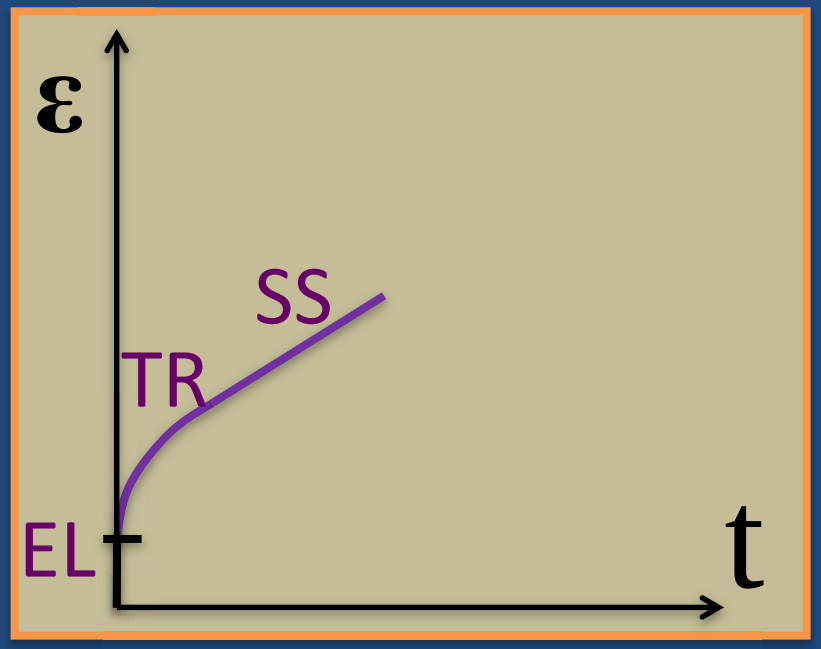
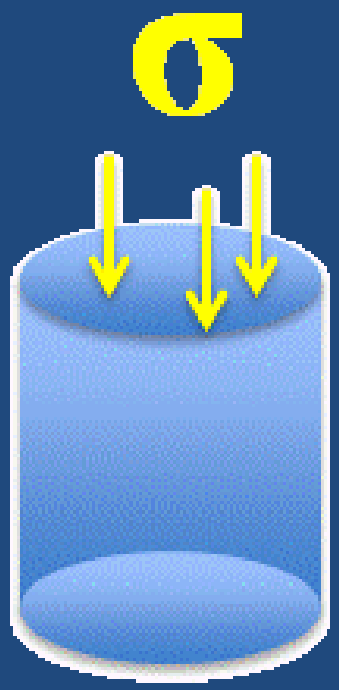
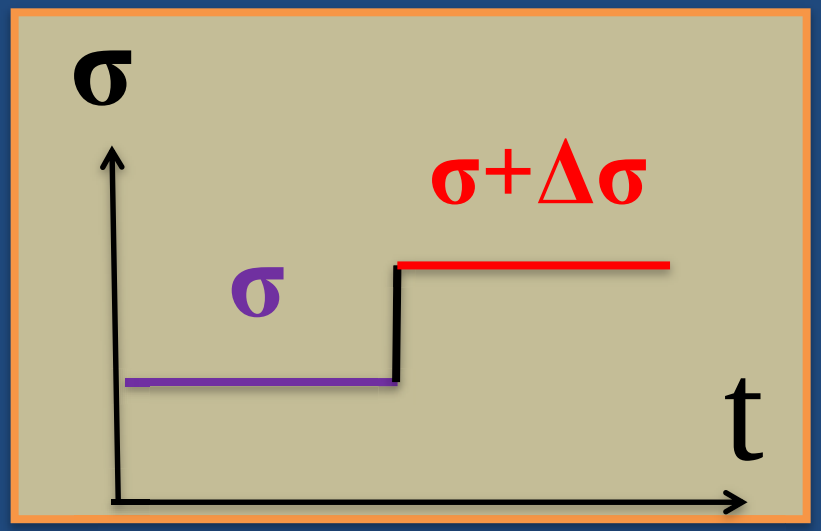
REVERSE CREEP
in the laboratory and in salt caverns

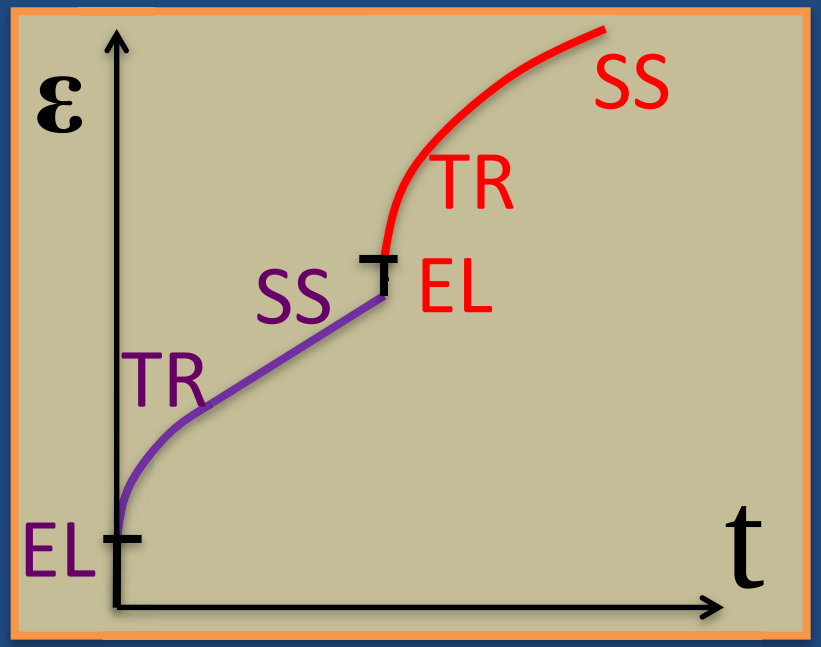
Pierre Bérest, Ecole Polytechnique
Benoît Brouard, Brouard Consulting
Hakim Gharbi, Ecole Polytechnique

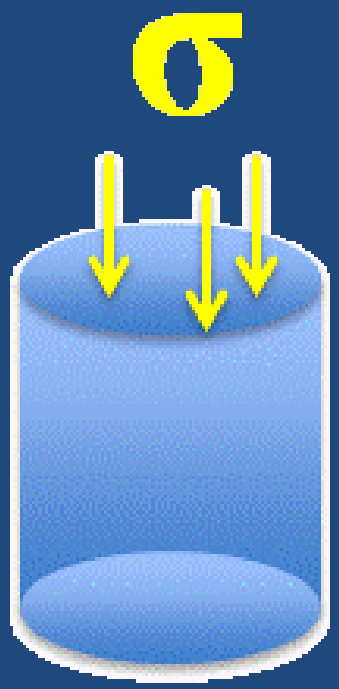

σ
σ
t

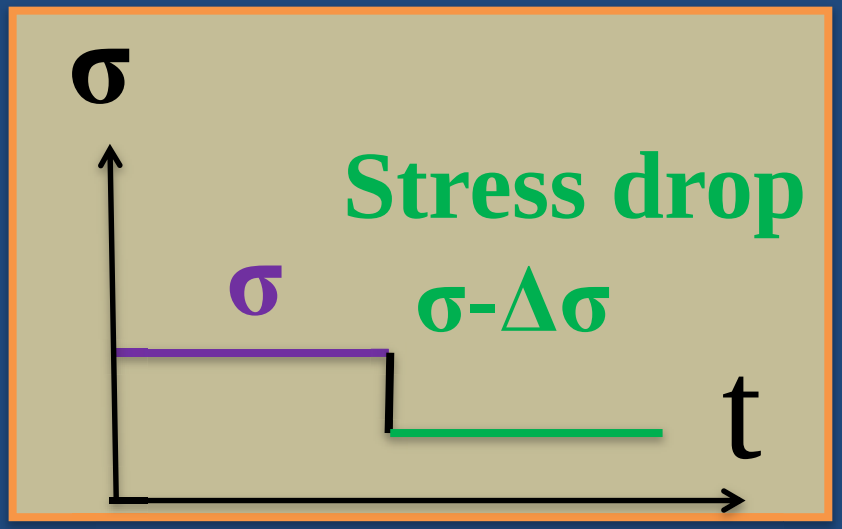

ε
SS
TR
EL
t

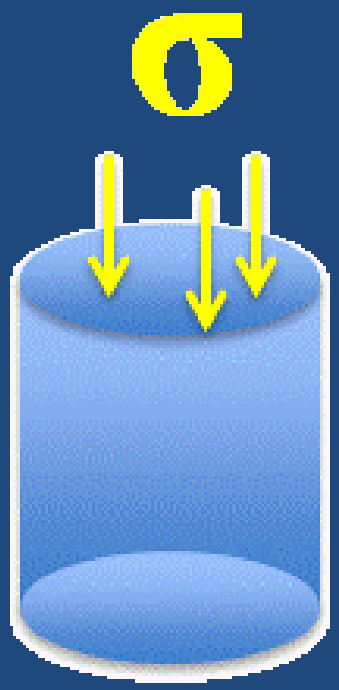

σ

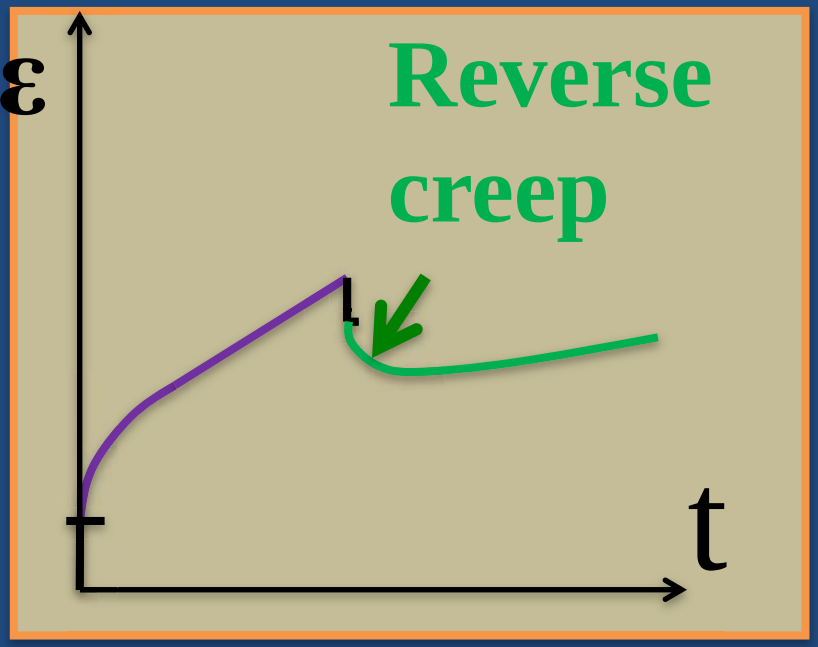

σ
σ+Δσ
σ
t


ε
SS
TR
SS
EL
TR
EL
t

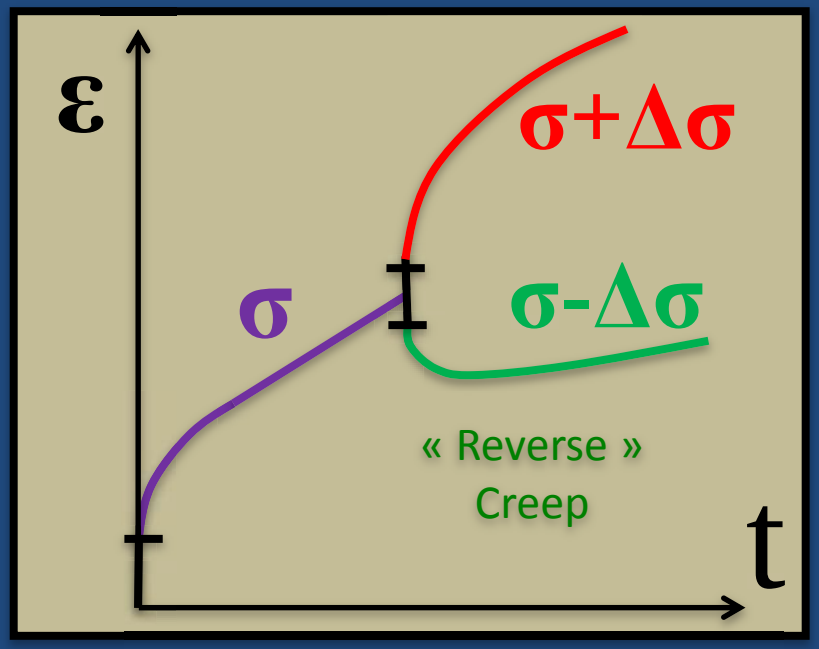

σ

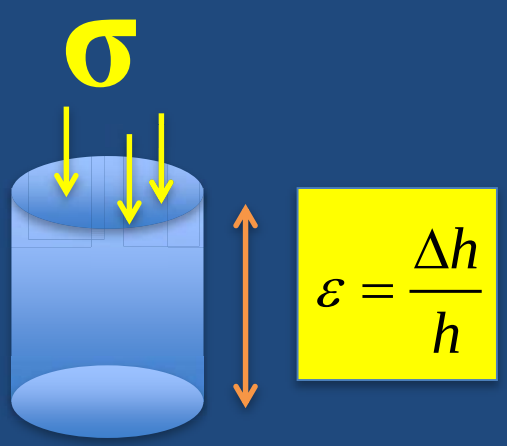


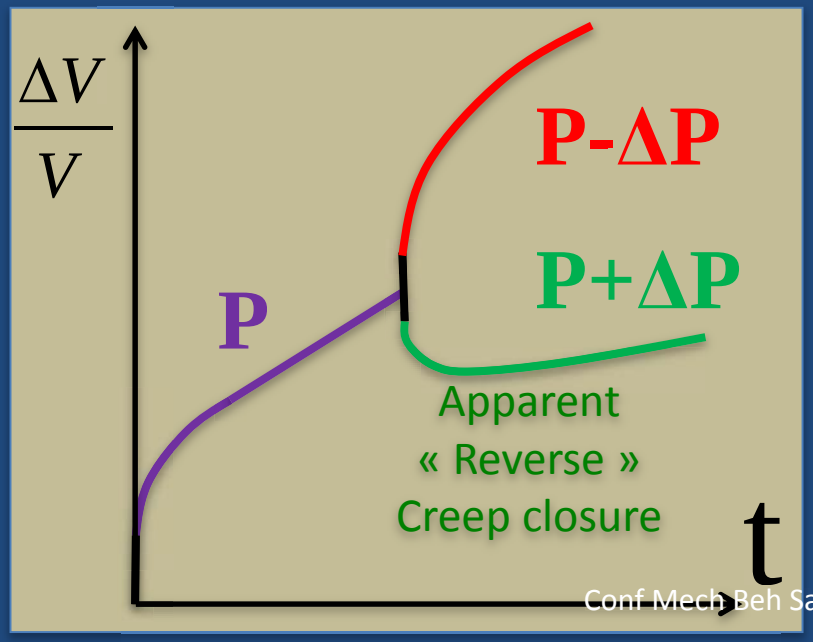


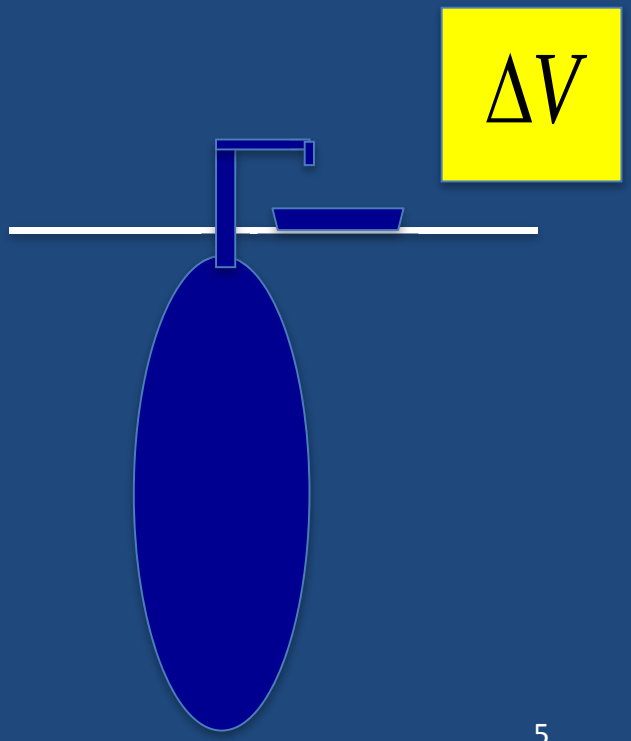


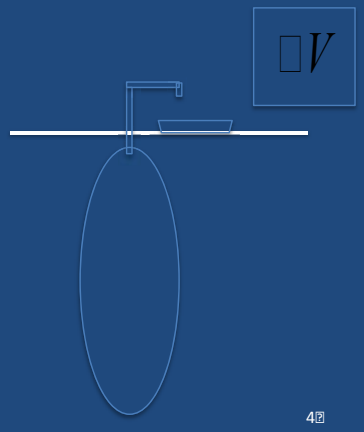
‘Rheological’
Reverse
Creep

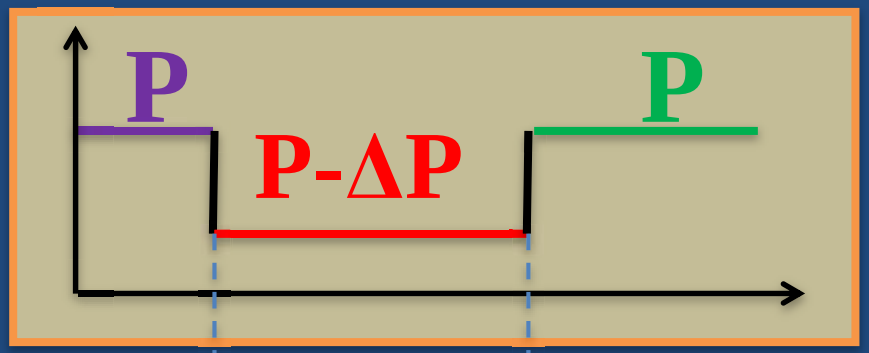

ε
σ+Δσ
σ
σ-Δσ
« Reverse »
Creep
t

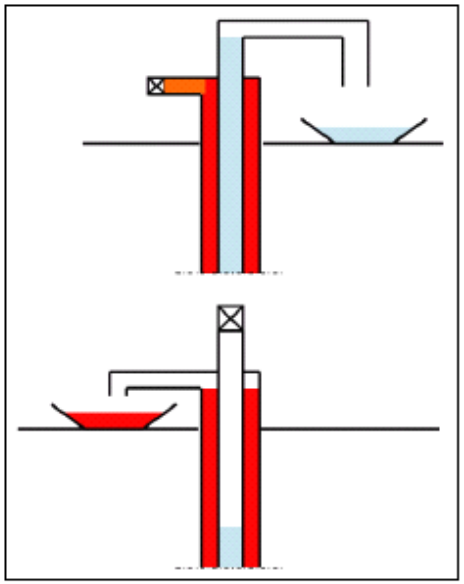

σ
$\varepsilon = \frac{\Delta h}{h}$

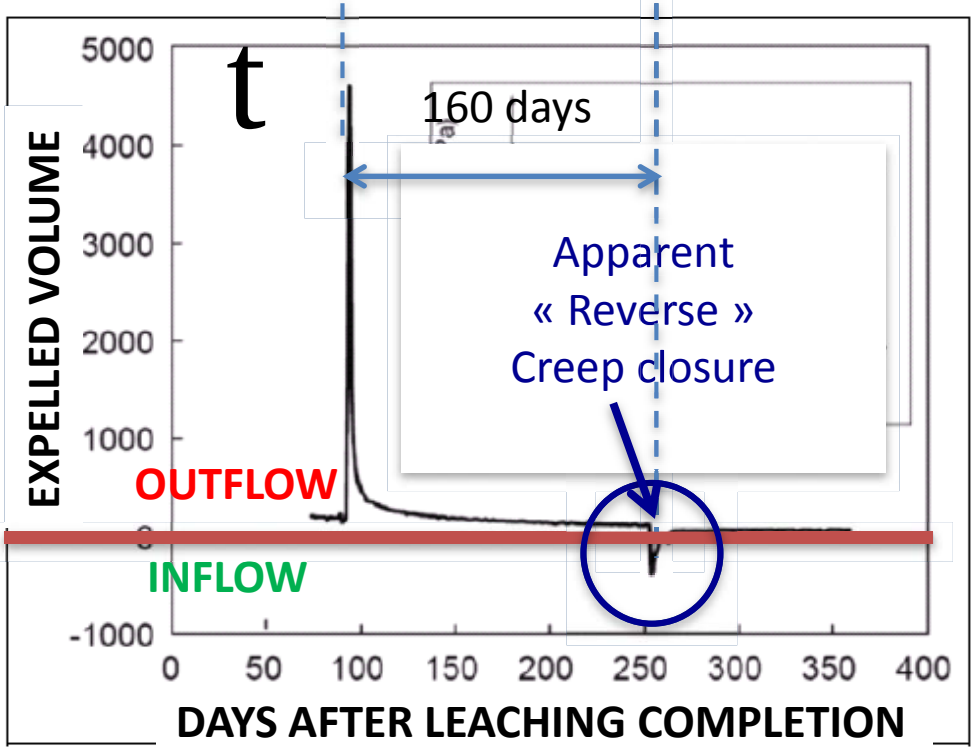

$\frac{\Delta V}{V}$
P-ΔP
P+ΔP
P
Apparent
« Reverse »
Creep closure
t


ΔV

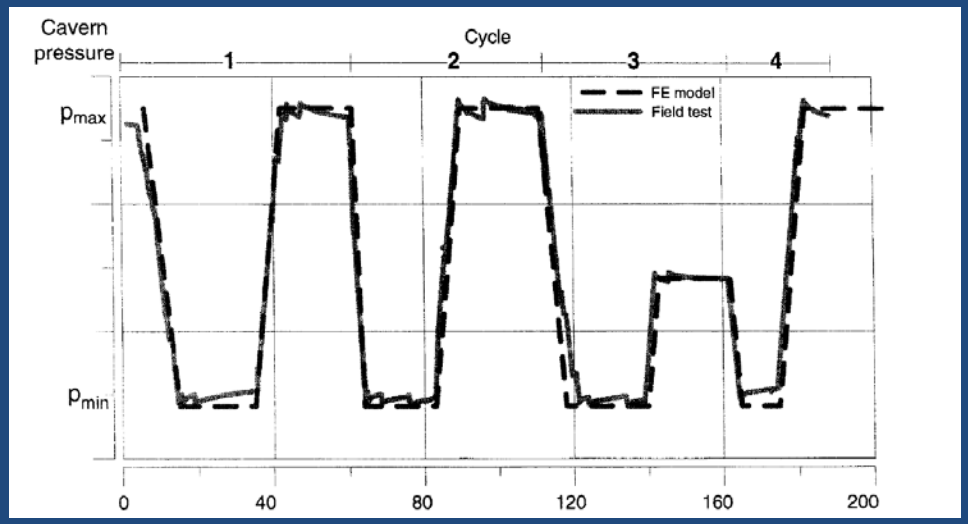


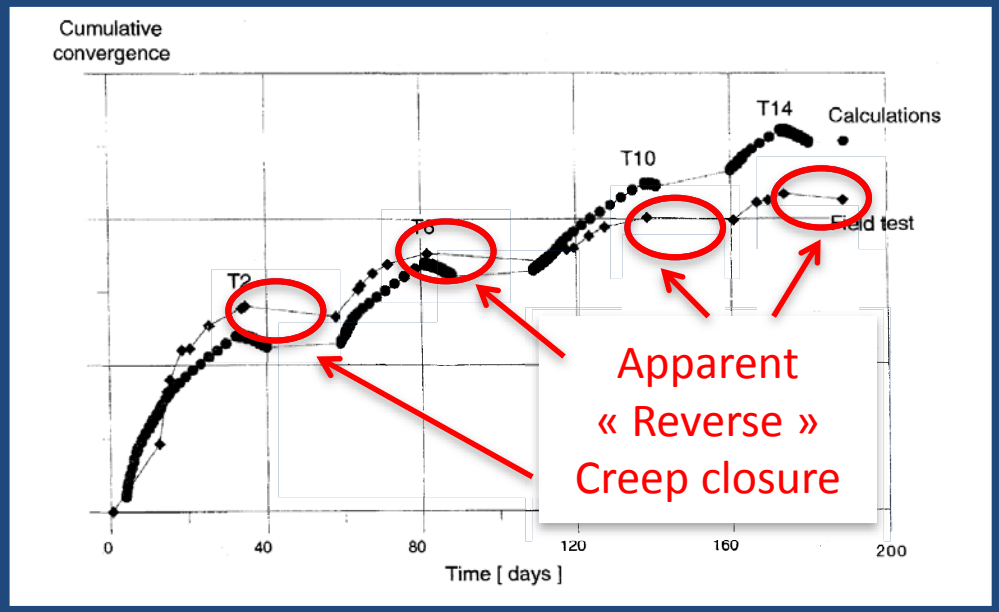


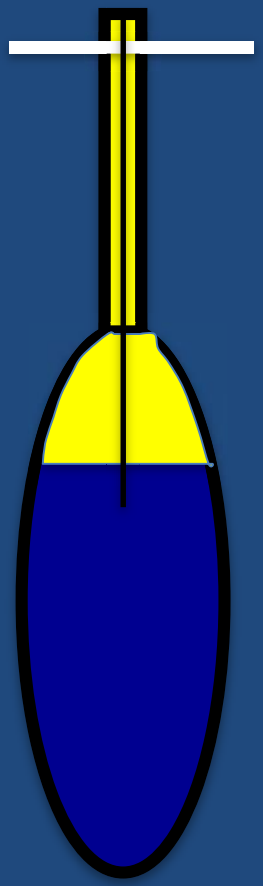




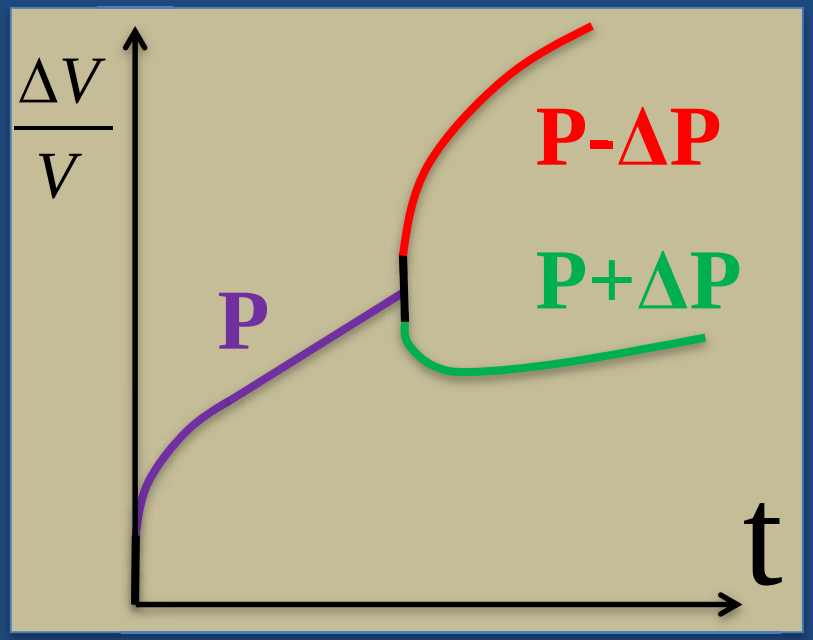
Hugout B. (1988). *Mechanical behavior of salt cavities —in situ tests— model for calculating the cavity volume evolution.* Proc. 2nd Conf. Mech. Beh. Salt.

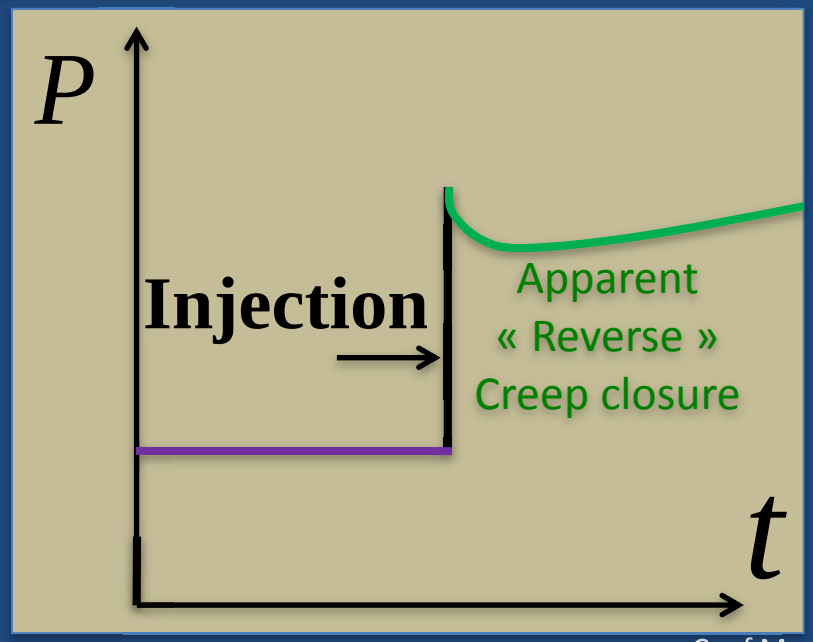


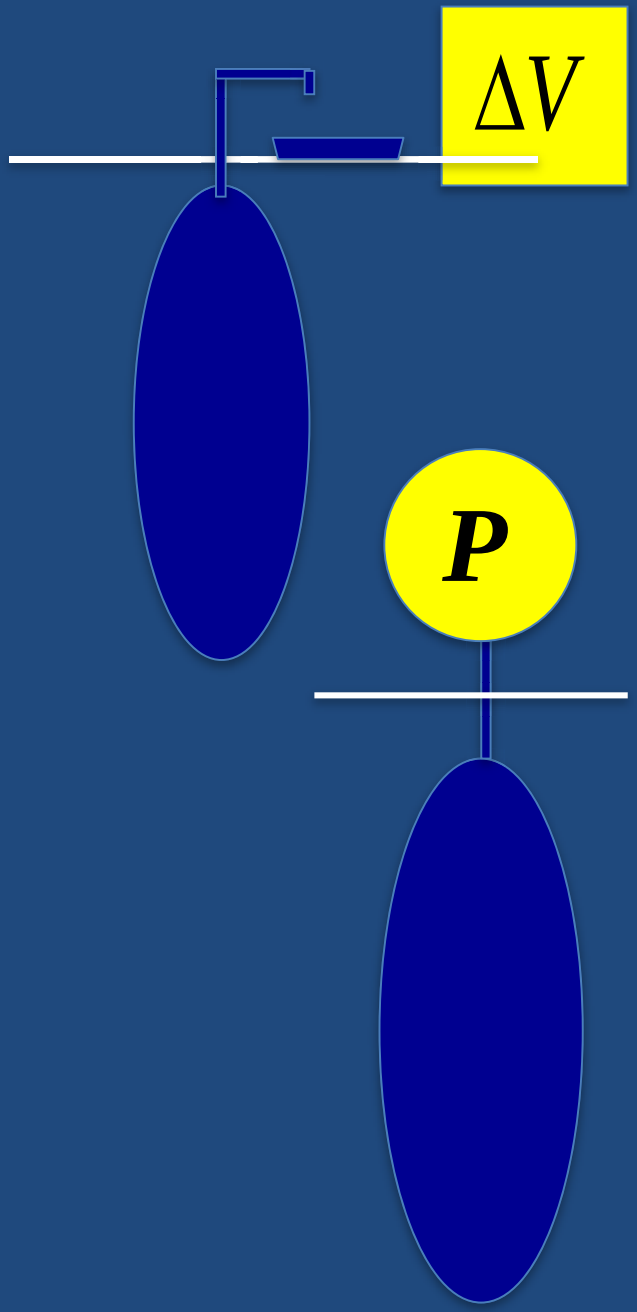


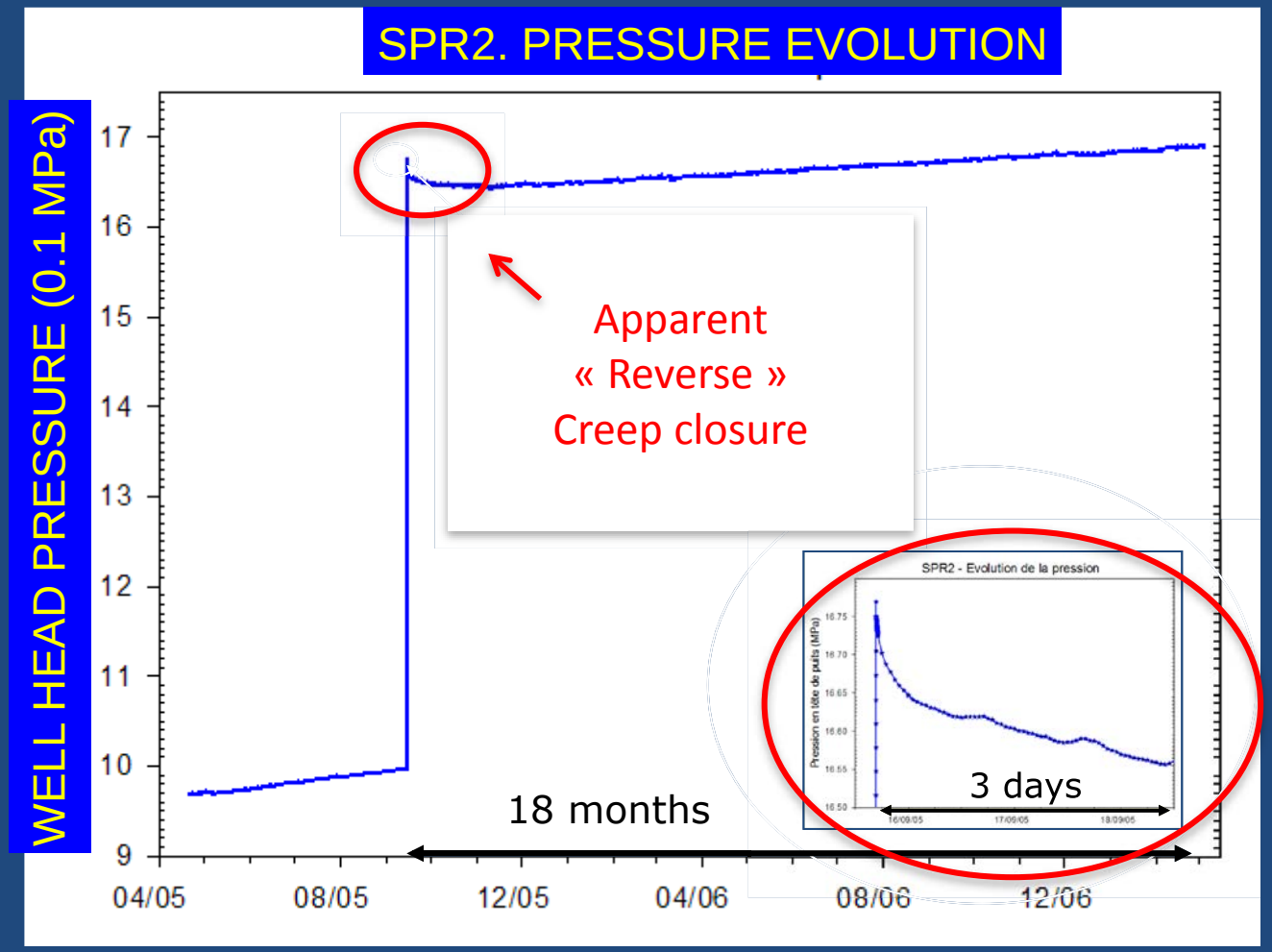


Denzau H. & Rudolph F. (1997). *Field test for determining the convergence of a gas storage cavern under load conditions frequently changing between maximum and minimum pressure and its finite element modelling. Proc. SMRI Spring meeting, Cracow, Poland.*


ΔV/V
P-ΔP
P+ΔP
P
t

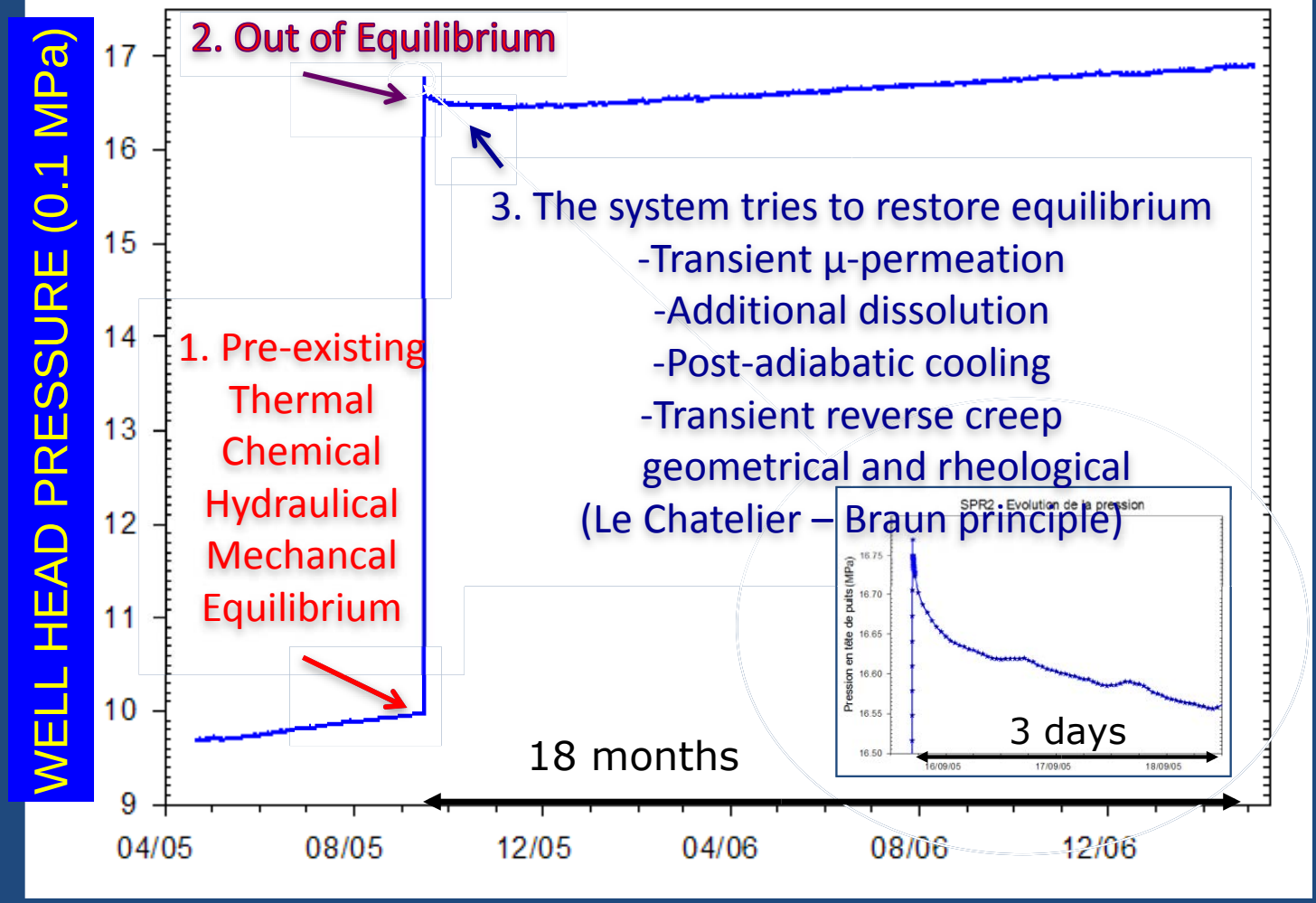

P
Injection
Apparent
« Reverse »
Creep closure
t


ΔV
P


SPR2. PRESSURE EVOLUTION
WELL HEAD PRESSURE (0.1 MPa)
17
16
15
14
13
12
11
10
9
04/05
08/05
12/05
04/06
08/06
12/06
Apparent
« Reverse »
Creep closure
18 months
SPR2 - Evolution de la pression
3 days

WHY ‘’APPARENT’’?

SPR2. PRESSURE EVOLUTION



‘’ APPARENT ’’ REVERSE CREEP CLOSURE

Any pressure change triggers a transient evolution which includes:

1. Various phenomena which tend to restore the initial thermodynamical equilibrium (Le Chatelier-Braun)
2. Geometrical transient creep (slow stress redistribution in the rock mass)
3. Rheological transient creep (as observed in the lab.)

Karimi-Jafari M., Bérest P. & Brouard B. (2007.) *Some aspects of the transient behavior of salt caverns.* Proc. 6thConf. Mech. Beh. Salt
Bérest P., Brouard B., Karimi-Jafari M., Van Sambeek L. (2007).*Transient behaviour of salt caverns. Interpretation of Mechanical Integrity Tests*. Int. J. Rock Mech. Min. Sc. 44, 767-786

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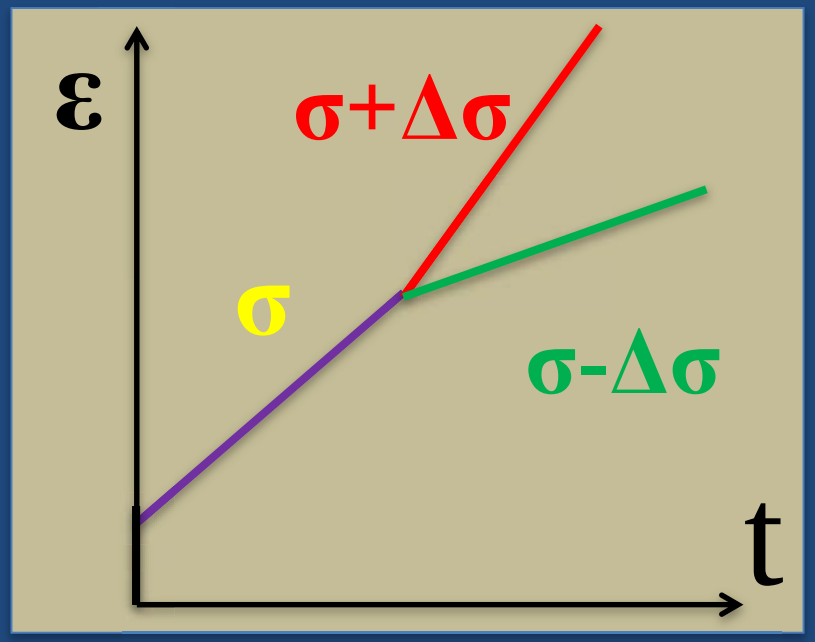
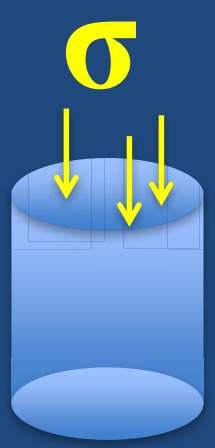
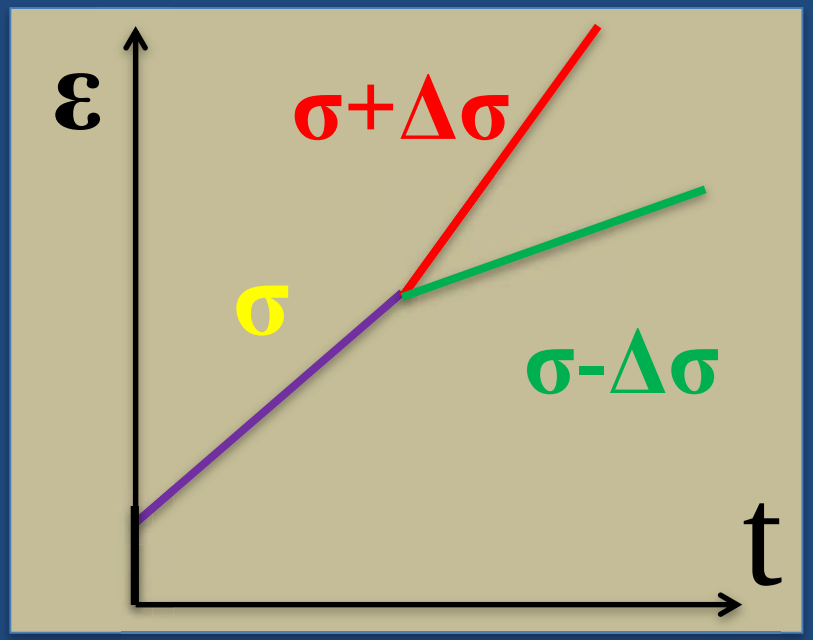
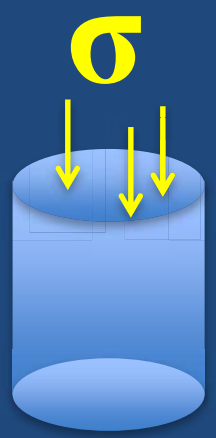


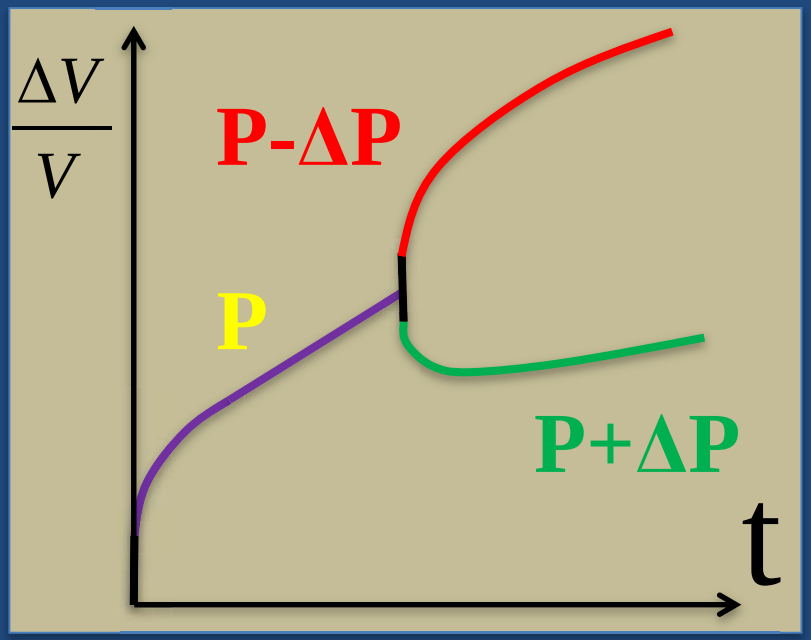


EVEN WHEN THE CONSTITUTIVE LAW INCLUDES NO TRANSIENT COMPONENT …





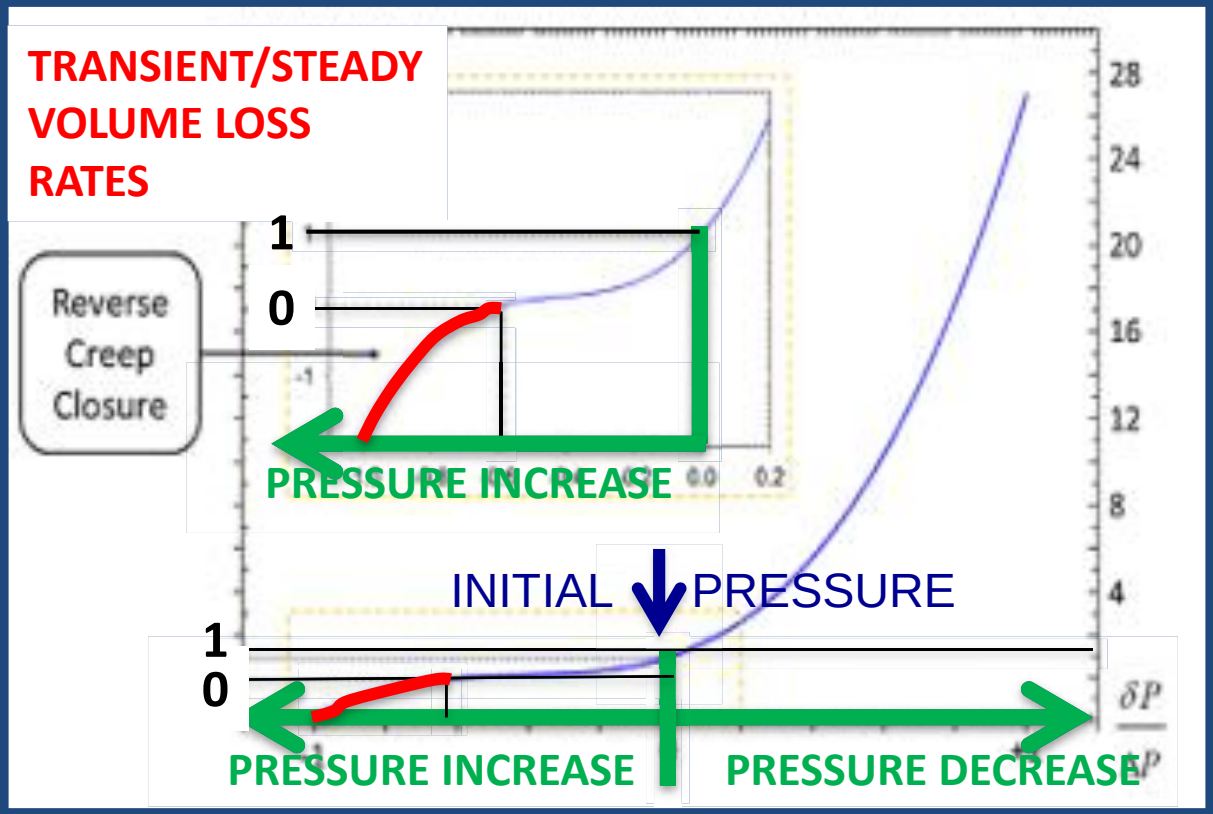
No stress redistribution
in the salt sample
following a stress change

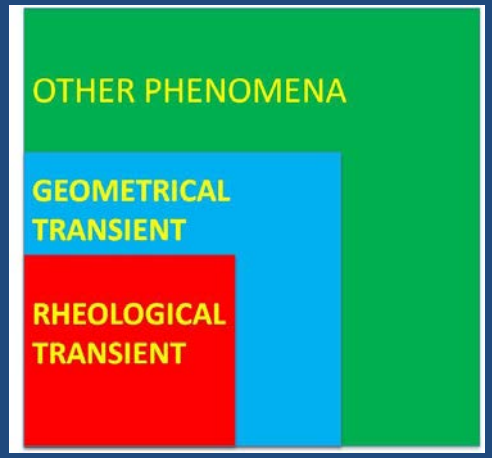


Stress redistribution
in the salt mass
following
a cavern pressure change

…. CAVERN BEHAVIOR EXHIBITS A TRANSIENT COMPONENT

EVEN WHEN NO TRANSIENT COMPONENT IS INCLUDED IN THE CREEP LAW (NORTON-HOFF LAW), A CAVERN EXPERIENCES A « REVERSE » TRANSIENT VOLUME INCREASE WHEN THE PRESSURE INCREASE IS LARGE ENOUGH (''GEOMETRICAL'' TRANSIENT CREEP)





Wang L., Bérest P. & Brouard B. (2015). *Mechanical Behavior of Salt Caverns: Closed-Form Solutions vs Numerical Computations*. Rock Mech Rock Eng

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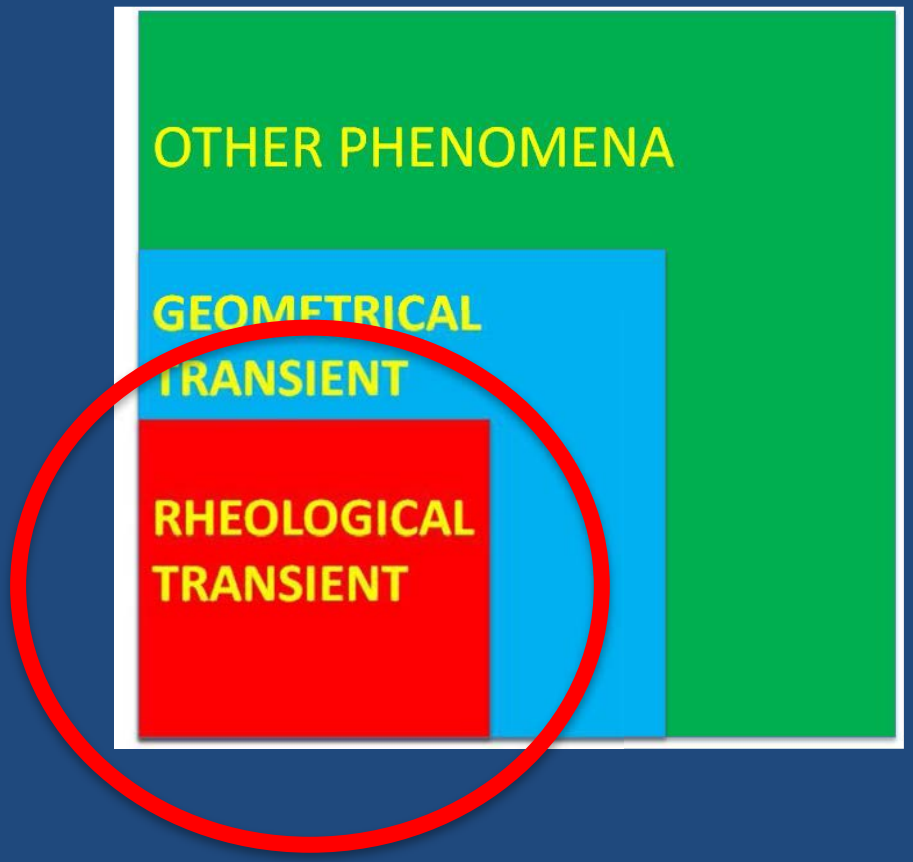
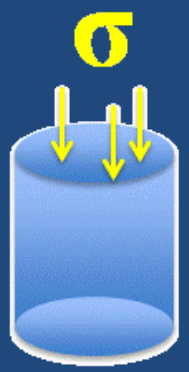
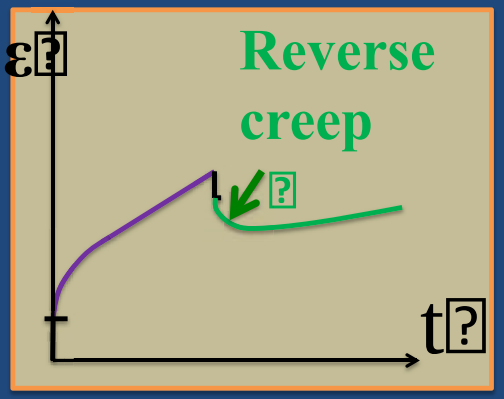
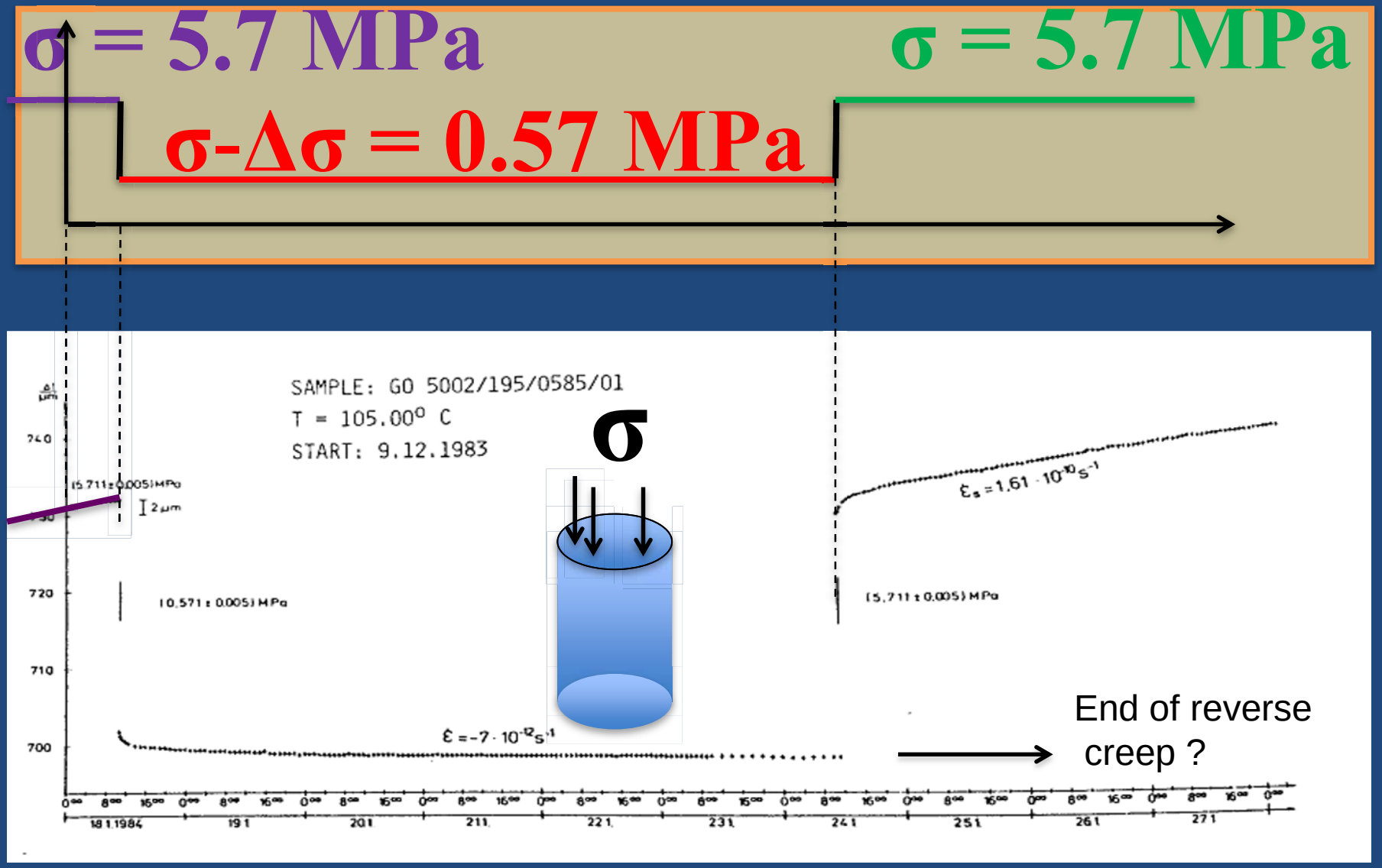
REVERSE CREEP IN A SALT CAVERN



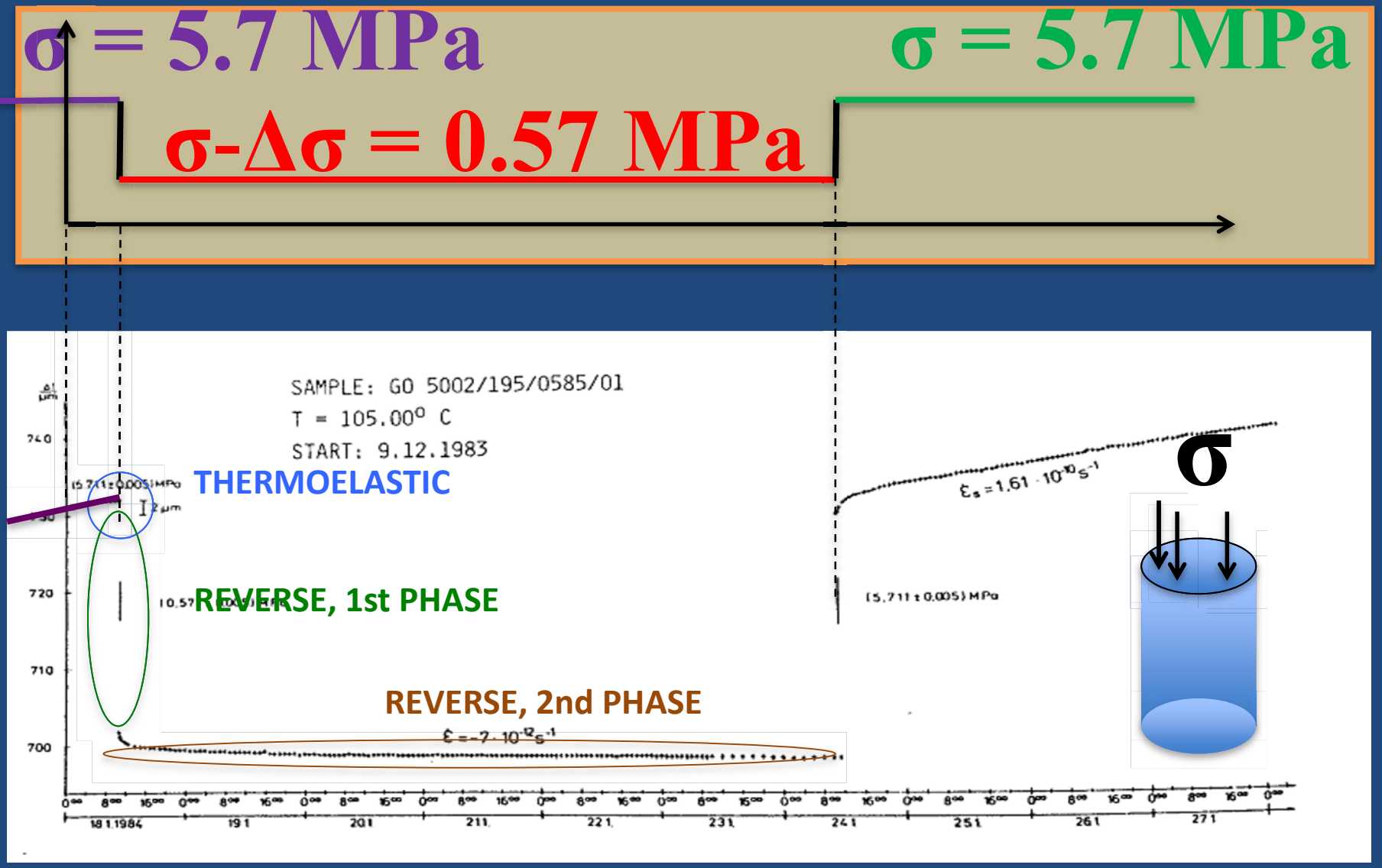




TEMPERATURE IS EXTREMELY WELL CONTROLLED (1/1000 ° C)



Hunsche U. (1988). *Measurement of creep in rock salt at small strain rates.* 5th Conf. Mech. Beh. Salt



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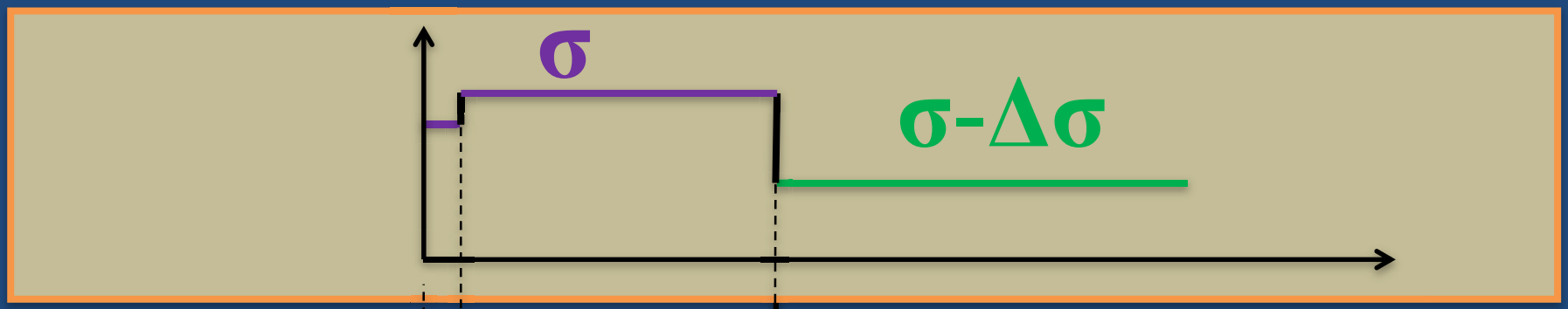
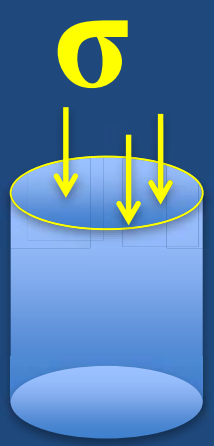
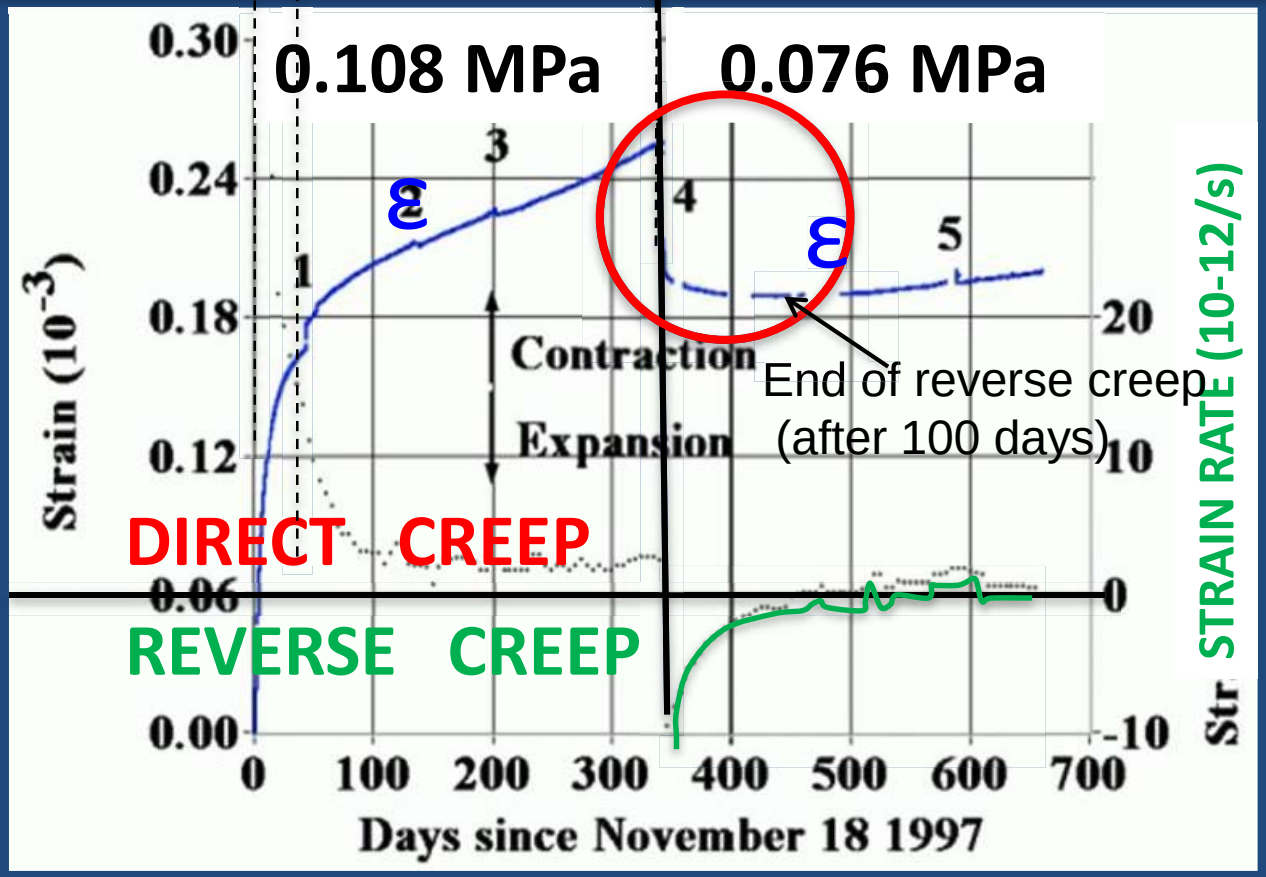
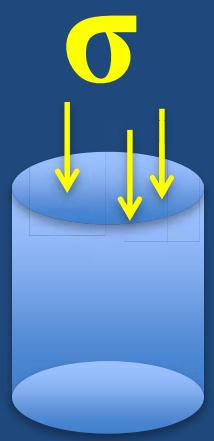


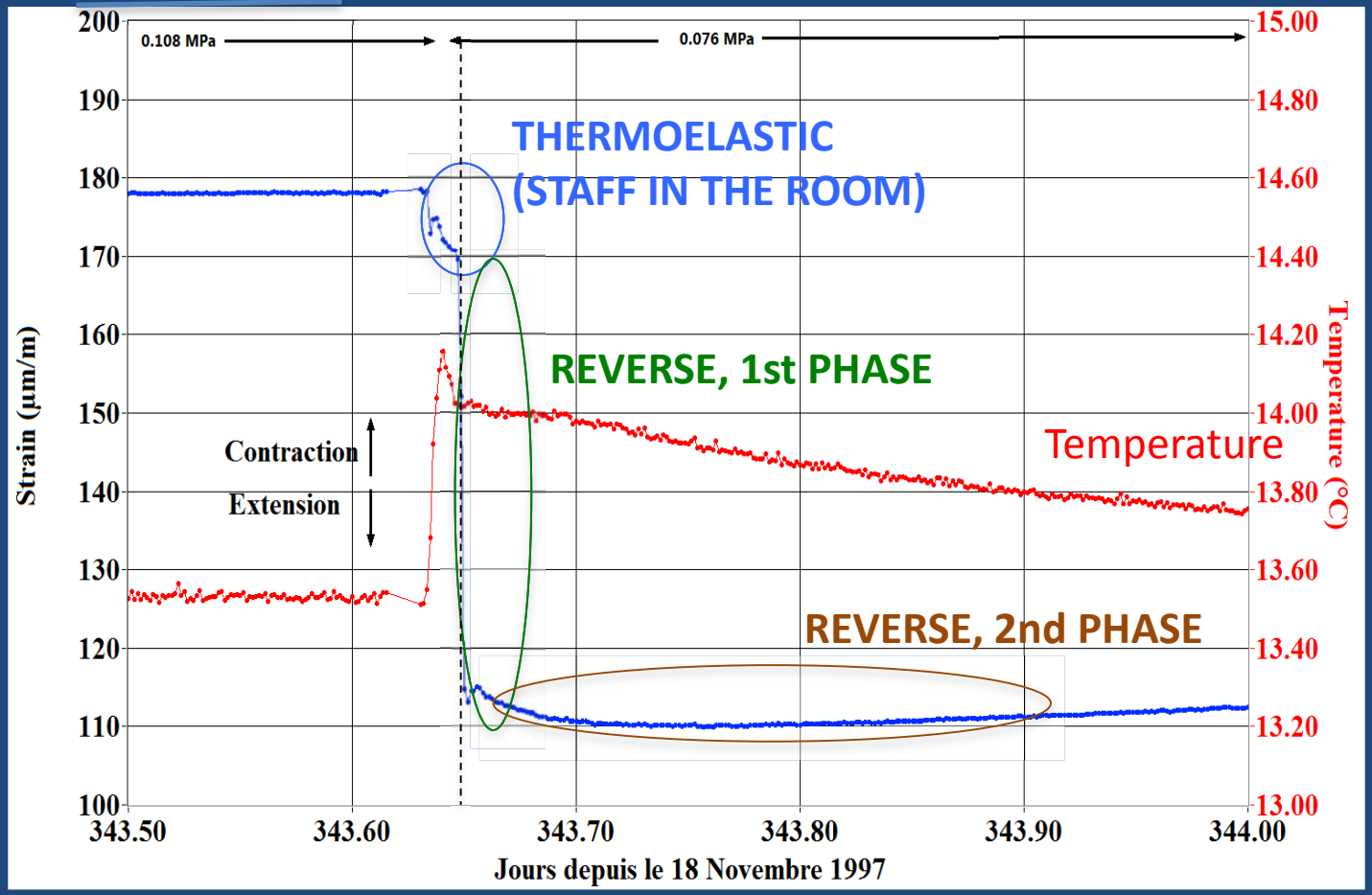


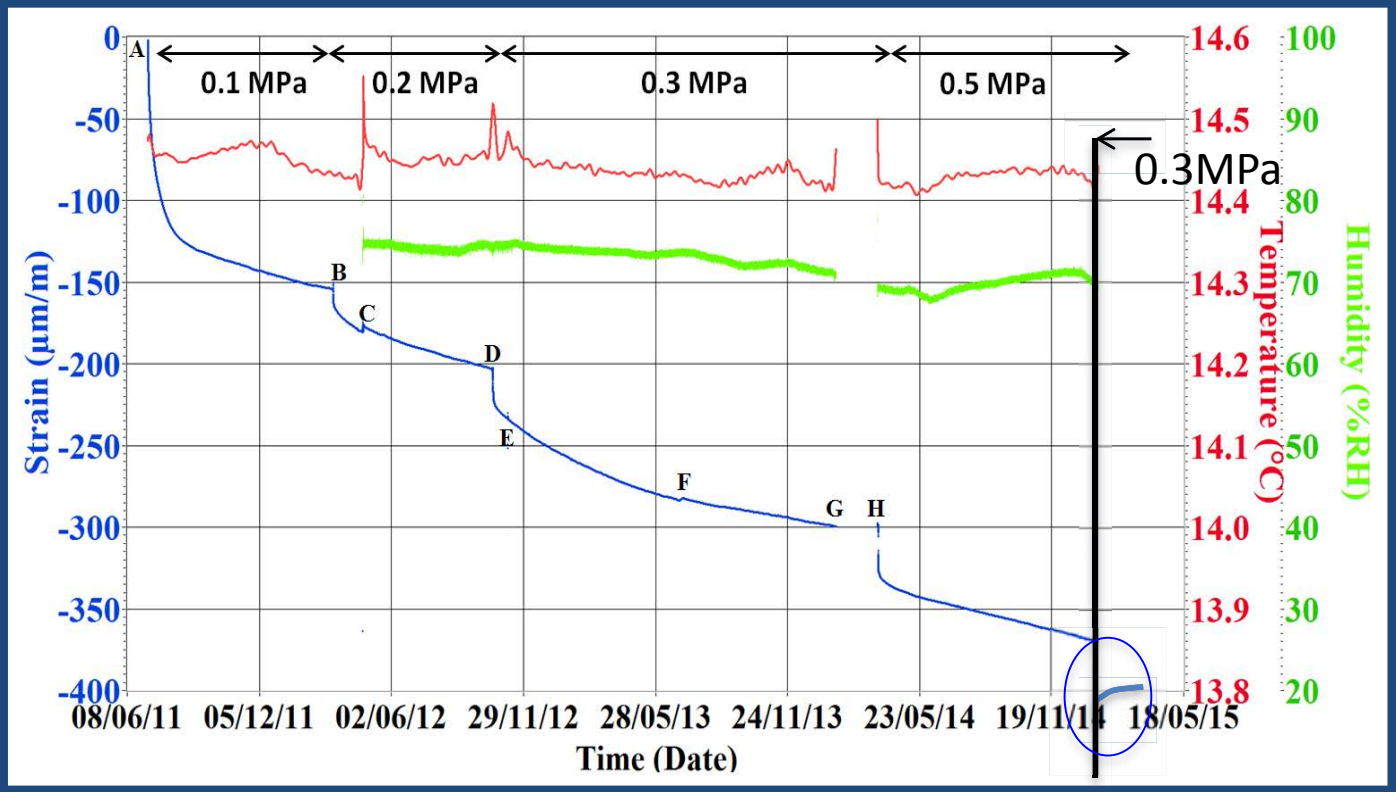


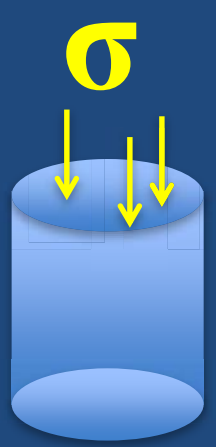
Bérest P., Blum P.A., Charpentier J.P., Gharbi H. & Valès F. (2005). *Very slow creep tests on rock samples*. Int. J. Rock Mech. Min. Sci. 42: 569-576.

STRAIN GAUGE RESOLUTION: nm
RECORDED EVERY MINUTE
STABLE TEMPERATURE (1/100 ° C)
WHEN NO STAFF IN THE ROOM



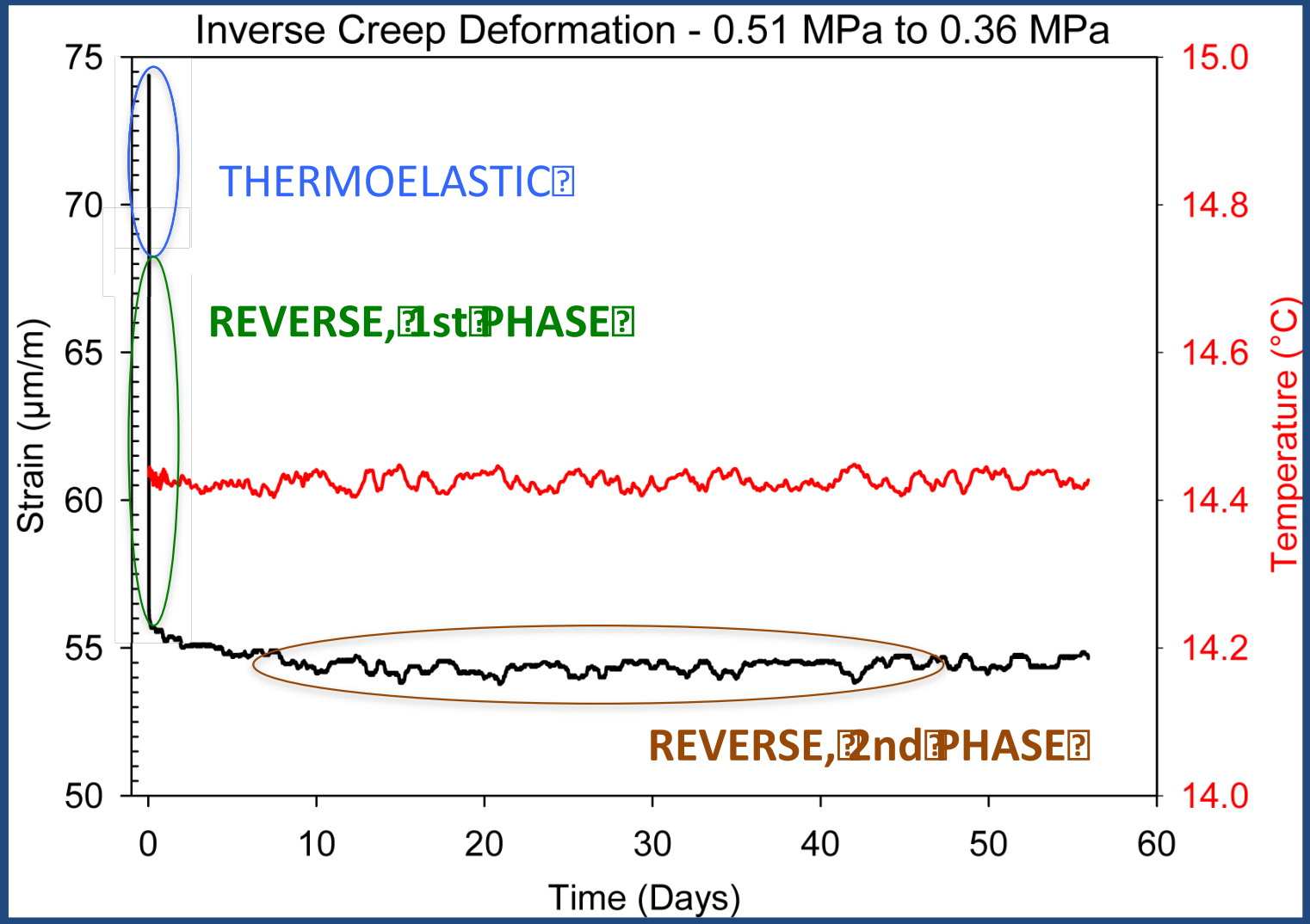




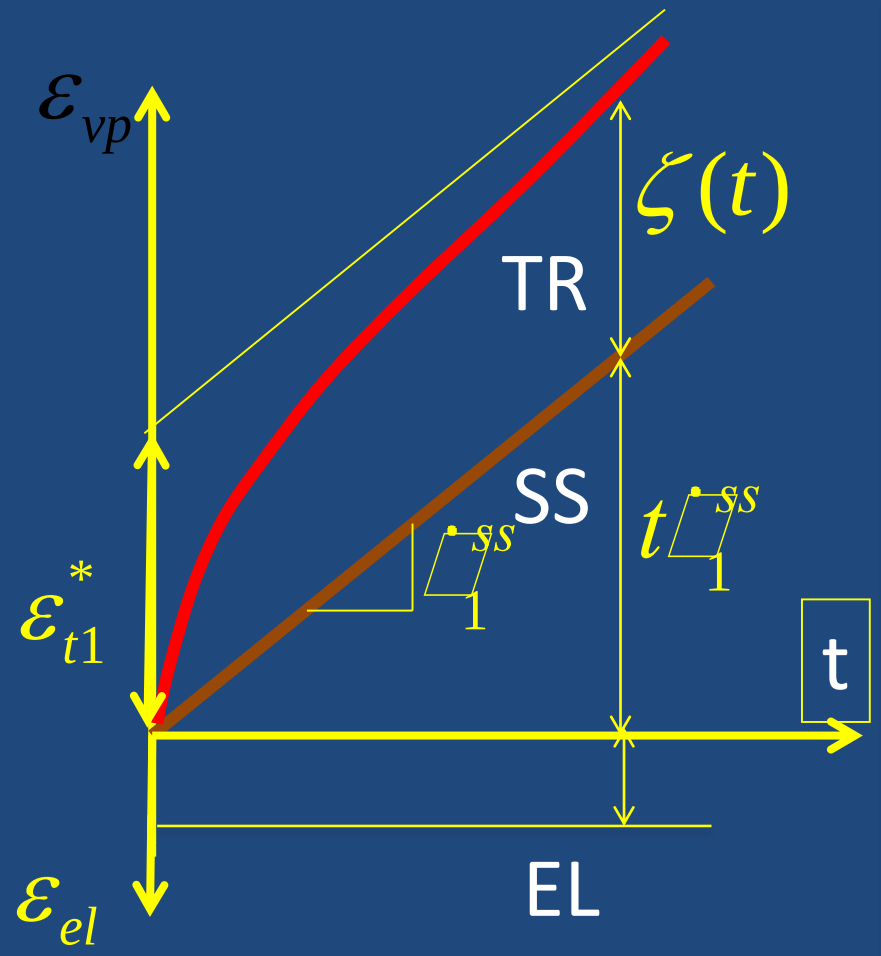


Bérest P., Béraud JF., Brouard B., DeVries K., Gharbi H. (2014).
A very slow creep test on an Avery Island salt sample. Proc. ARMA Symp.

STRAIN GAUGE RESOLUTION: 1/80 µm
RECORDED EVERY TWO SECONDS
STABLE TEMPERATURE (1/100 ° C)



MODELLING

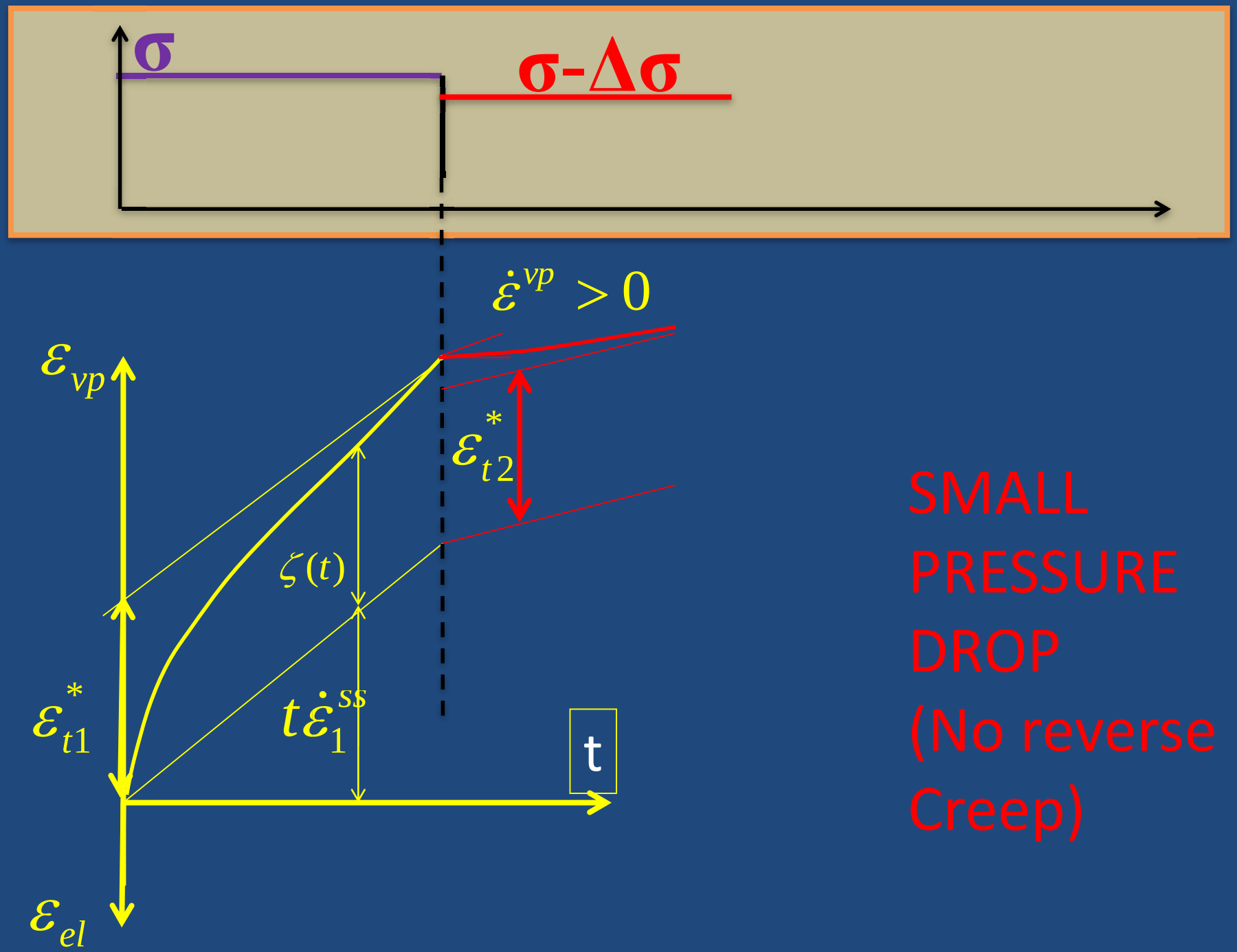


$$\frac{\varepsilon_{t1}}{\varepsilon^*_{t1}} = 0 \quad \text{when } t = 0$$

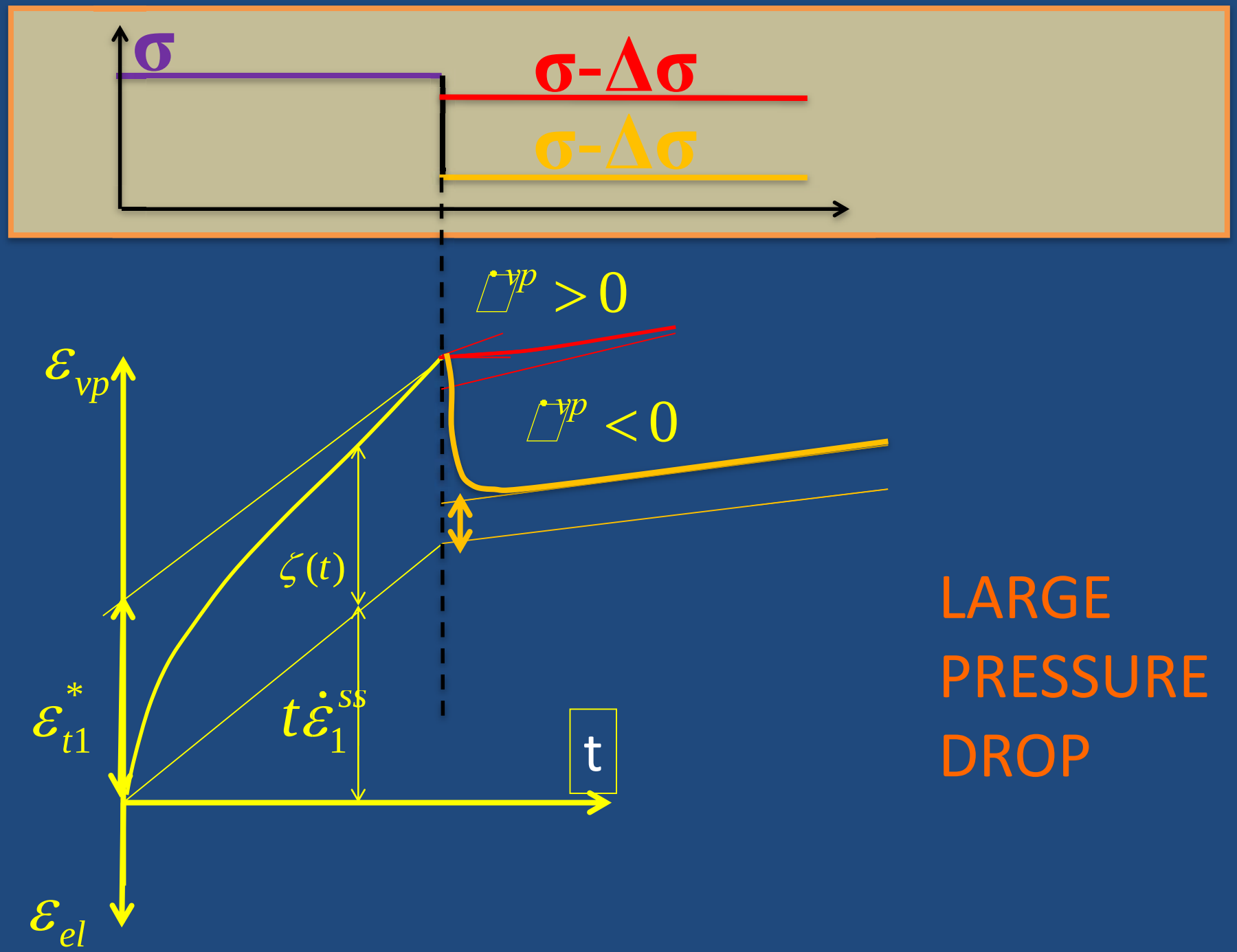
$$\frac{\varepsilon_{t1}}{\varepsilon^*_{t1}} = 1 \quad \text{when } t \to \infty$$

MUNSON-DAWSON

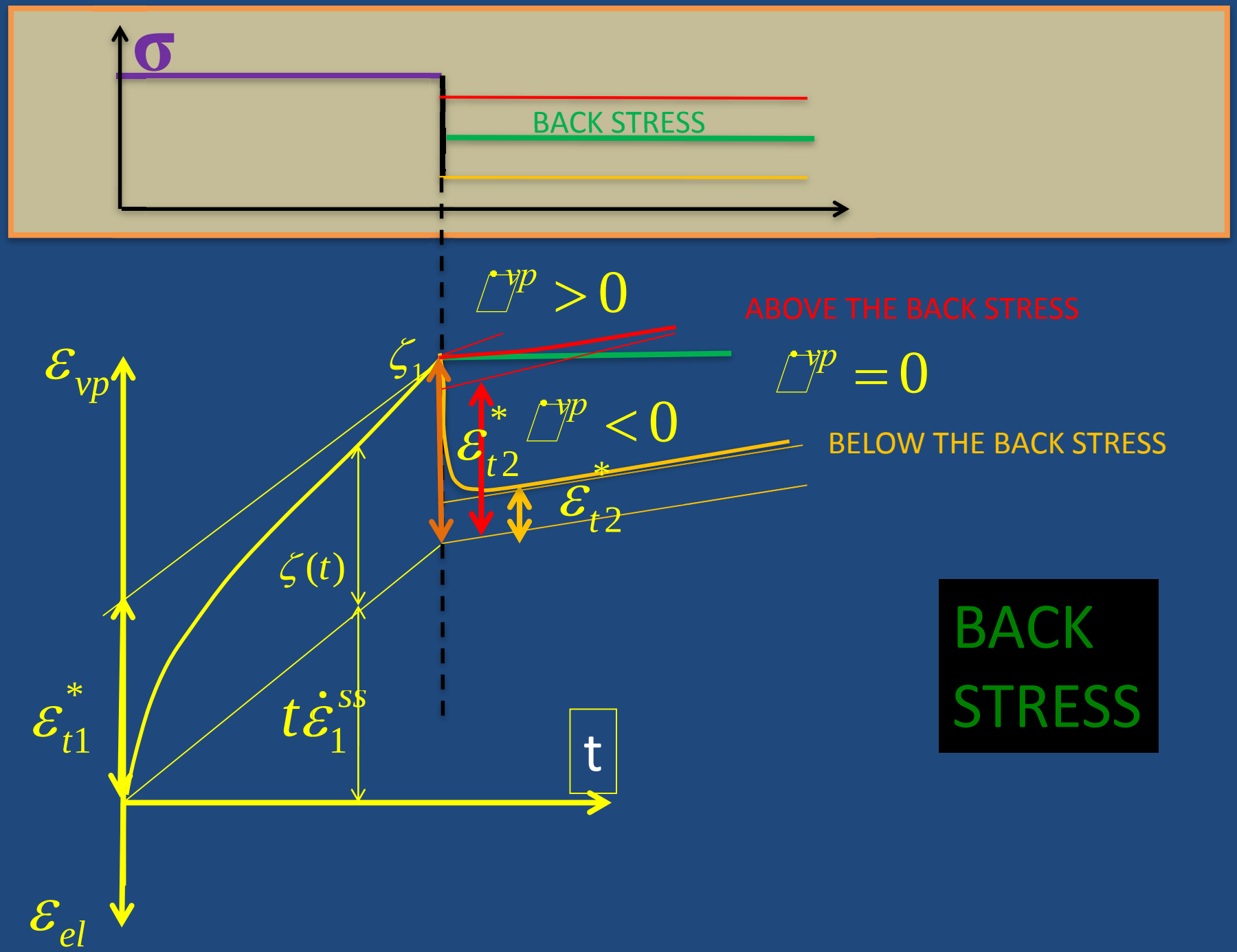
$$\frac{\dot{\varepsilon}_{t1}}{\dot{\varepsilon}^*_{t1}} = \frac{1}{\varepsilon}\left(\exp\left(\left(\frac{\varepsilon_{t1}}{\varepsilon^*_{t1}} - 1\right)^2 - 1\right)\right)$$



SMALL PRESSURE DROP (No reverse Creep)



LARGE PRESSURE DROP


σ
BACK STRESS
$\dot{\varepsilon}^{vp} > 0$
ABOVE THE BACK STRESS
$\dot{\varepsilon}^{vp} = 0$
$\dot{\varepsilon}^{vp} < 0$
BELOW THE BACK STRESS
ε_{vp}
ζ_1
ε_{t2}^{*}
ε_{t2}^{*}
$\zeta(t)$
$t\dot{\varepsilon}_1^{ss}$
ε_{t1}^{*}
t
ε_{el}
BACK STRESS

« BACK STRESS »

- The back stress is the post-drop stress below which reverse creep can be observed
- Most authors believe that the back stress equals 70% of the pre-drop stress
- However more recent tests (strain resolution $\Delta\varepsilon$ = 10-7, strain recorded every second) strongly suggest that the back stress is much larger (90% of the pre-drop stress?)

REQUIREMENTS

$\sigma(t_1) = \sigma_1$

$\sigma(t) \to \sigma^*_{t2}$ when $t \to \infty$

$\dot{\sigma}^{vp} = \dot{\sigma}^{s} + \dot{\sigma} > 0$ when $\sigma^*_{t2} > \sigma_1 / k$

$\dot{\sigma}^{vp} = \dot{\sigma}^{s} + \dot{\sigma} < 0$ when $\sigma^*_{t2} < \sigma_1 / k$

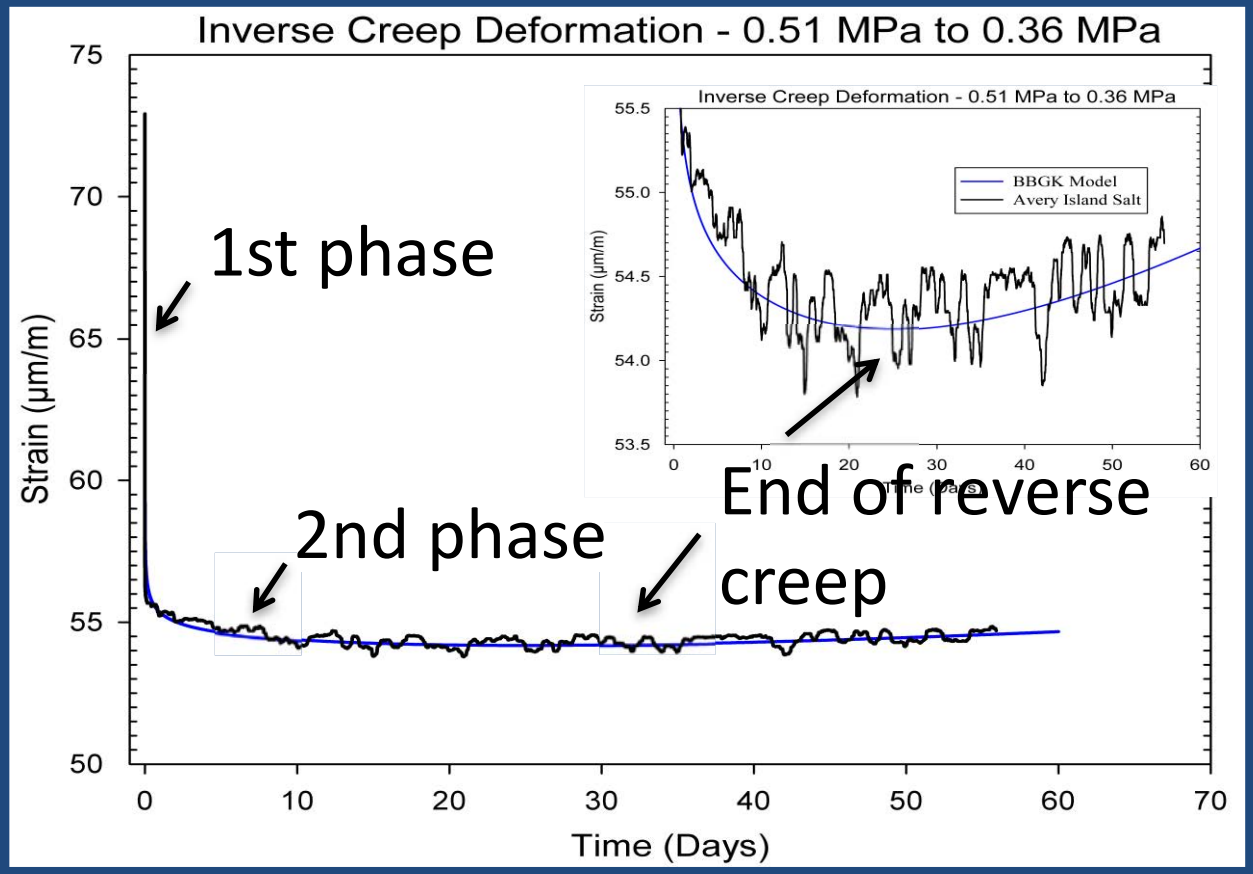
$\dot{\sigma}$ is very fast during a few dozens of s

$\dot{\sigma}$ vanishes to zero after a few years

A TENTATIVE CONSTITUTIVE LAW ACCOUNTINGFOR THE 1st AND 2nd REVERSE PHASES

$$\frac{\dot{\sigma}}{\sigma^*_t} = \alpha\left(\frac{\frac{\sigma}{\sigma^*_t} - 1}{k - 1}\right)^p \left(1 + \frac{\sigma}{\bar{\sigma}} < \frac{\sigma}{\sigma^*_t} - k >^q\right)$$

$$\frac{\dot{\varepsilon}}{\varepsilon_t^*} = \alpha\left(\frac{\frac{\sigma}{\sigma_t^*} - 1}{k - 1}\right)^p \left(1 + \frac{\sigma}{\sigma_{\equiv}} < \frac{\sigma}{\sigma_t^*} - k >^q\right)$$



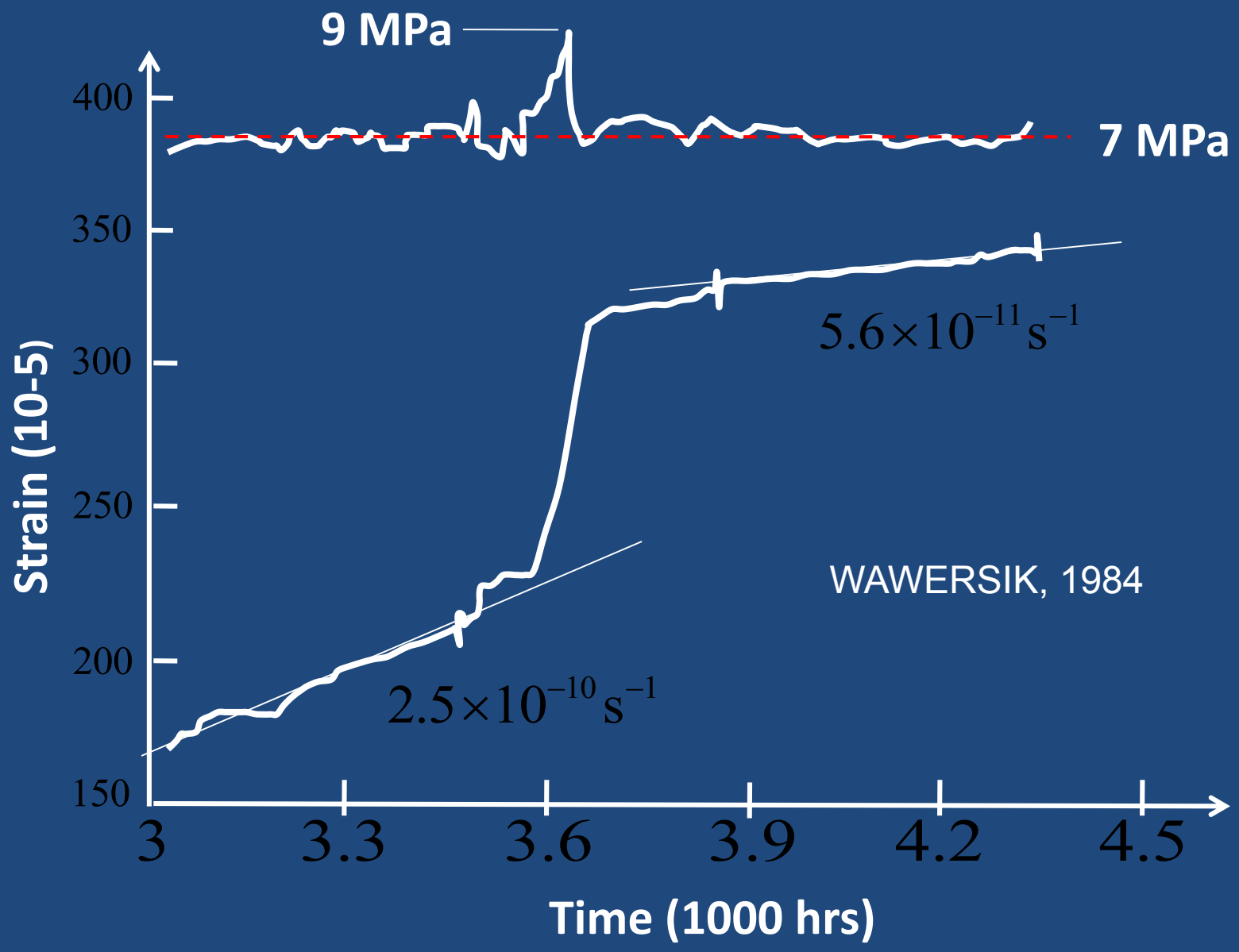
CONCLUSIONS

- In a cavern, the apparent ‘’Reverse creep closure’’ following a pressure increase includes: transient evolution to thermal, chemical, hydraulical equilibrium + ‘’geometrical’’ reverse creep + ‘’rheological’’ reverse creep.
- Rheological reverse creep (observed during lab tests) include two phases (fast and short /slow and long).
- Recent tests suggest that the back stress is not much smaller than the pre-drop stress.

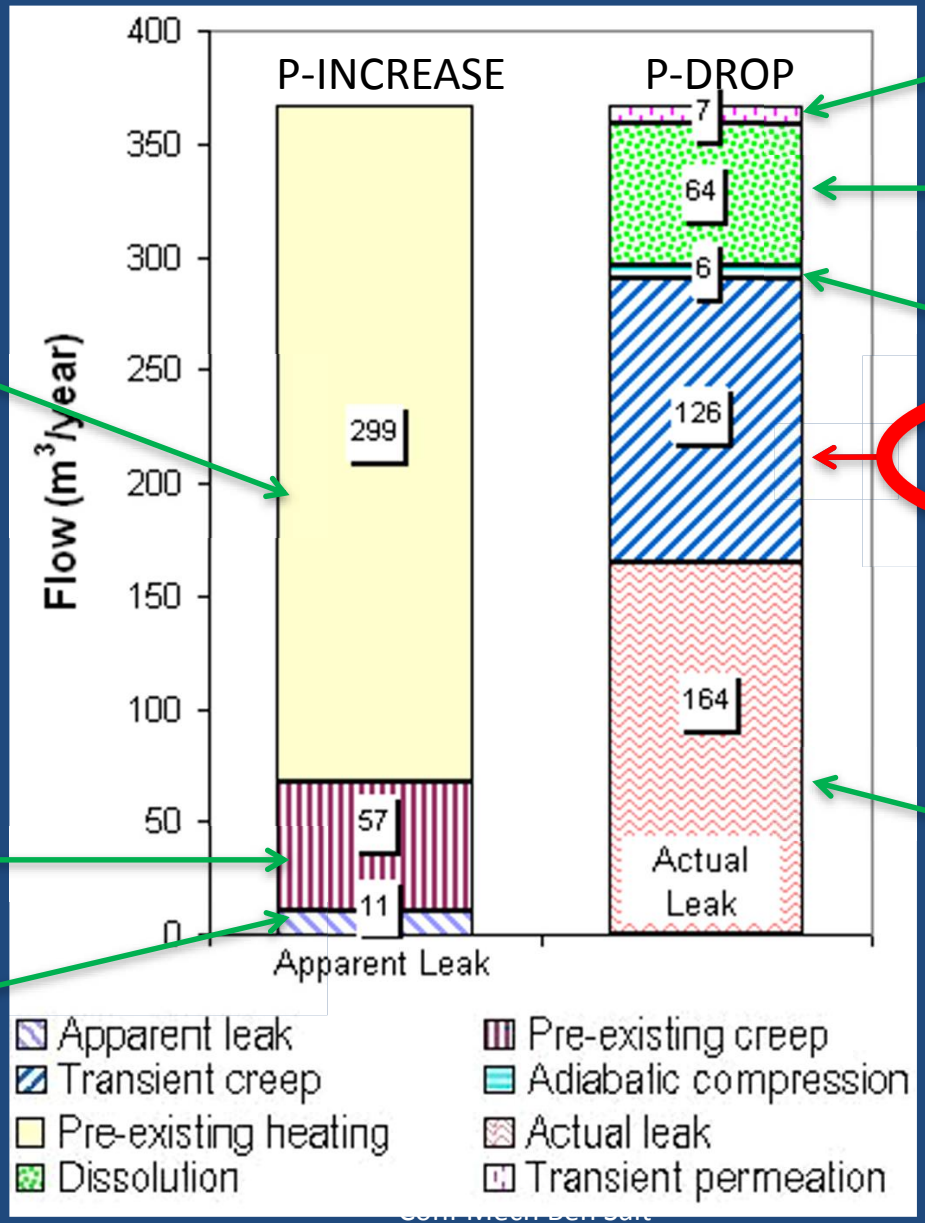
- When interpreting an MIT, the effects of reverse creep closure must be taken into account.
- Stress control is a concern during a creep test, as the effects of stress fluctuations are not symmetrical (Wawersik, 1st Conf. Mech. Beh. Salt)

QUESTIONS?

BONUS


9 MPa
7 MPa
400
350
300
250
200
150
Strain (10-5)
$5.6\times10^{-11}\,s^{-1}$
$2.5\times10^{-10}\,s^{-1}$
WAWERSIK, 1984
3
3.3
3.6
3.9
4.2
4.5
Time (1000 hrs)

STEADY-STATE AND TRANSIENT PHENOMENA FOLLOWING A PRESSURE INCREASE



TRANSIENT PERMEATION

ADDITIONAL DISSOLUTION

ADIABATIC COMPRESSION

BRINE WARMING

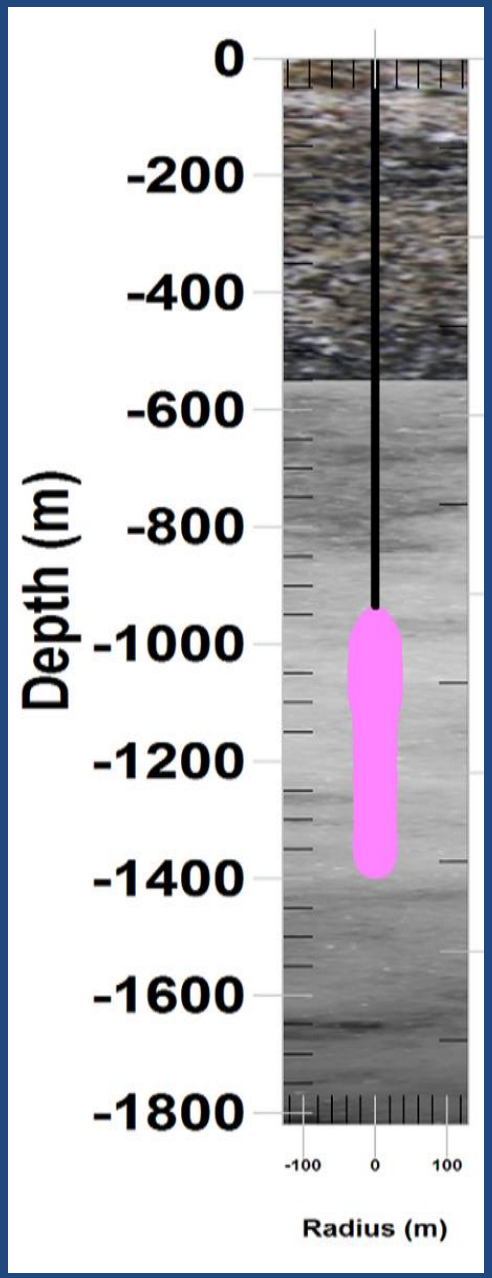
REVERSE CREEP

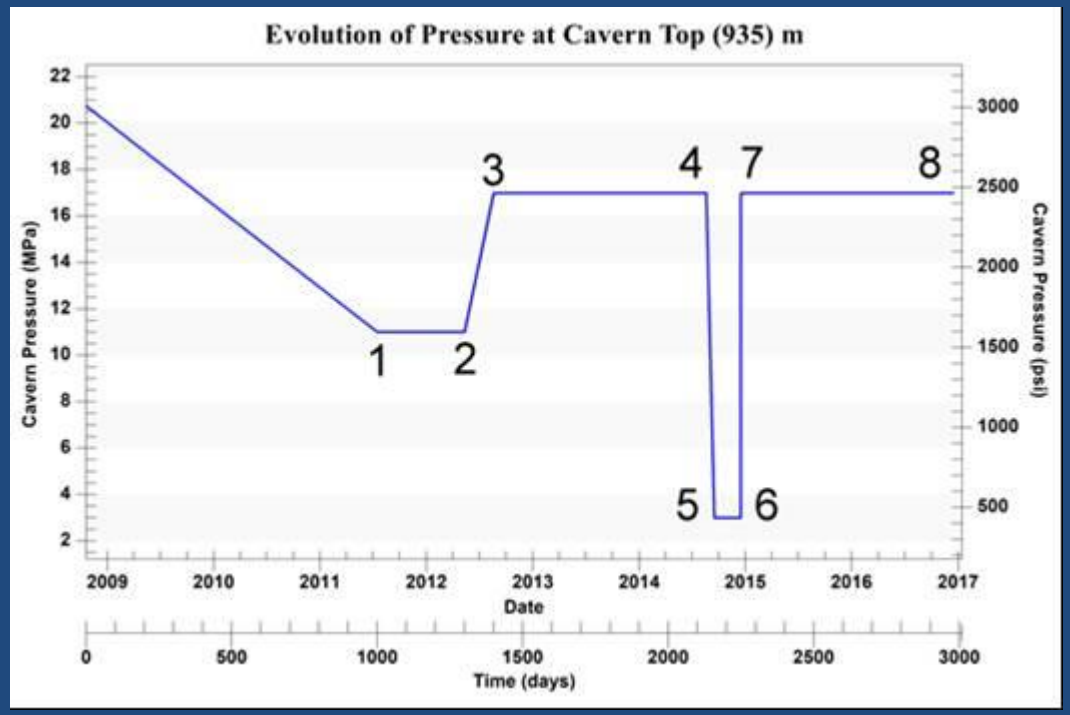
ACTUAL LEAK

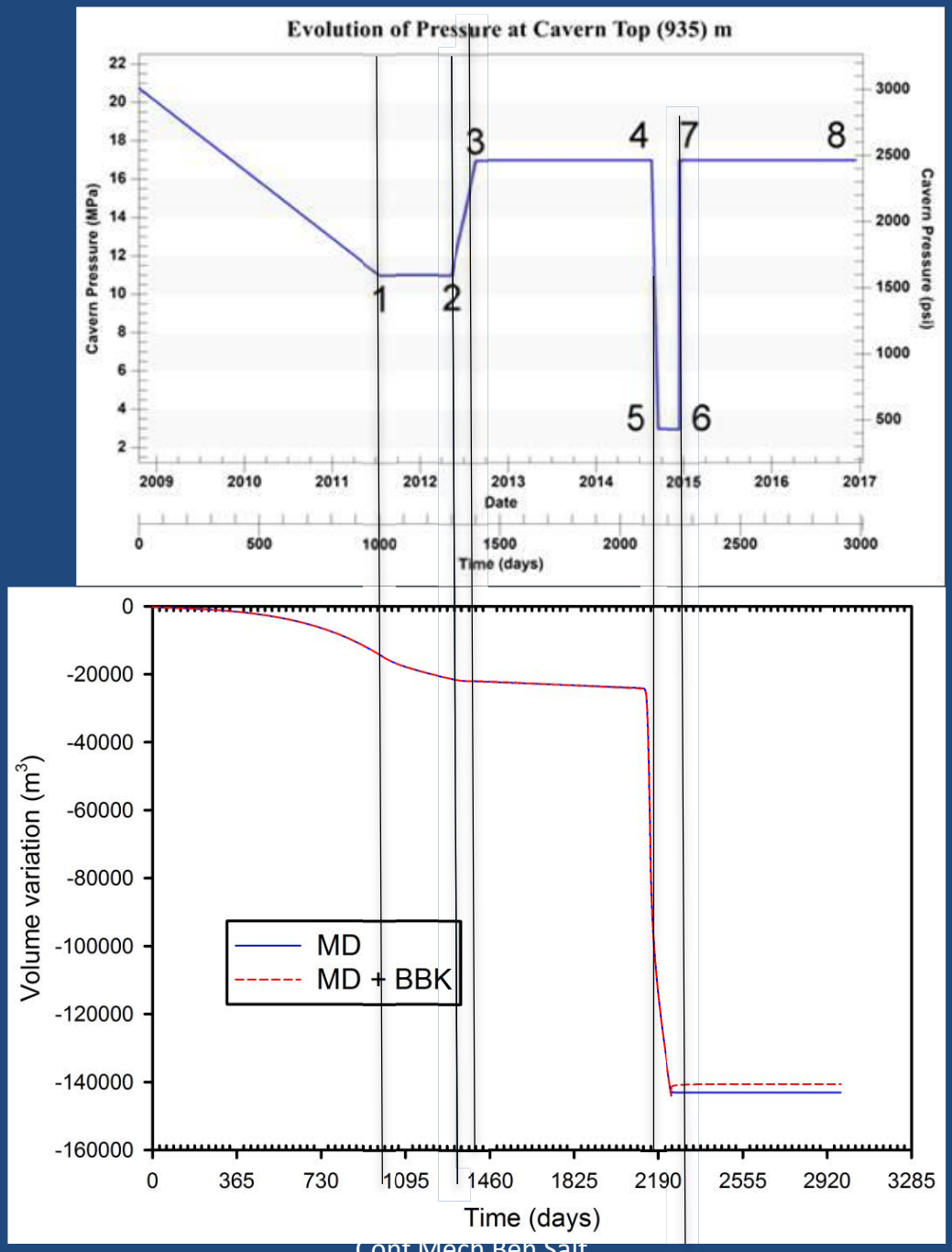
PRE-EXISTING CREEP

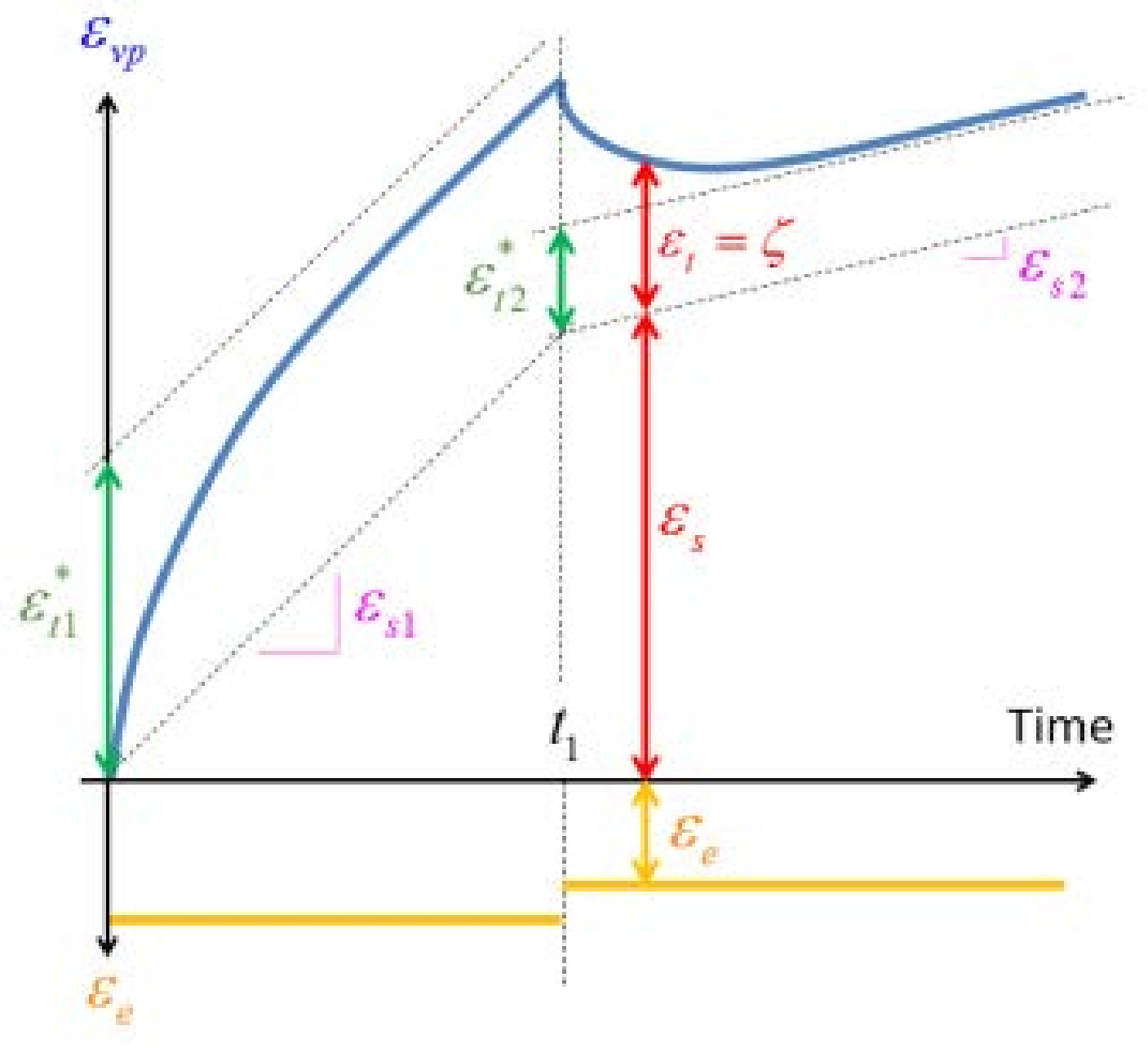
PRESSURE DROP

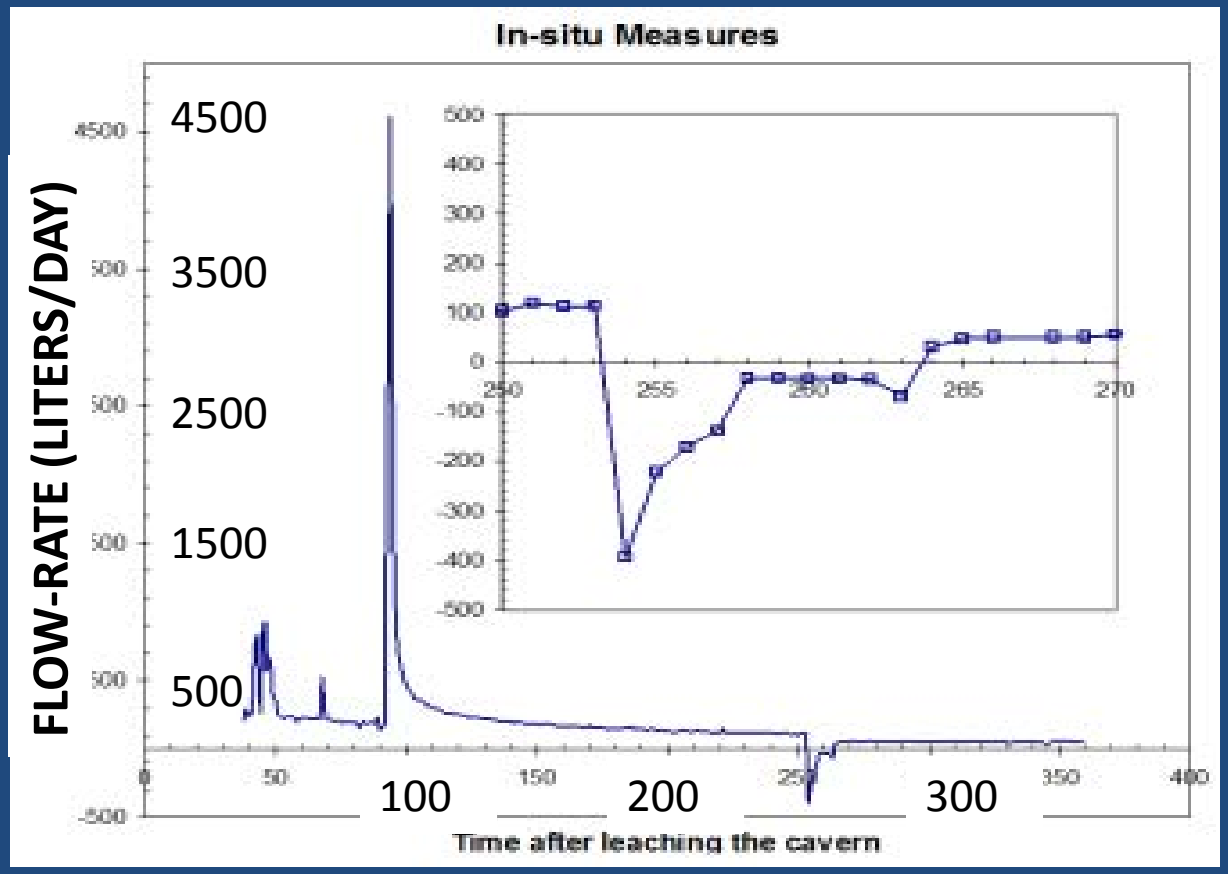
Bérest P., Brouard B., Karimi-Jafari M. & Van Sambeek L. 2007. Transient behavior of salt caverns — Interpretation of mechanical integrity tests. *Int. J. Rock Mech. Min. Sci.*.

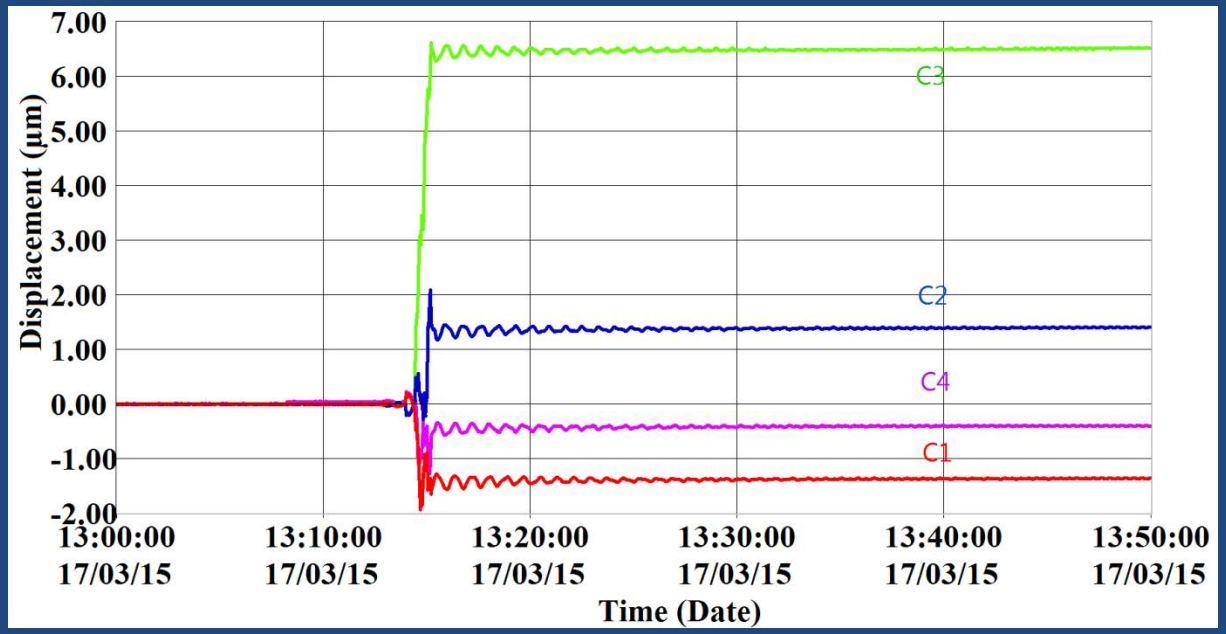

0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
Depth (m)
-100
0
100
Radius (m)

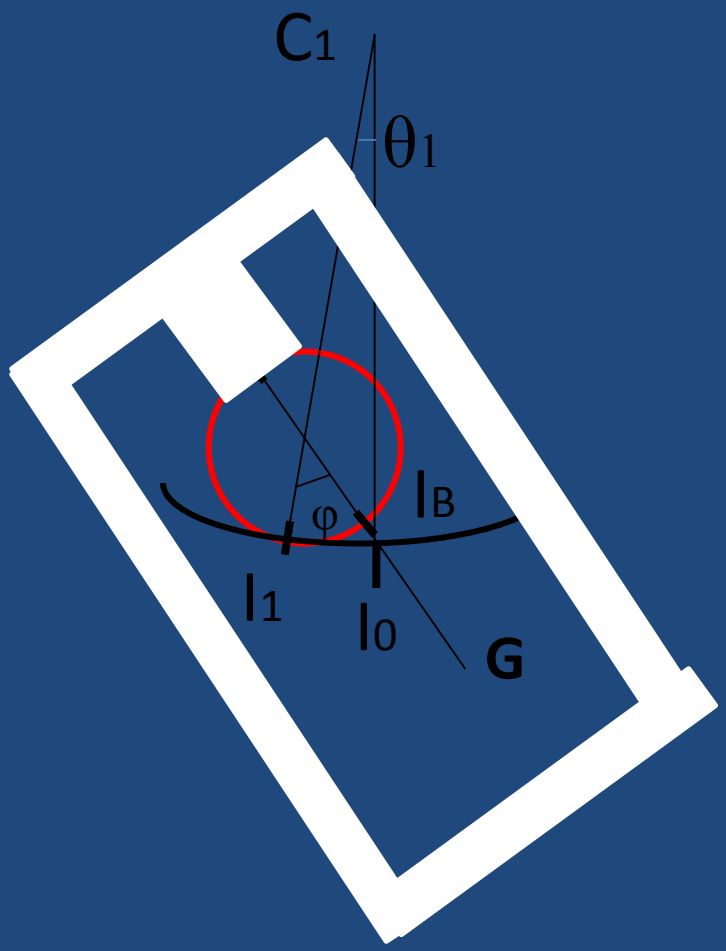

Evolution of Pressure at Cavern Top (935) m
Cavern Pressure (MPa)
Cavern Pressure (psi)
1
2
3
4
5
6
7
8
2009
2010
2011
2012
2013
2014
2015
2016
2017
Date
0
500
1000
1500
2000
2500
3000
Time (days)


Evolution of Pressure at Cavern Top (935) m
Cavern Pressure (MPa)
Cavern Pressure (psi)
Date
Time (days)
1
2
3
4
5
6
7
8
MD
MD + BBK
Volume variation (m3)
Time (days)


ε_{vp}
ε_{12}^{*}
$\varepsilon_{t} = \zeta$
ε_{s2}
ε_{s}
ε_{11}^{*}
ε_{s1}
t_1
Time
ε_{e}
ε_{e}


In-situ Measures
FLOW-RATE (LITERS/DAY)
4500
3500
2500
1500
500
100
200
300
Time after leaching the cavern


7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
Displacement (µm)
C3
C2
C4
C1
13:00:00 17/03/15
13:10:00 17/03/15
13:20:00 17/03/15
13:30:00 17/03/15
13:40:00 17/03/15
13:50:00 17/03/15
Time (Date)


C1
θ1
lB
φ
l1
l0
G