Cavern Closure Consortium

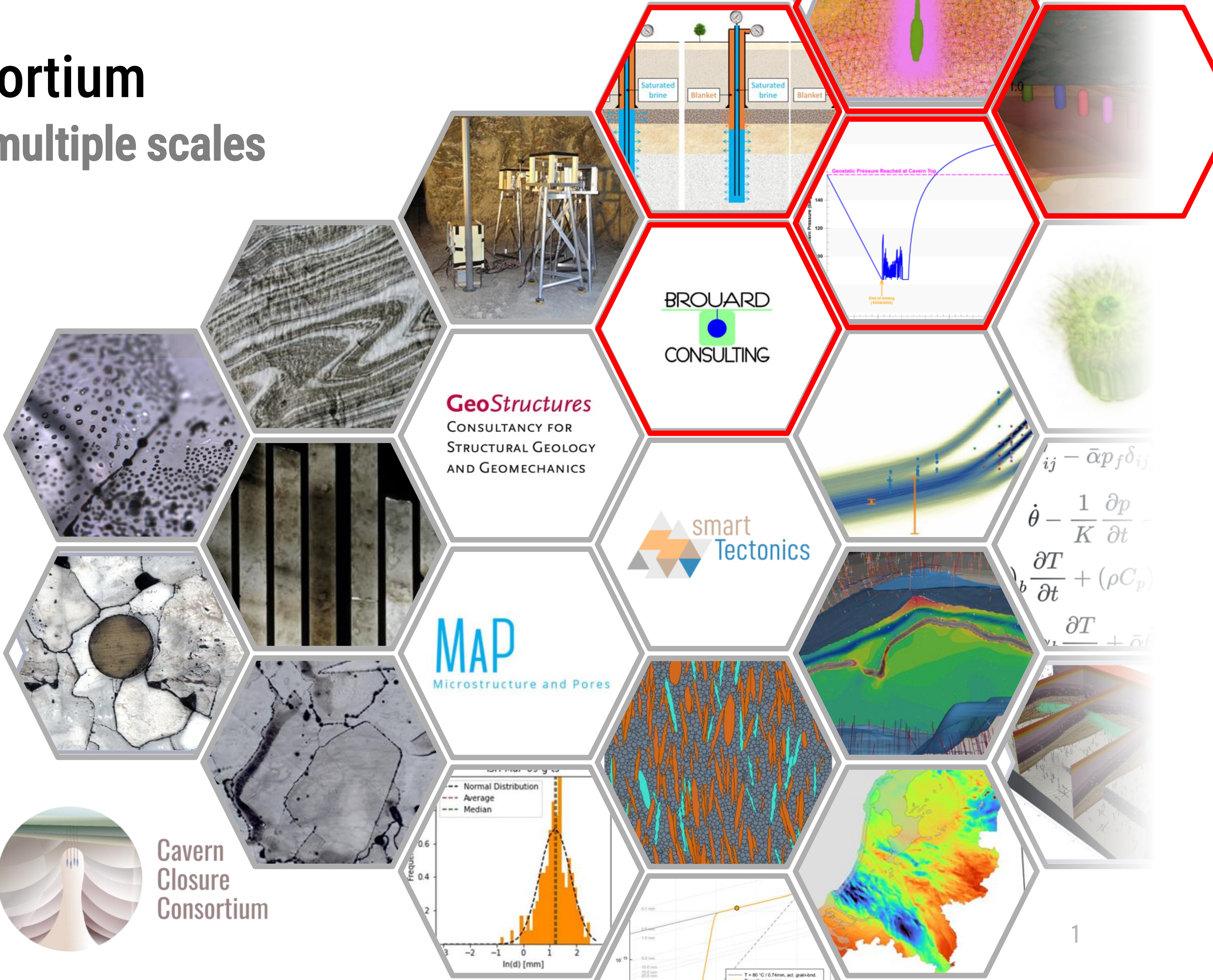
Combined expertise from multiple scales

Integrated multiscale concept

- Site-specific rock salt characteristics
- Current state of the salt dome

- Identification of key model parameters

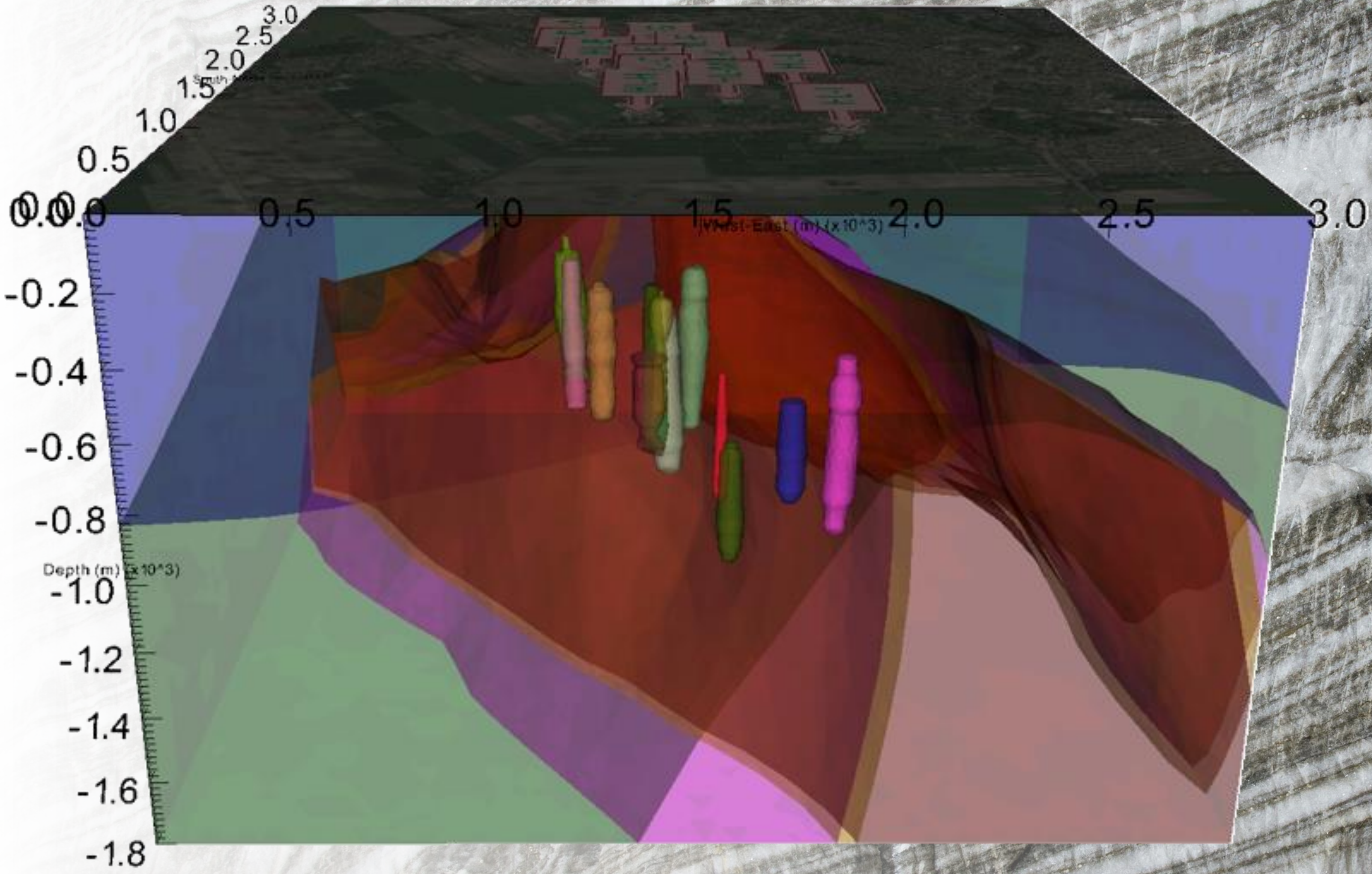
- Optimized cavern operation and safe abandonment
- Uncertainty quantification



Cavern Closure Consortium

BROUARD CONSULTING

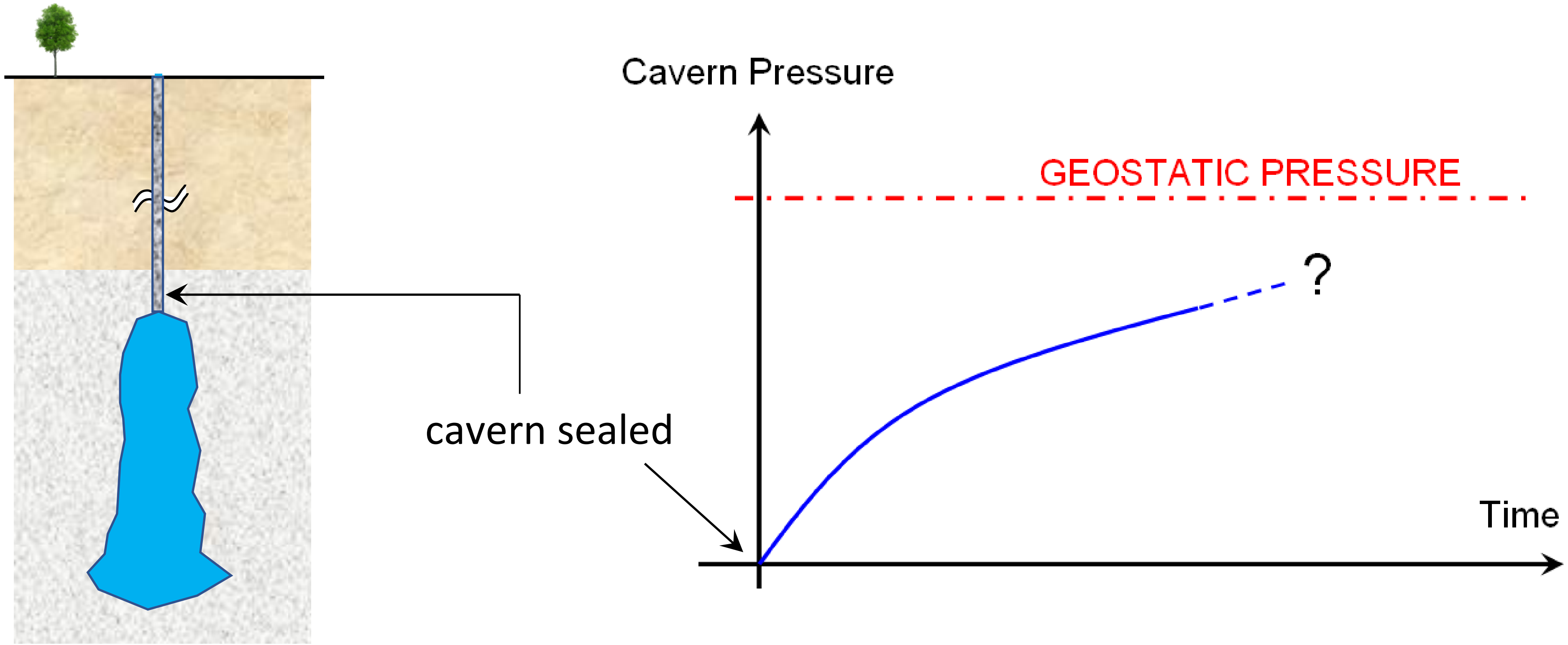
Cavern-scale abandonment modelling



Benoit Brouard

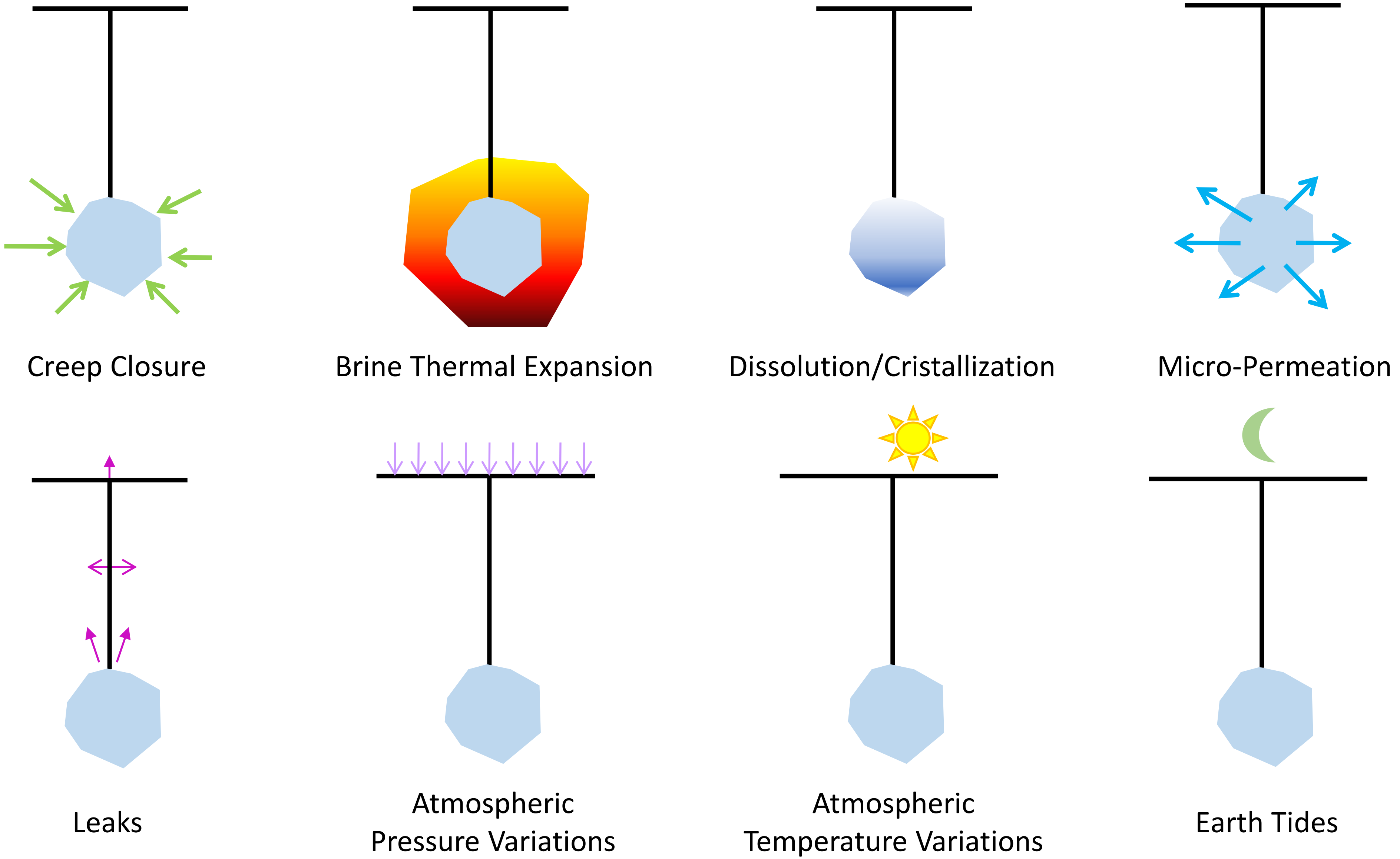
Cavern Closure Consortium

The problem of abandoning caverns



1. Why cavern pressure increases?
2. Can we predict the long-term behaviour of the cavern?

Pressure Variations in a Cavern – Involved Phenomena



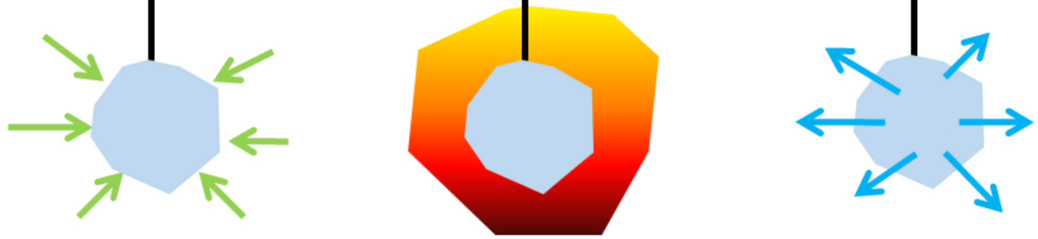
Behavior on The Long Term: 3 Main Phenomena

Cavern-Pressure Rate (psi/day)

$$\beta V \times \dot{P} = \dot{V}_{creep} + \dot{V}_{therm} - \dot{V}_{perm}$$

Rate of change of the volume of the cavern (bbl/day)

Cavern Compressibility (bbl/psi)



Creep Closure

Brine Thermal Expansion

Brine Micro-Permeation

Full Coupling is Required

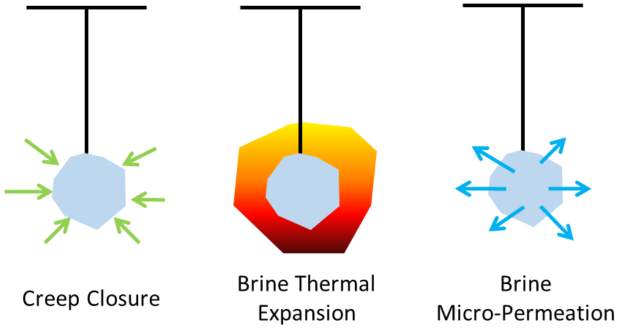
Since the pressure increase in the cavern cannot be predicted in advance, since it is the result of the calculation, the calculation has to be performed with a <u>fully coupled code</u> that takes into account the important phenomena.

Cavern-Pressure Rate (psi/day)

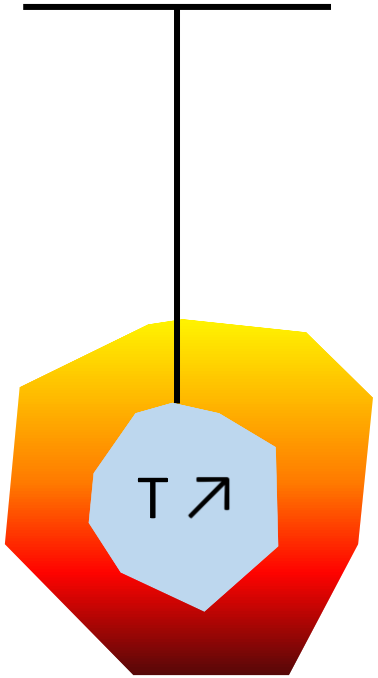
$$\beta V \times \dot{P} = \boxed{\dot{V}_{creep} + \dot{V}_{therm} - \dot{V}_{perm}}$$

Cavern Compressibility (bbl/psi)

Rate of change of the volume of the cavern (bbl/day)



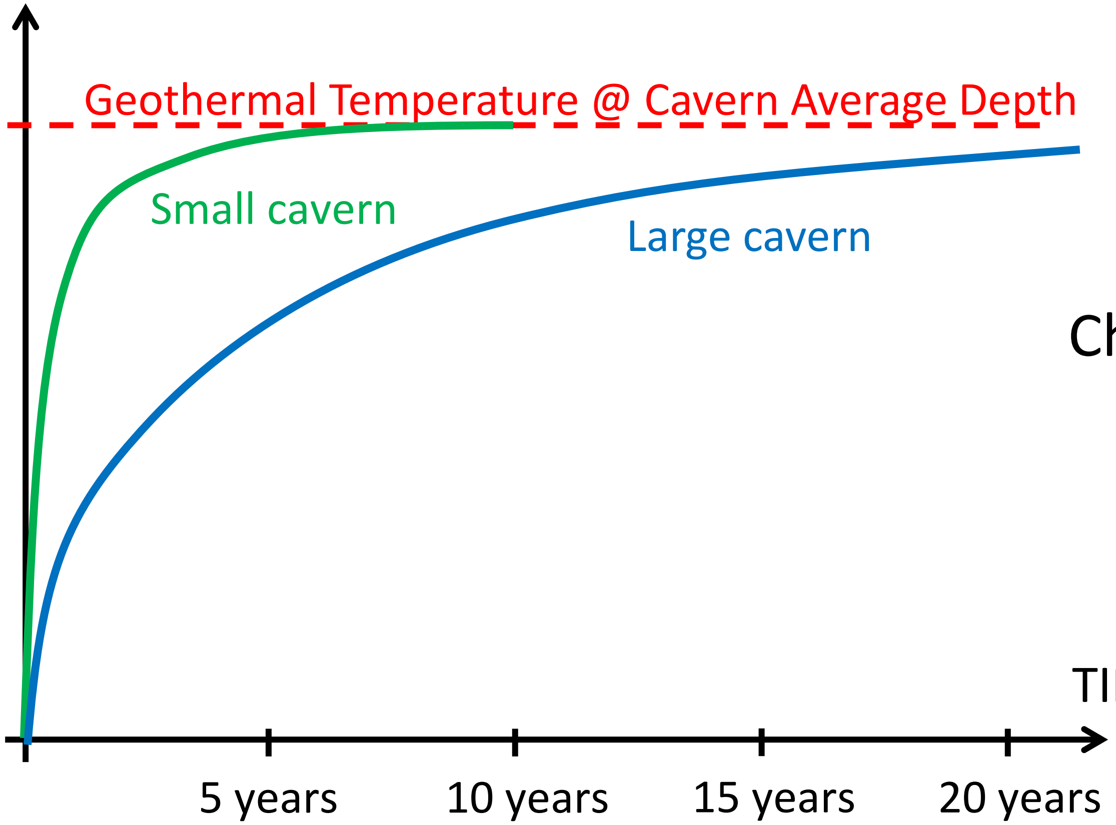
Brine heating can be very slow!



Rule of thumb

+10 bar/°C
+ 80 psi/°F

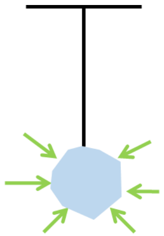
(Bérest et al., 1979)



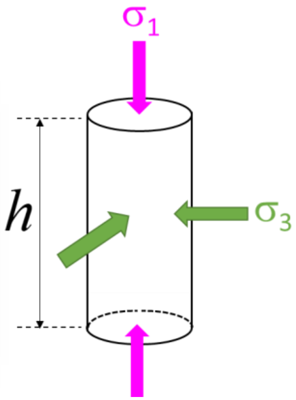
Characteristic Time

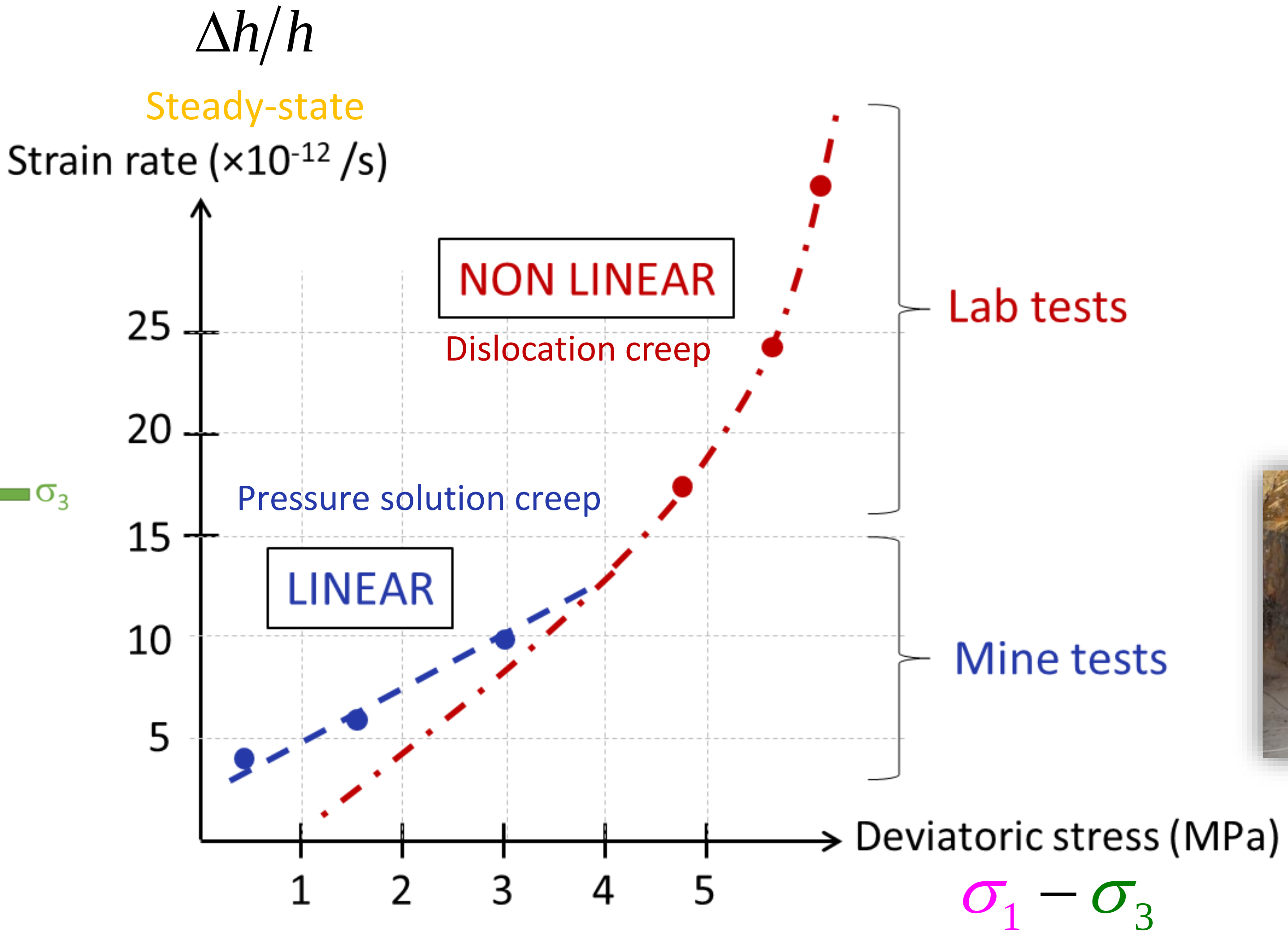
$$t_c = \frac{V^{2/3}}{400}$$

Two mechanisms for Steady-State Creep



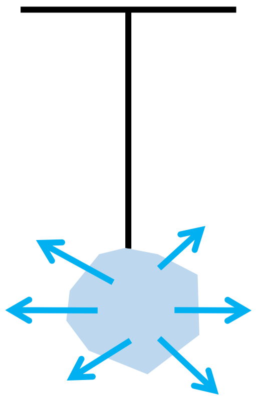
Creep Closure





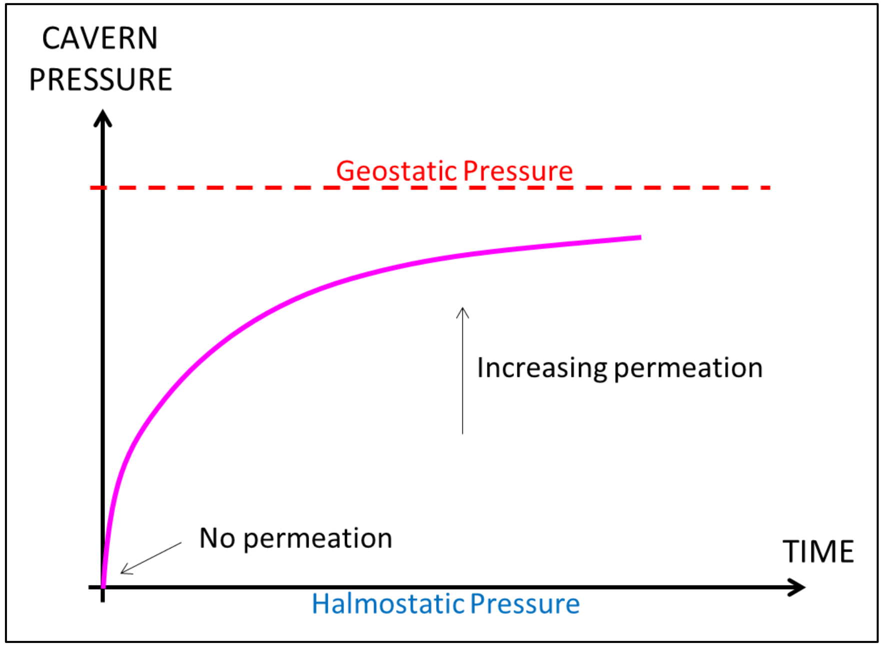
(Bérest et al., 1999+)

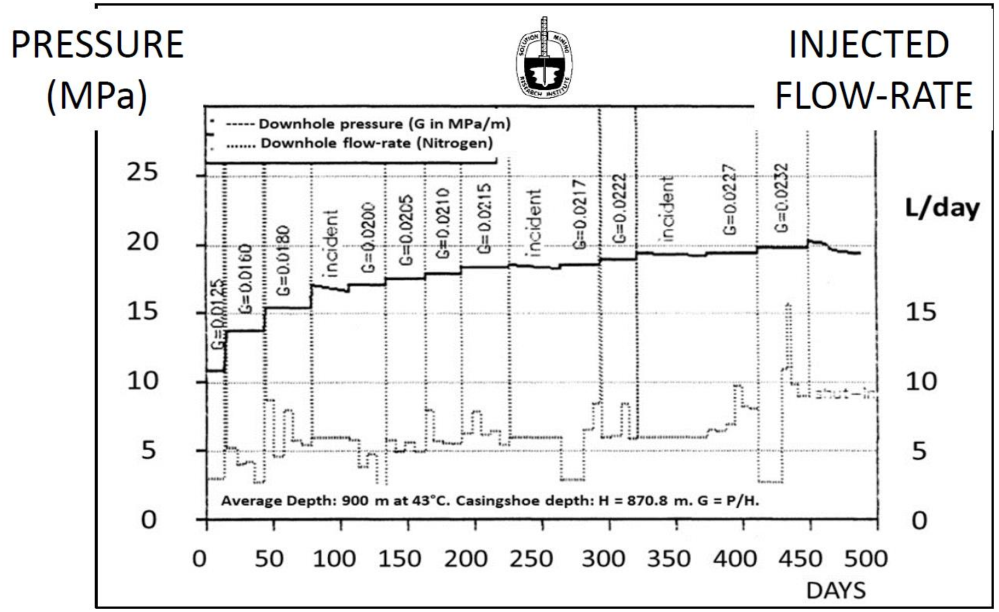
Brine micro-permeation is an increasing function of cavern pressure



Brine
Micro-Permeation

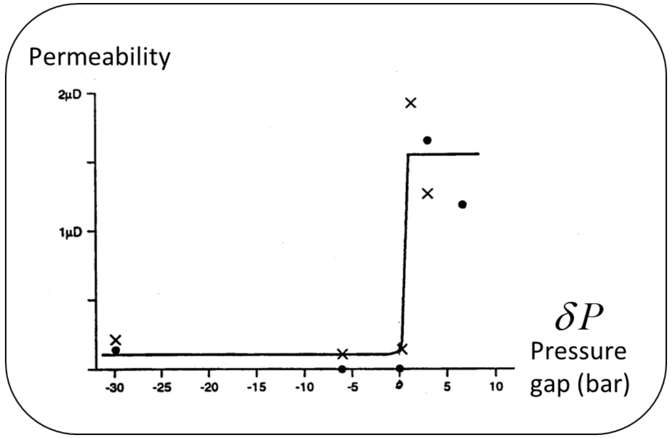
- The permeability of natural salt is exceedingly small (10^{-22} - 10^{-20} m^2)
- Darcy’s law holds (Durup, 1991)
- No threshold, permeation starts above halmostatic pressure



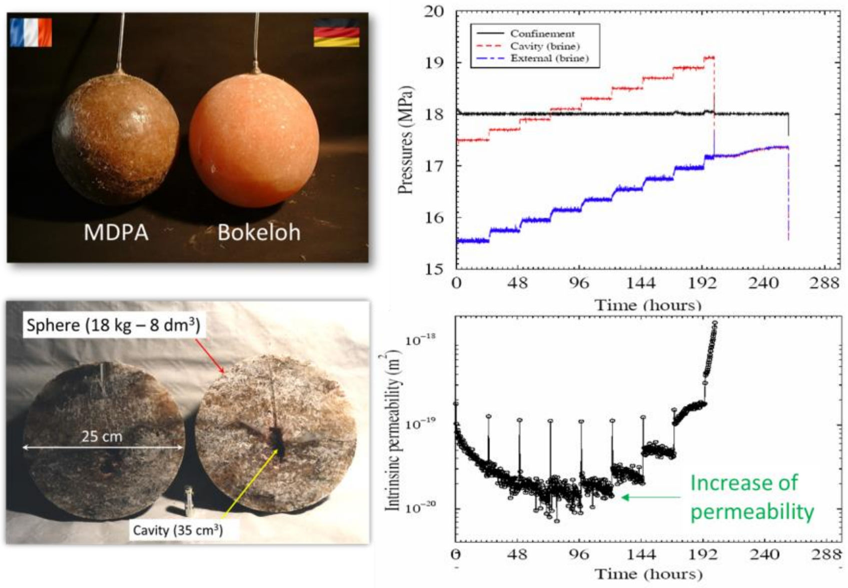


Durup J.G. (1994) *Long term tests for tightness evaluations with brine and gas in salt (Field test n°2 with gas)* - Research Project Report n°94-002-S.

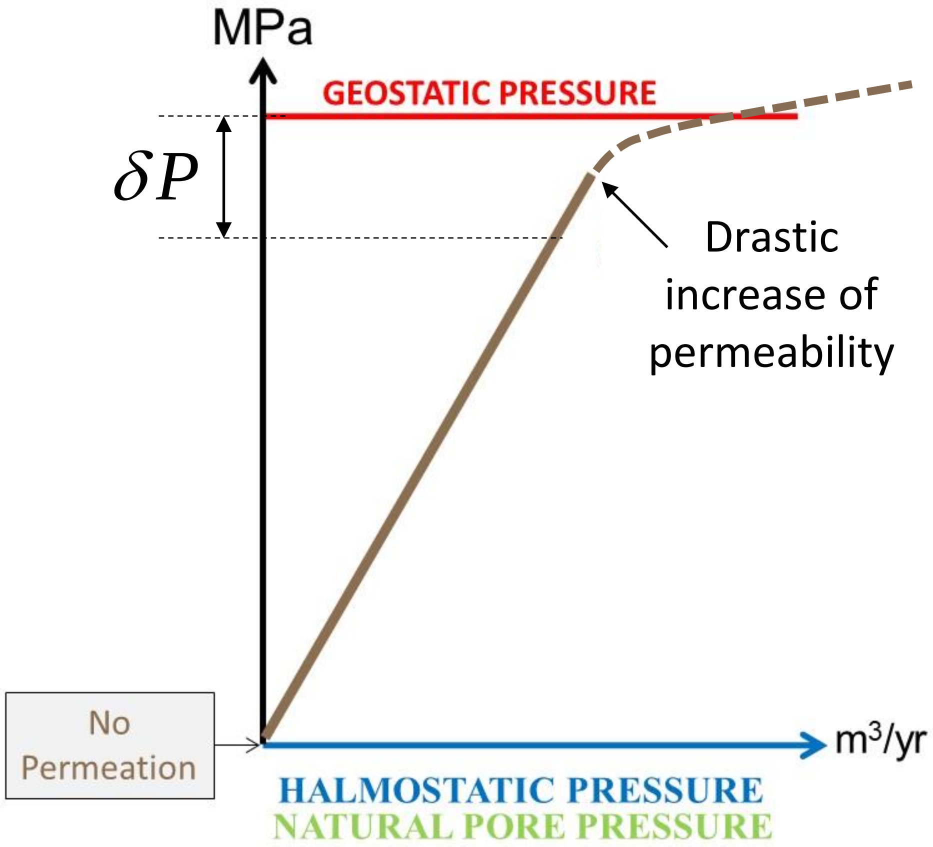
Permeability increases when cavern pressure is close to geostatic



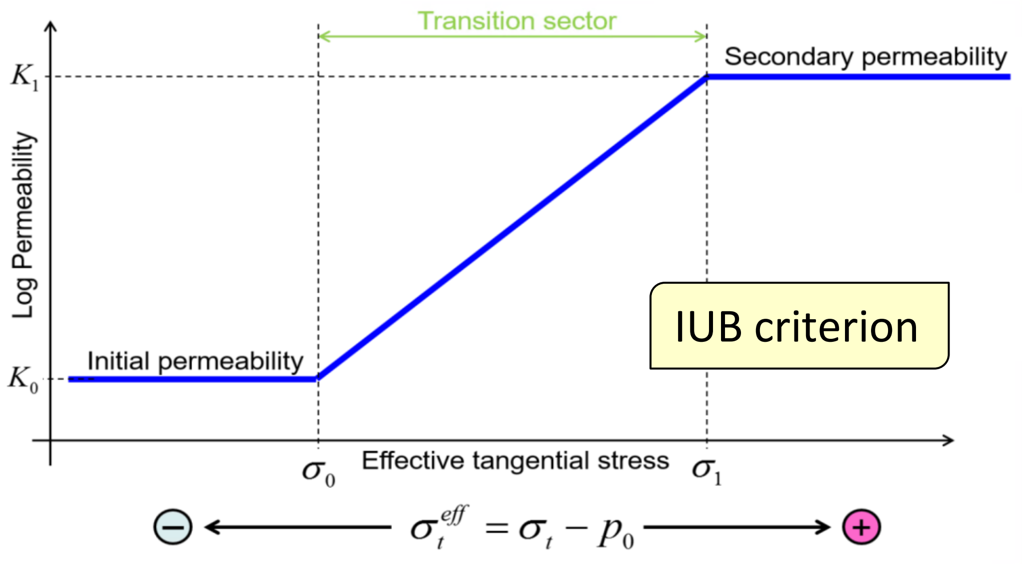
(After Fokker, 1995)

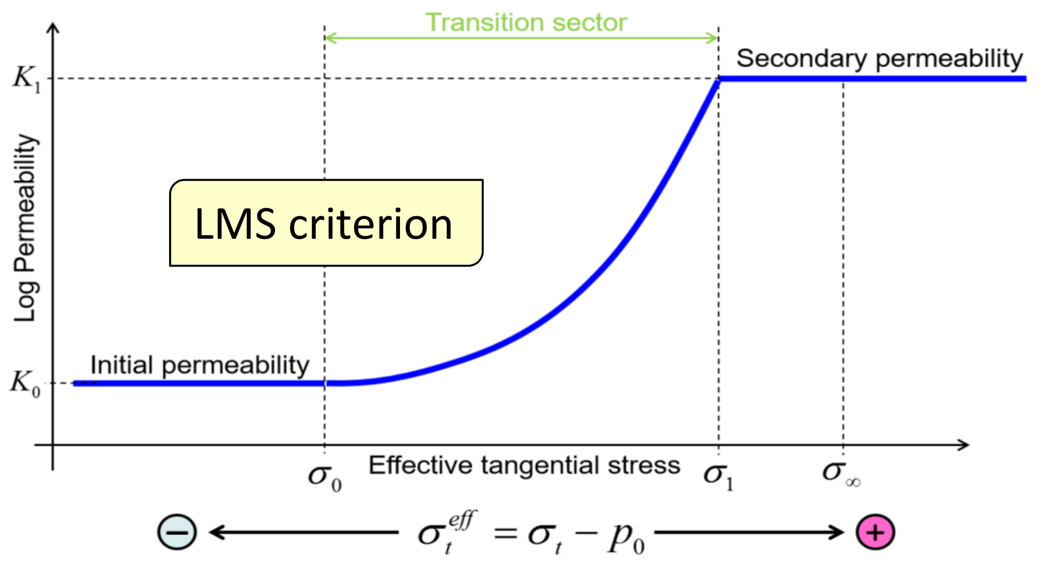


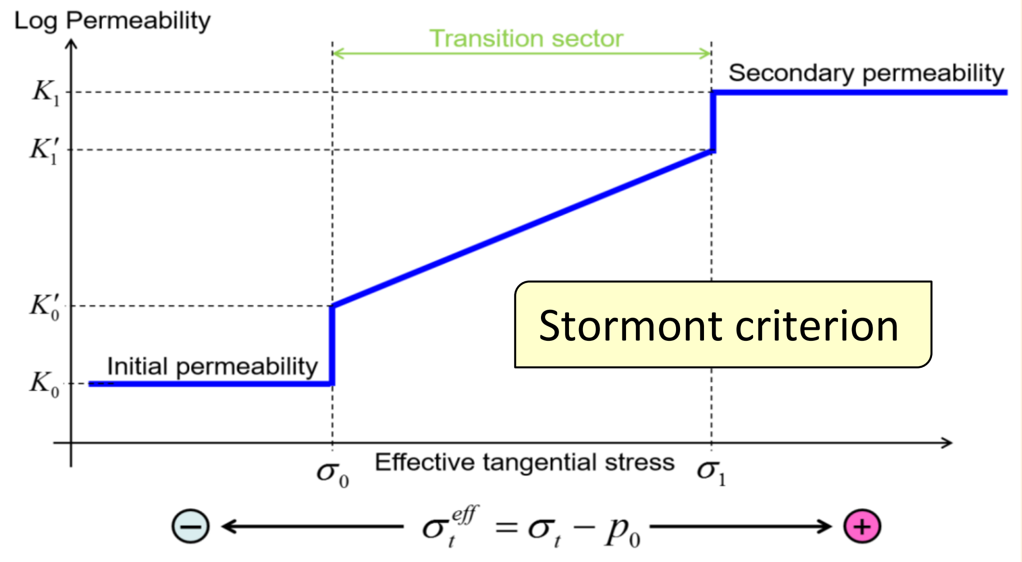
(Bérest et al., 2000)



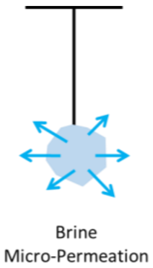
Salt Permeability vs. Effective Tangential Stress: 3 Criteria







<u>Example of selected parameters:</u>

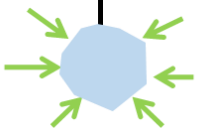


- ❑ IUB criterion
- ❑ K_0 = 10^{-21} m² ← Virgin permeability
- ❑ K_1 = 10^{-15} m² ← Damaged salt
- ❑ σ_0 = 0
- ❑ σ_1 = 1 MPa

Can some parameters be calibrated on a cavern scale using in situ tests?

Cavern Abandonment – Measurements Workflow

Measurement of cavern compressibility



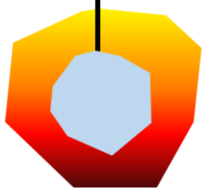
Cavern
Creep Closure

Dislocation creep

Standard creep tests at the lab
and/or
In situ creep test

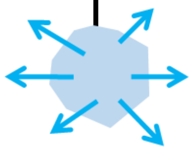
Pressure-solution creep

Very slow creep tests
and/or
In situ creep test



Brine Thermal
Expansion

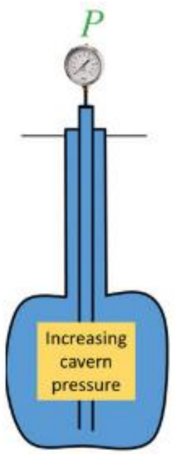
In situ measurement
of cavern-temperature rate



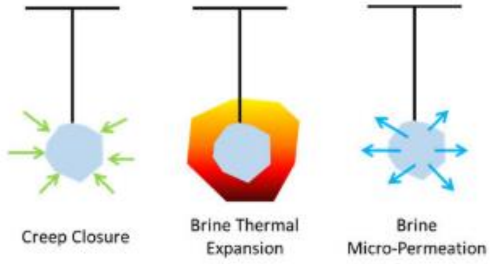
Brine
Micro-Permeation

Permeability measurement
at the lab
and/or
In situ measurement
in an openhole
and/or
Back-calculation from
an abandonment test

Calibration Workflow in 2 Steps



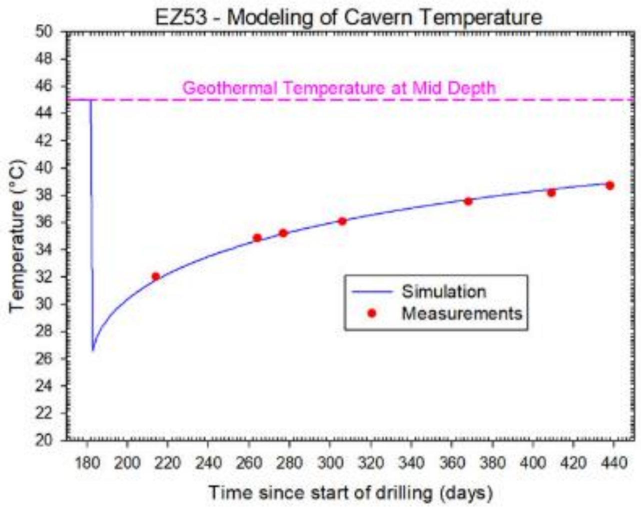
$$\beta V \times \dot{P} = \dot{V}_{therm} + \dot{V}_{creep} - \cancel{\dot{V}_{perm}}$$



Depends on thermal parameters

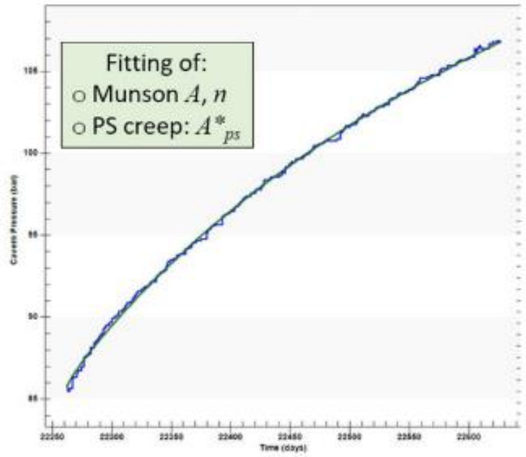
Depends on creep parameters

1. Calibration of thermal parameters



$$\dot{V}_{therm} = \alpha_b V \dot{T}$$

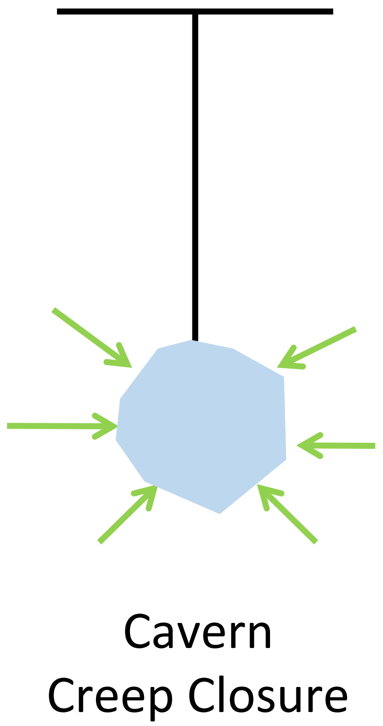
2. Calibration of mechanical parameters

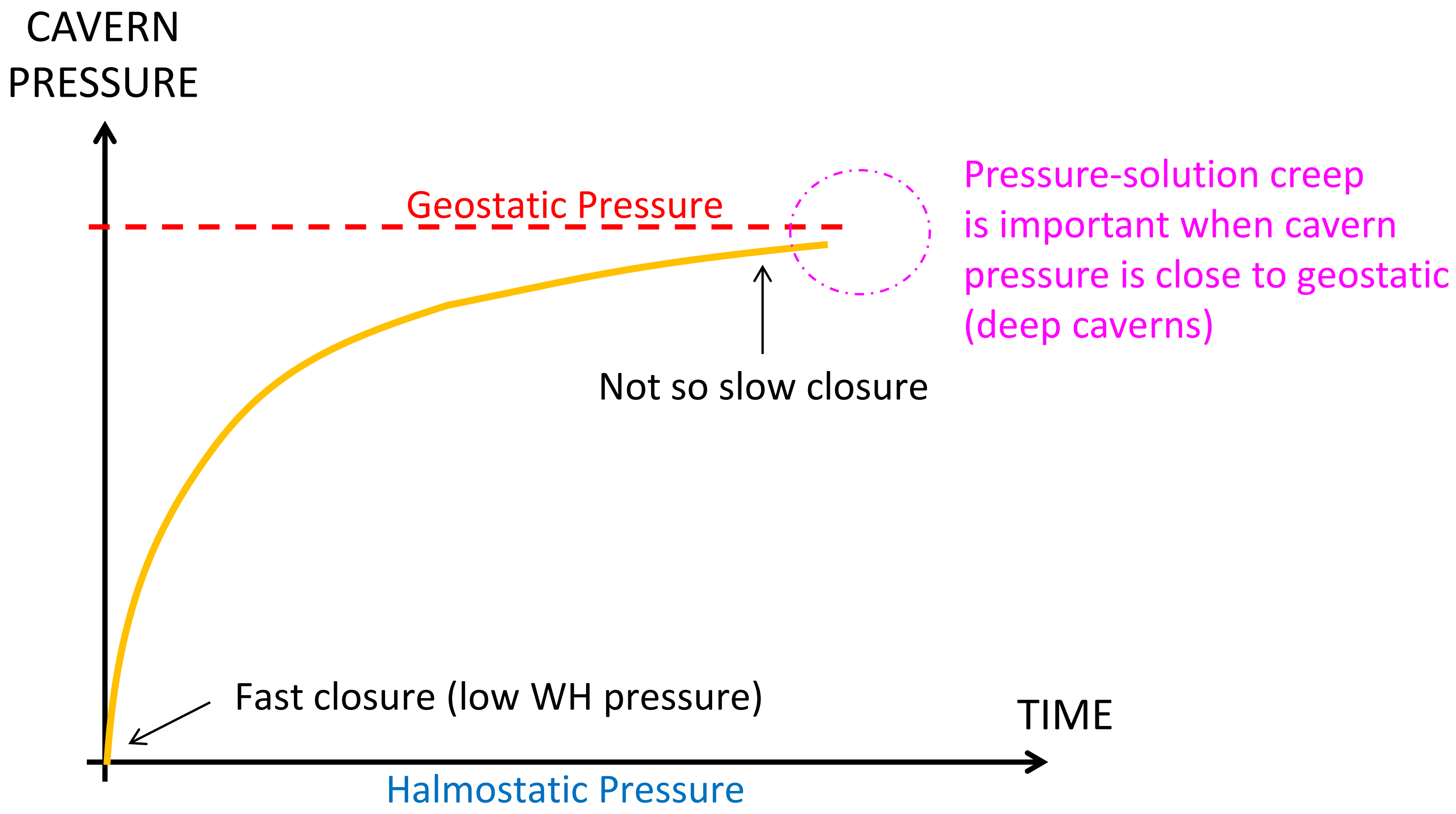


… but how to distinguish between dislocation creep and pressure solution creep?

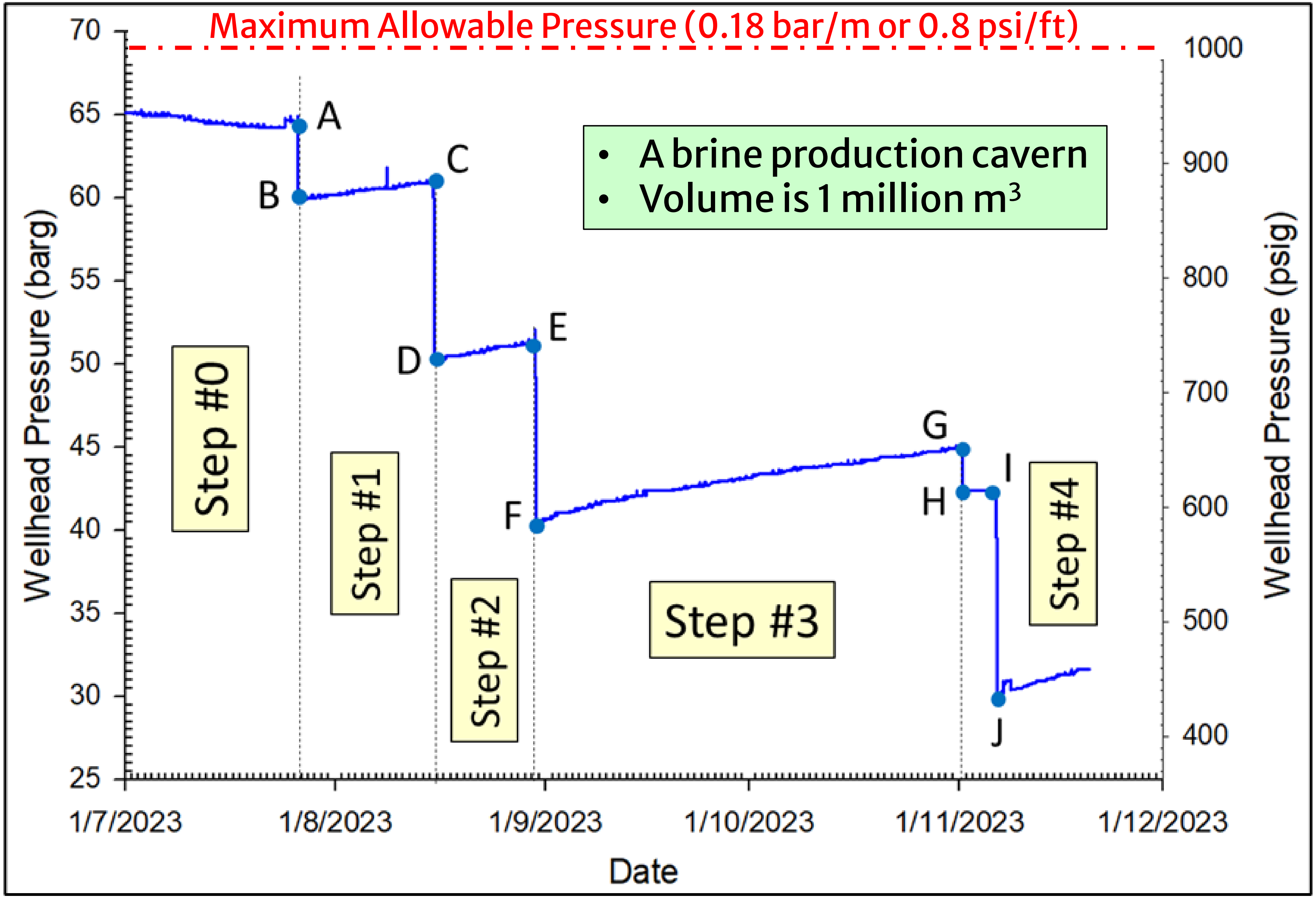
Cavern Creep-closure Rate is a Decreasing Function of Cavern Pressure

DC virtually disappears at high pressure, but not PS!



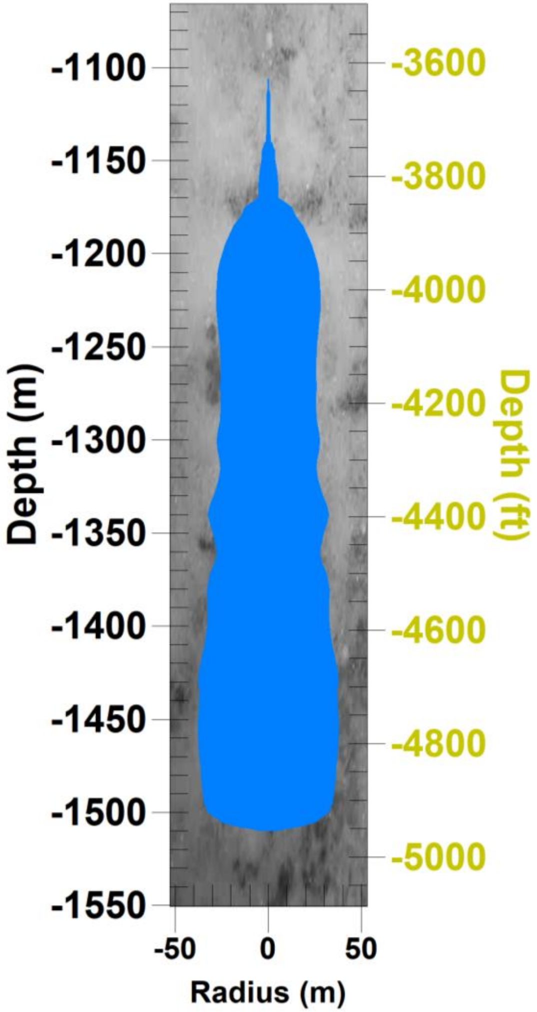


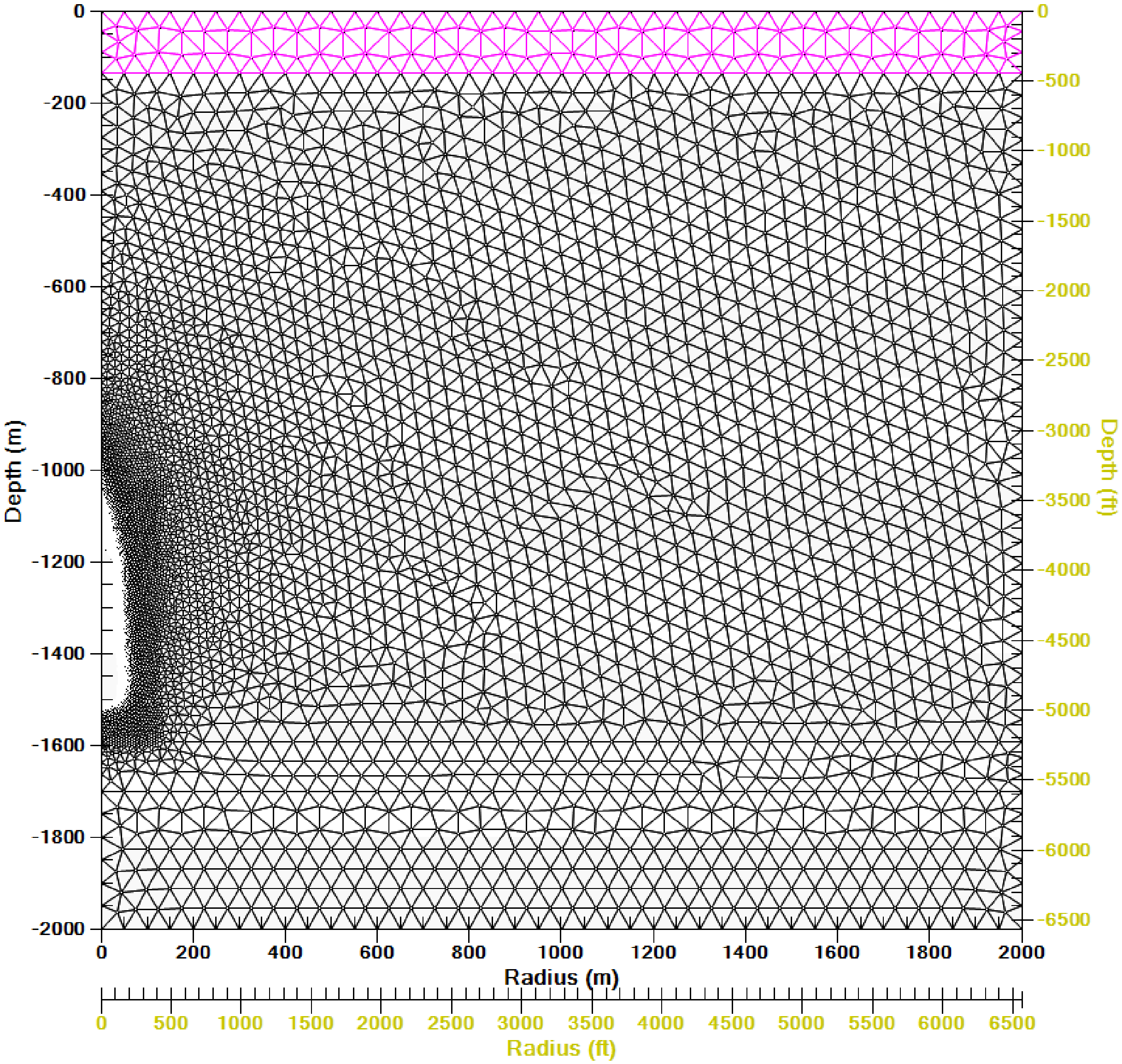
NOBIAN



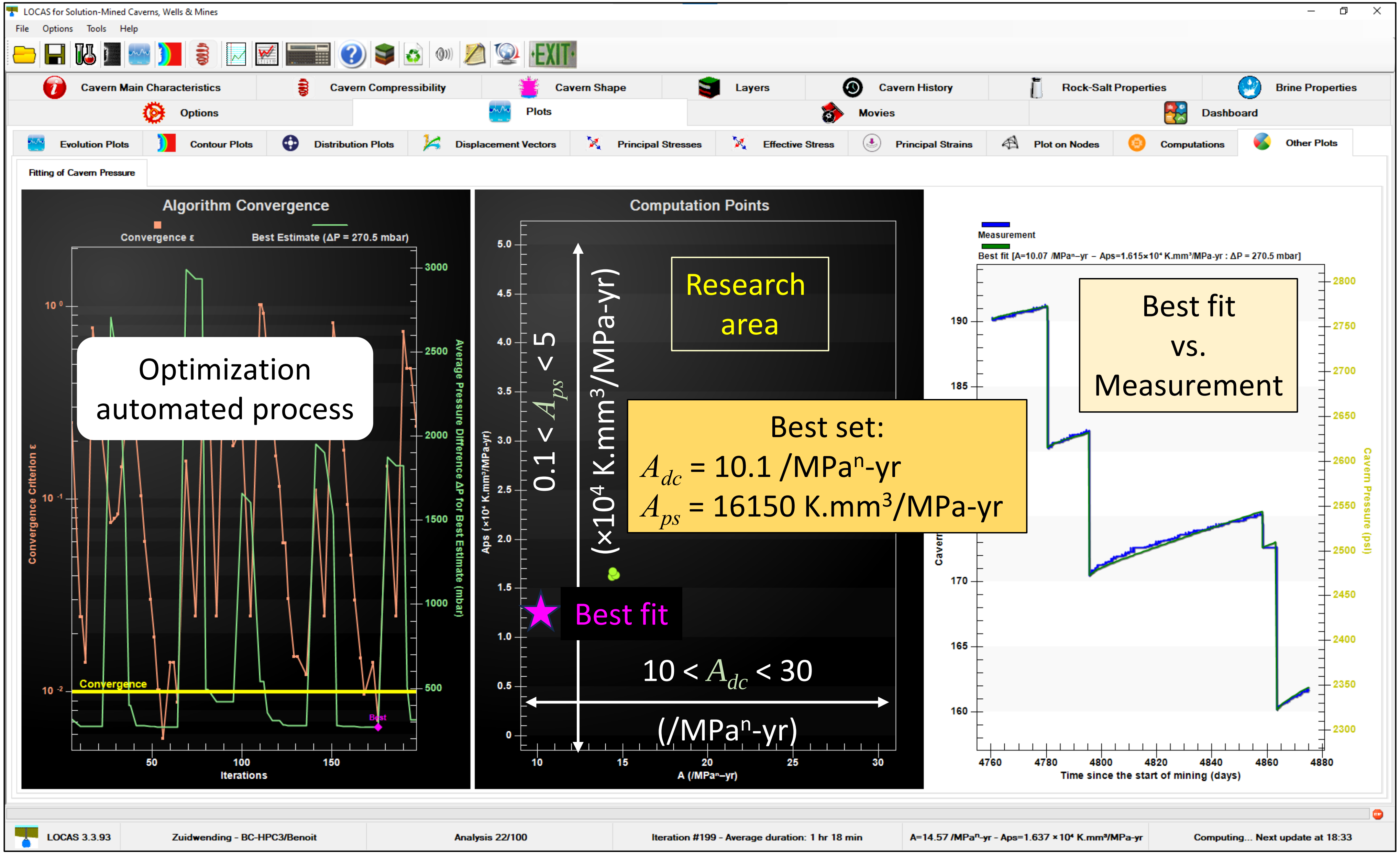
Maximum Allowable Pressure (0.18 bar/m or 0.8 psi/ft)
A brine production cavern
Volume is 1 million m³
Step #0
Step #1
Step #2
Step #3
Step #4
A
B
C
D
E
F
G
H
I
J
Wellhead Pressure (barg)
Wellhead Pressure (psig)
70
65
60
55
50
45
40
35
30
25
1000
900
800
700
600
500
400
1/7/2023
1/8/2023
1/9/2023
1/10/2023
1/11/2023
1/12/2023
Date

FINITE ELEMENT MODEL

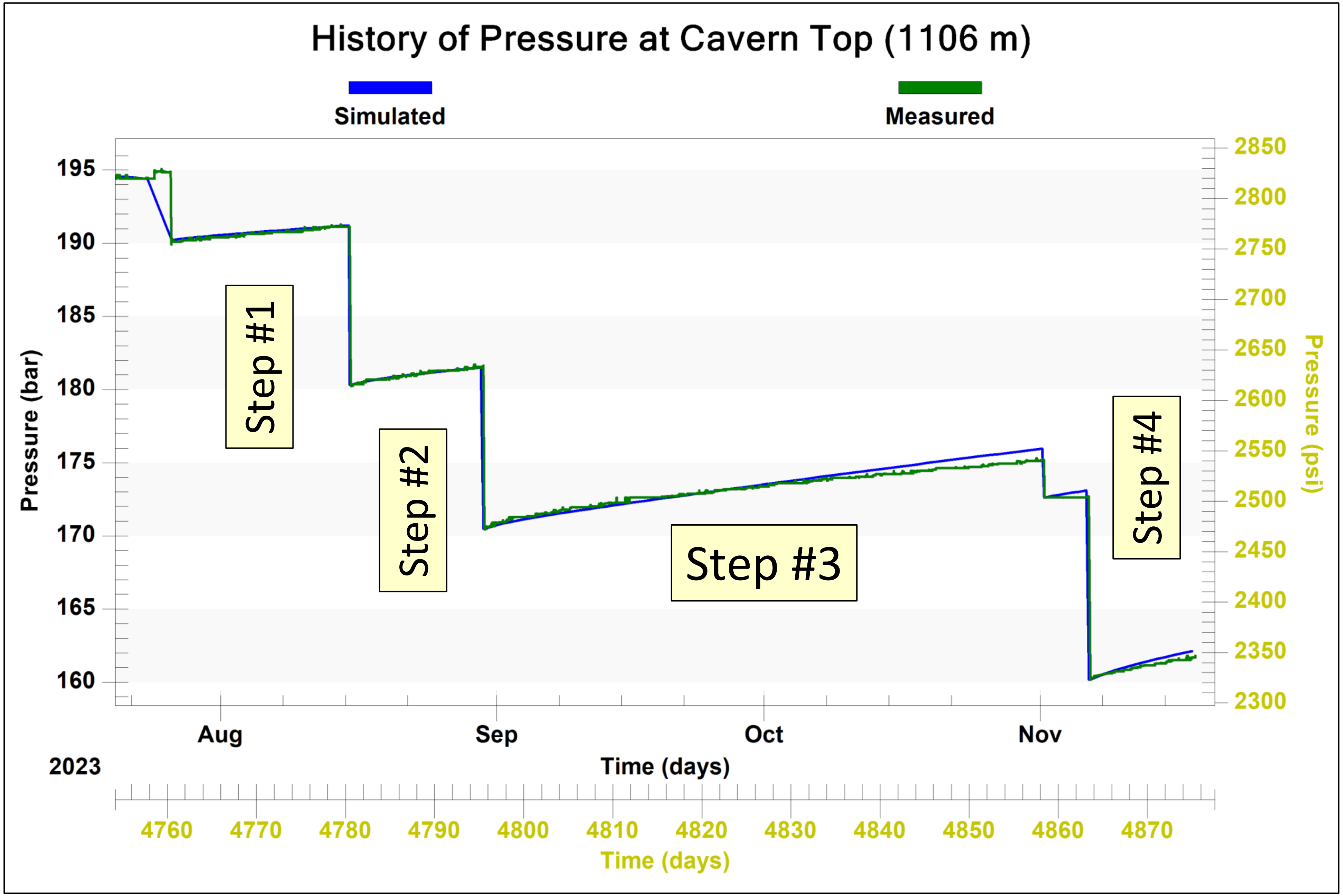




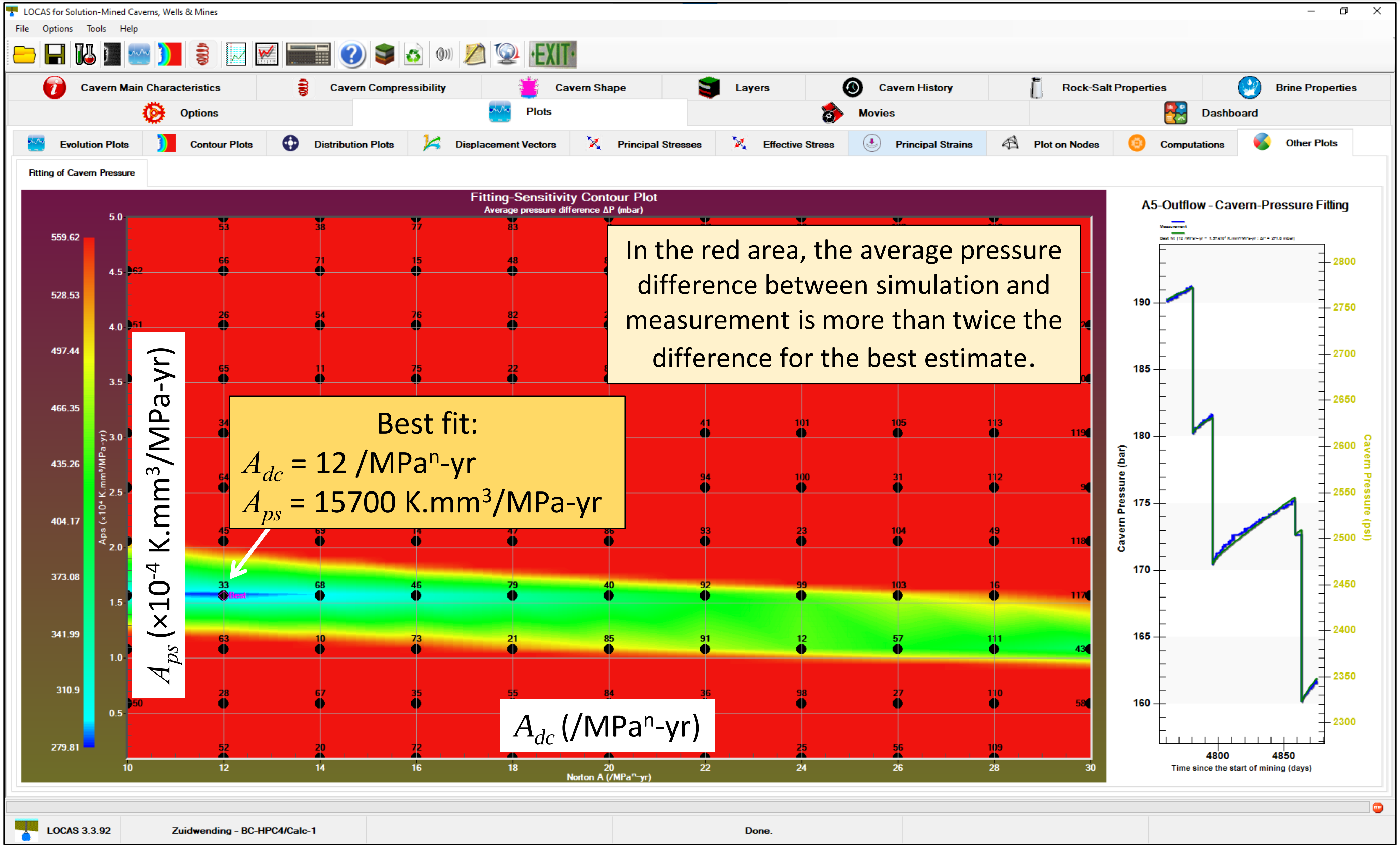
Search for the best calibration for the A_{dc} (Norton-Hoff) and A_{ps} (Pressure Solution) parameters

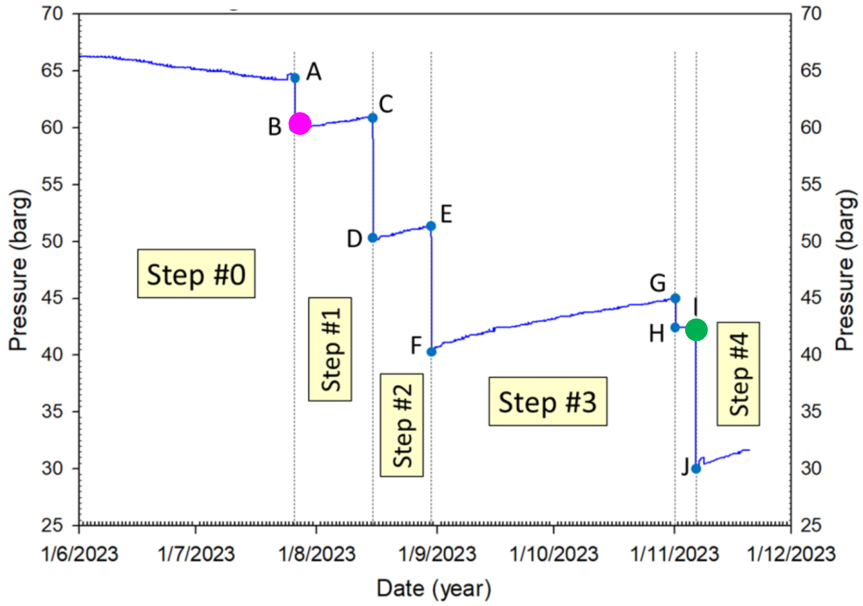


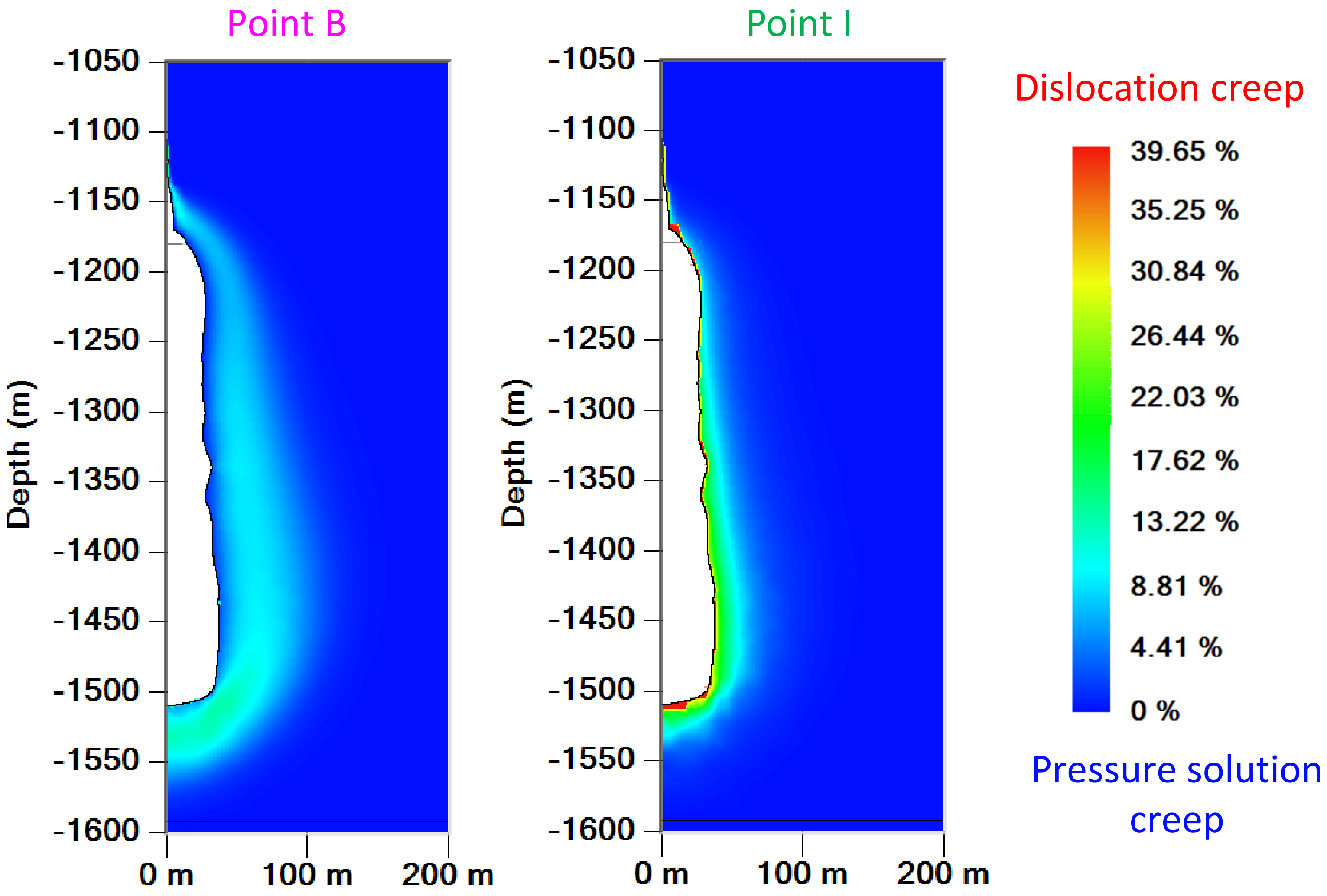
NOBIAN


History of Pressure at Cavern Top (1106 m)
Simulated
Measured
Pressure (bar)
195
190
185
180
175
170
165
160
2850
2800
2750
2700
2650
2600
2550
2500
2450
2400
2350
2300
Pressure (psi)
Step #1
Step #2
Step #3
Step #4
Aug
Sep
Oct
Nov
2023
Time (days)
4760
4770
4780
4790
4800
4810
4820
4830
4840
4850
4860
4870
Time (days)

Sensitivity Map: A_{dc} (Norton-Hoff) and A_{ps} (Pressure Solution)



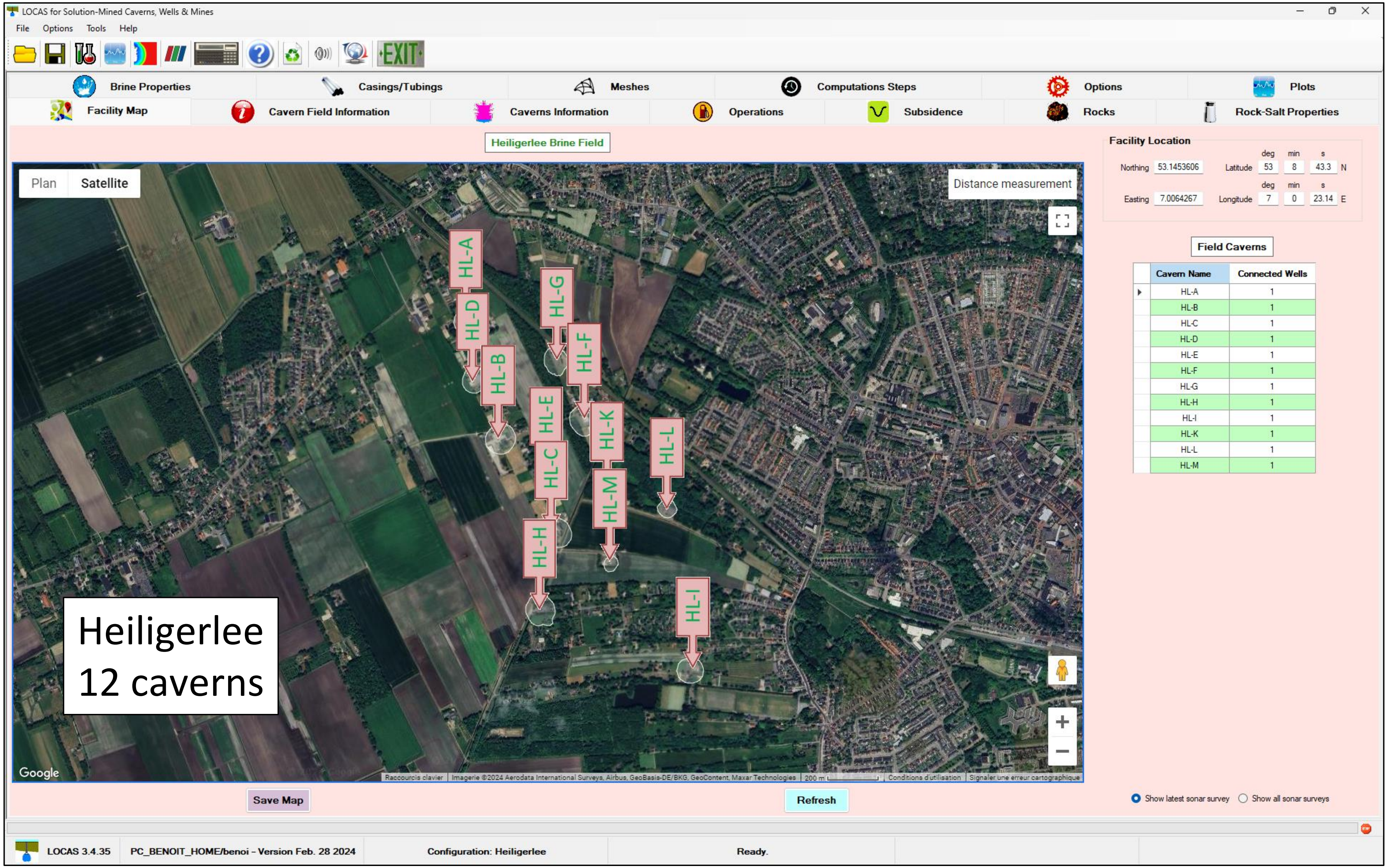


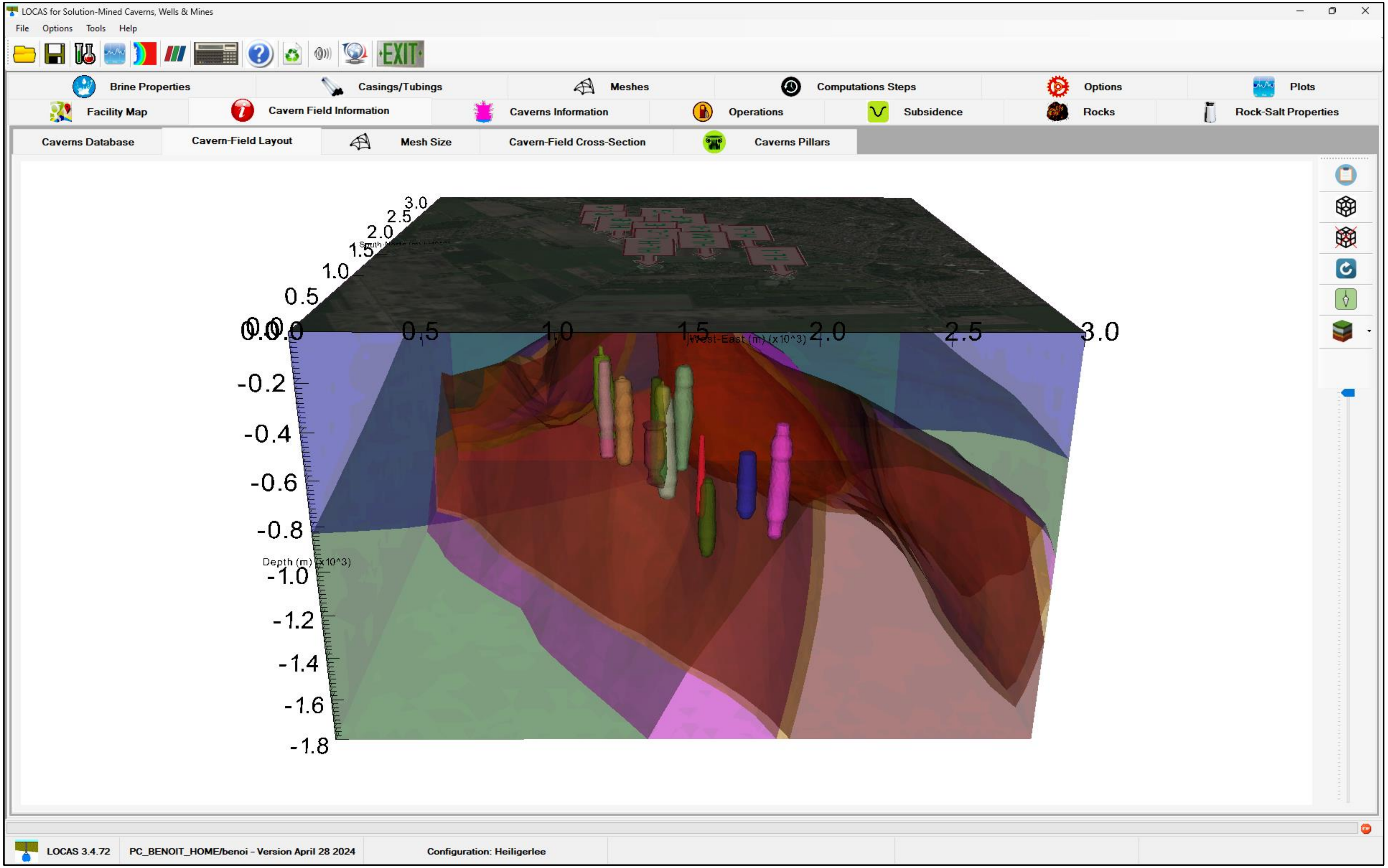


Pressure solution creep vs. Dislocation creep at the beginning (left) and at the end of the test (right). A value of 0% indicates that only pressure solution creep is active, while a value of 100% indicates that only dislocation creep is active.

3D NUMERICAL MODELING

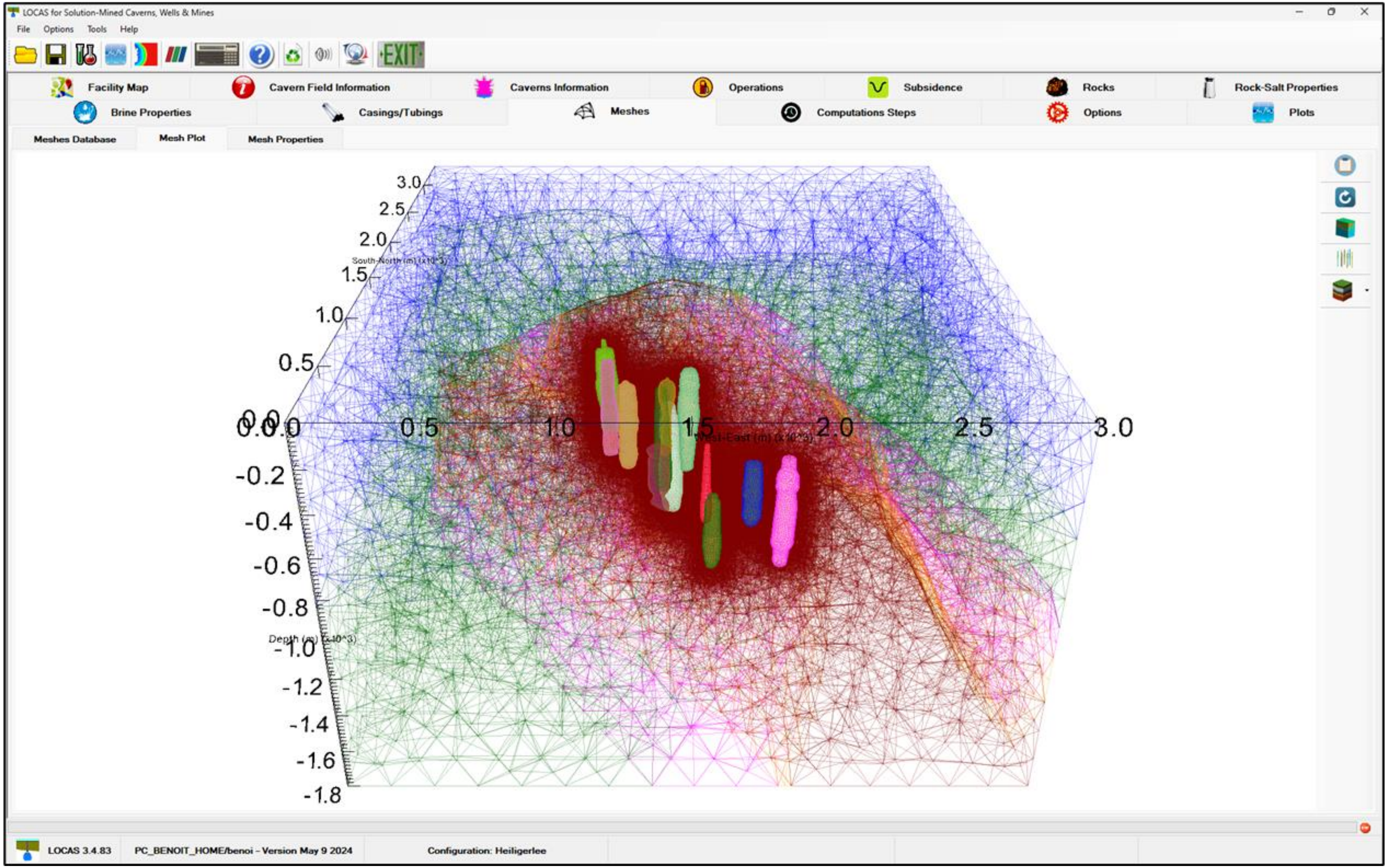
NOBIAN


LOCAS for Solution-Mined Caverns, Wells & Mines
File Options Tools Help
Brine Properties
Casings/Tubings
Meshes
Computations Steps
Options
Plots
Facility Map
Cavern Field Information
Caverns Information
Operations
Subsidence
Rocks
Rock-Salt Properties
Heiligerlee Brine Field
Plan
Satellite
Distance measurement
HL-A
HL-B
HL-C
HL-D
HL-E
HL-F
HL-G
HL-H
HL-I
HL-K
HL-L
HL-M
Heiligerlee
12 caverns
Google
Facility Location
Northing 53.1453606 Latitude 53 8 43.3 N
Easting 7.0064267 Longitude 7 0 23.14 E
Field Caverns
Cavern Name | Connected Wells
HL-A 1
HL-B 1
HL-C 1
HL-D 1
HL-E 1
HL-F 1
HL-G 1
HL-H 1
HL-I 1
HL-K 1
HL-L 1
HL-M 1
Save Map
Refresh
Show latest sonar survey
Show all sonar surveys
LOCAS 3.4.35
PC_BENOIT_HOME/benoi – Version Feb. 28 2024
Configuration: Heiligerlee
Ready.

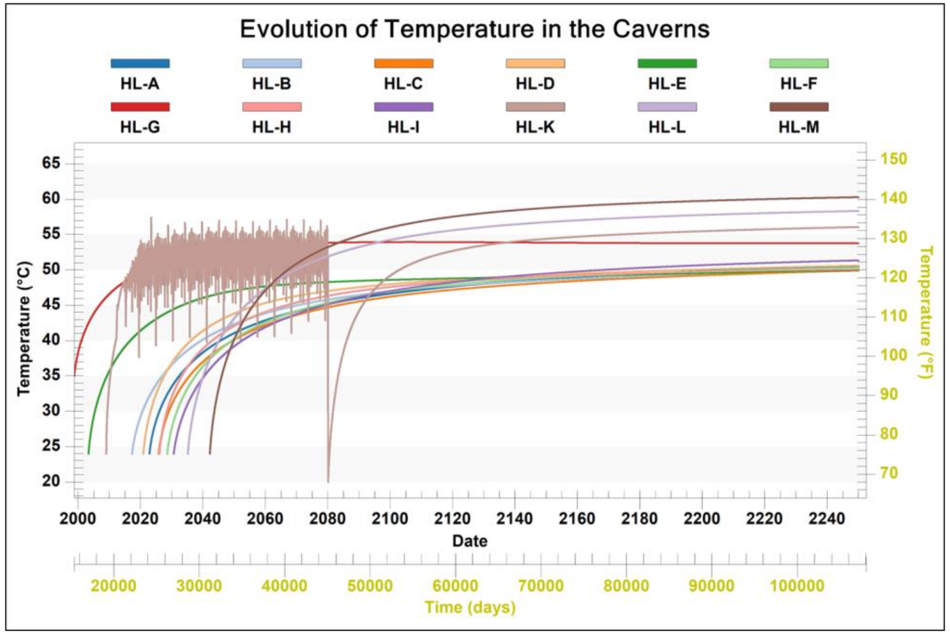


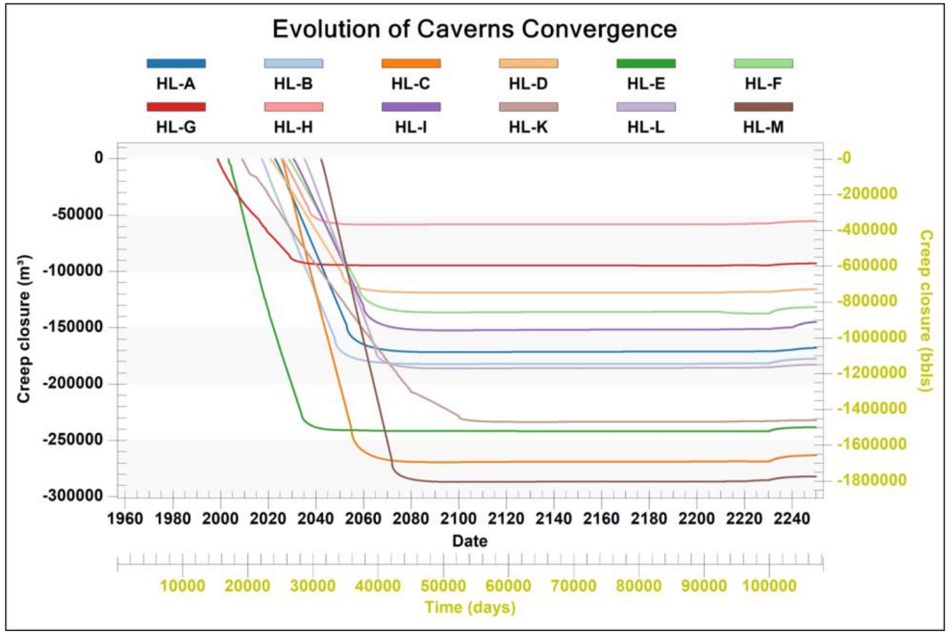
LOCAS for Solution-Mined Caverns, Wells & Mines
File
Options
Tools
Help
EXIT
Brine Properties
Casings/Tubings
Meshes
Computations Steps
Options
Plots
Facility Map
Cavern Field Information
Caverns Information
Operations
Subsidence
Rocks
Rock-Salt Properties
Caverns Database
Cavern-Field Layout
Mesh Size
Cavern-Field Cross-Section
Caverns Pillars
West-East (m) (x10^3)
Depth (m) (x10^3)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
LOCAS 3.4.72
PC_BENOIT_HOME/benoi - Version April 28 2024
Configuration: Heiligerlee

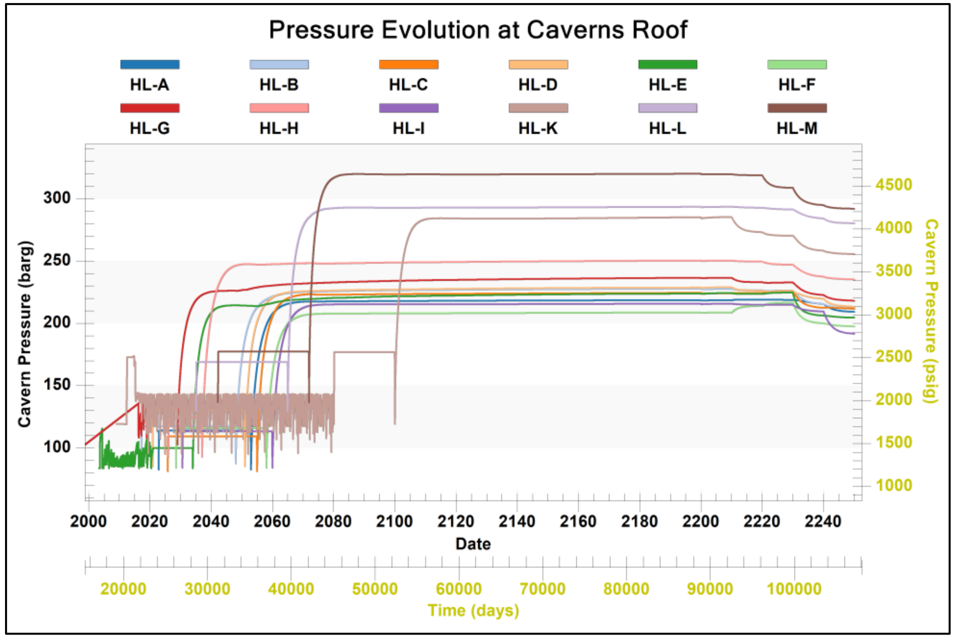
NOBIAN

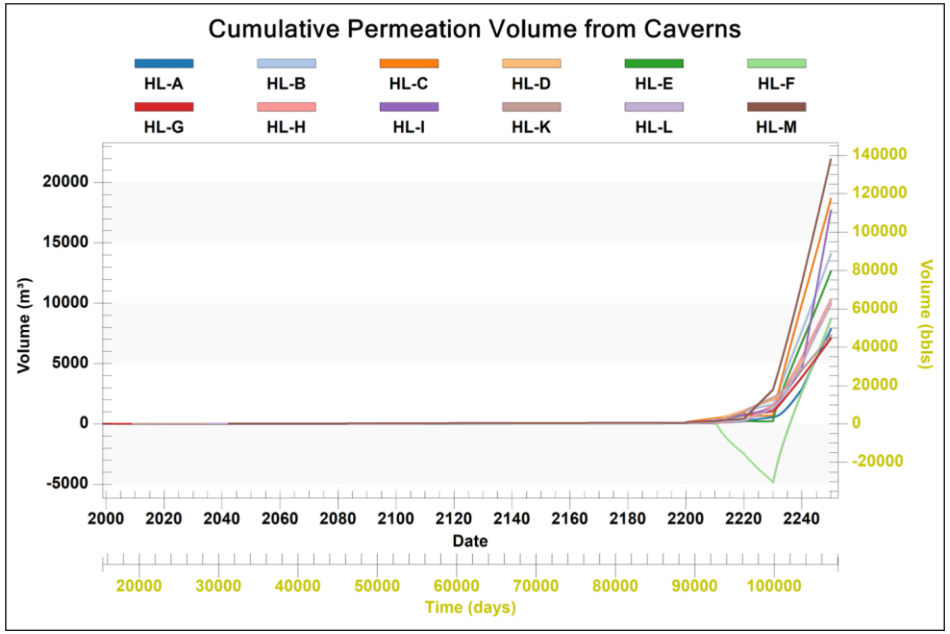

LOCAS for Solution-Mined Caverns, Wells & Mines
File Options Tools Help
EXIT
Facility Map
Cavern Field Information
Caverns Information
Operations
Subsidence
Rocks
Rock-Salt Properties
Brine Properties
Casings/Tubings
Meshes
Computations Steps
Options
Plots
Meshes Database
Mesh Plot
Mesh Properties
South-North (m) (x10^3)
West-East (m) (x10^3)
Depth (m) (x10^3)
LOCAS 3.4.83
PC_BENOIT_HOME/benoi - Version May 9 2024
Configuration: Heiligerlee

NOBIAN

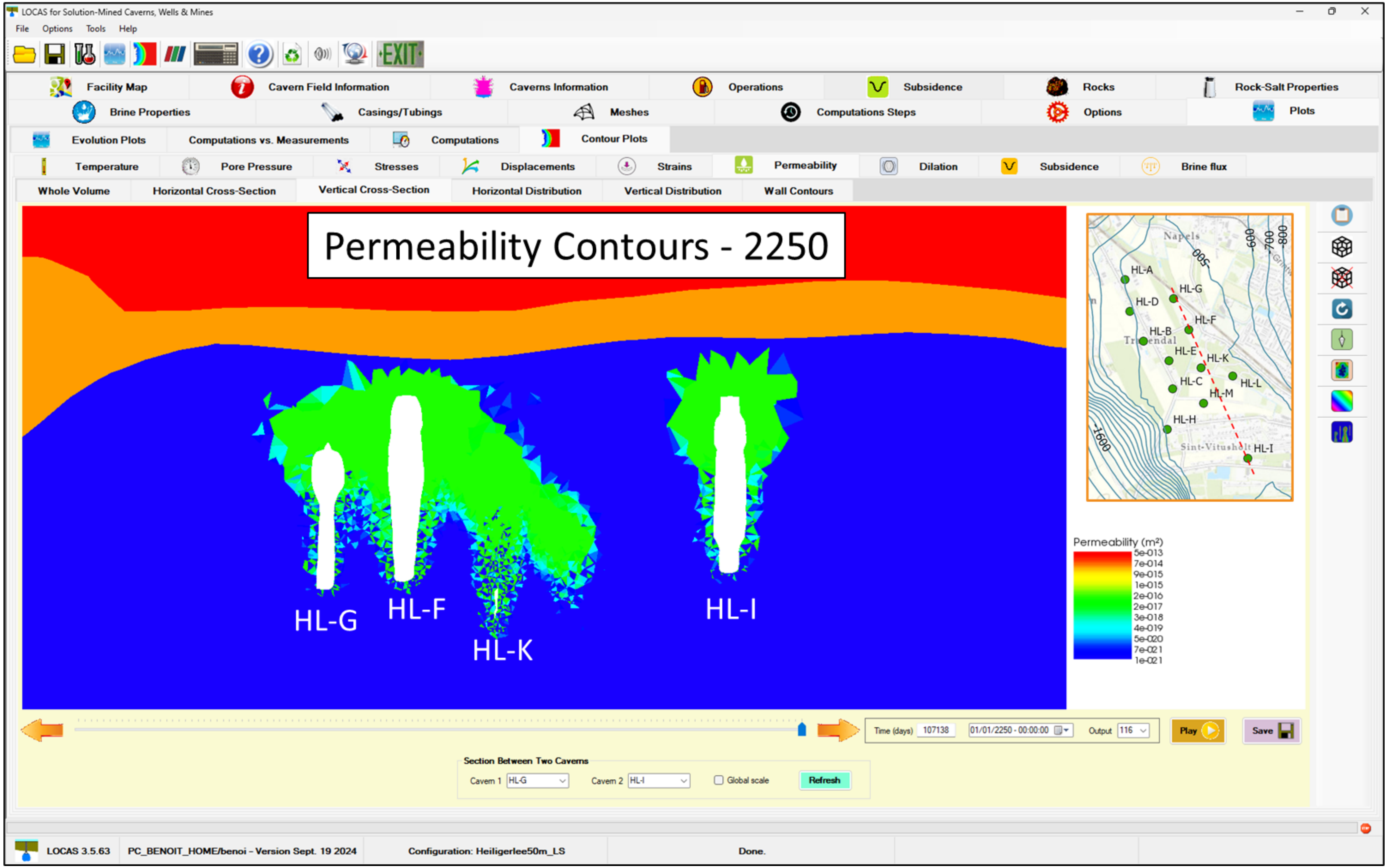








BROUARD CONSULTING


LOCAS for Solution-Mined Caverns, Wells & Mines
File Options Tools Help
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Operations
Subsidence
Rocks
Rock-Salt Properties
Brine Properties
Casings/Tubings
Meshes
Computations Steps
Options
Plots
Evolution Plots
Computations vs. Measurements
Computations
Contour Plots
Temperature
Pore Pressure
Stresses
Displacements
Strains
Permeability
Dilation
Subsidence
Brine flux
Whole Volume
Horizontal Cross-Section
Vertical Cross-Section
Horizontal Distribution
Vertical Distribution
Wall Contours
Permeability Contours - 2250
HL-G
HL-F
HL-K
HL-I
Permeability (m²)
5e-013
7e-014
9e-015
1e-015
2e-016
2e-017
3e-018
4e-019
5e-020
7e-021
1e-021
Time (days) 107138
01/01/2250 - 00:00:00
Output 116
Play
Save
Section Between Two Caverns
Cavern 1 HL-G
Cavern 2 HL-I
Global scale
Refresh
LOCAS 3.5.63
PC_BENOIT_HOME/benoi - Version Sept. 19 2024
Configuration: Heiligerlee50m_LS
Done.


LOCAS for Solution-Mined Caverns, Wells & Mines
File Options Tools Help
Facility Map
Cavern Field Information
Caverns Information
Operations
Subsidence
Rocks
Rock-Salt Properties
Brine Properties
Casings/Tubings
Meshes
Computations Steps
Options
Plots
Evolution Plots
Computations vs. Measurements
Computations
Contour Plots
Temperature
Pore Pressure
Stresses
Displacements
Strains
Permeability
Dilation
Subsidence
Brine flux
Horizontal Cross-Section
Vertical Cross-Section
Horizontal Distribution
Vertical Distribution
Wall Contours
Dilation FOS (b=1) Contours in 2250
HL-G
HL-K
HL-F
HL-I
HL-A
HL-D
HL-B
HL-E
HL-C
HL-M
HL-L
HL-H
Factor Of Safety
10
9
8
7
6
5
4
3
2
1
0
Time (days)
0
01/09/1956 - 00:00:00
Output
1
Play
Save
Section Between Two Caverns
Cavern 1
HL-G
Cavern 2
HL-I
Global scale
Refresh
LOCAS 3.5.63
PC_BENOIT_HOME/benoi - Version Sept. 19 2024
Configuration: Heiligerlee50m_LS