BAS-2 Cavern abandonment

Abandonment concept meeting with
SODM representatives

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- Introduction
- Convergence rate
- Sump compaction
- Well integrity
- Permeation process

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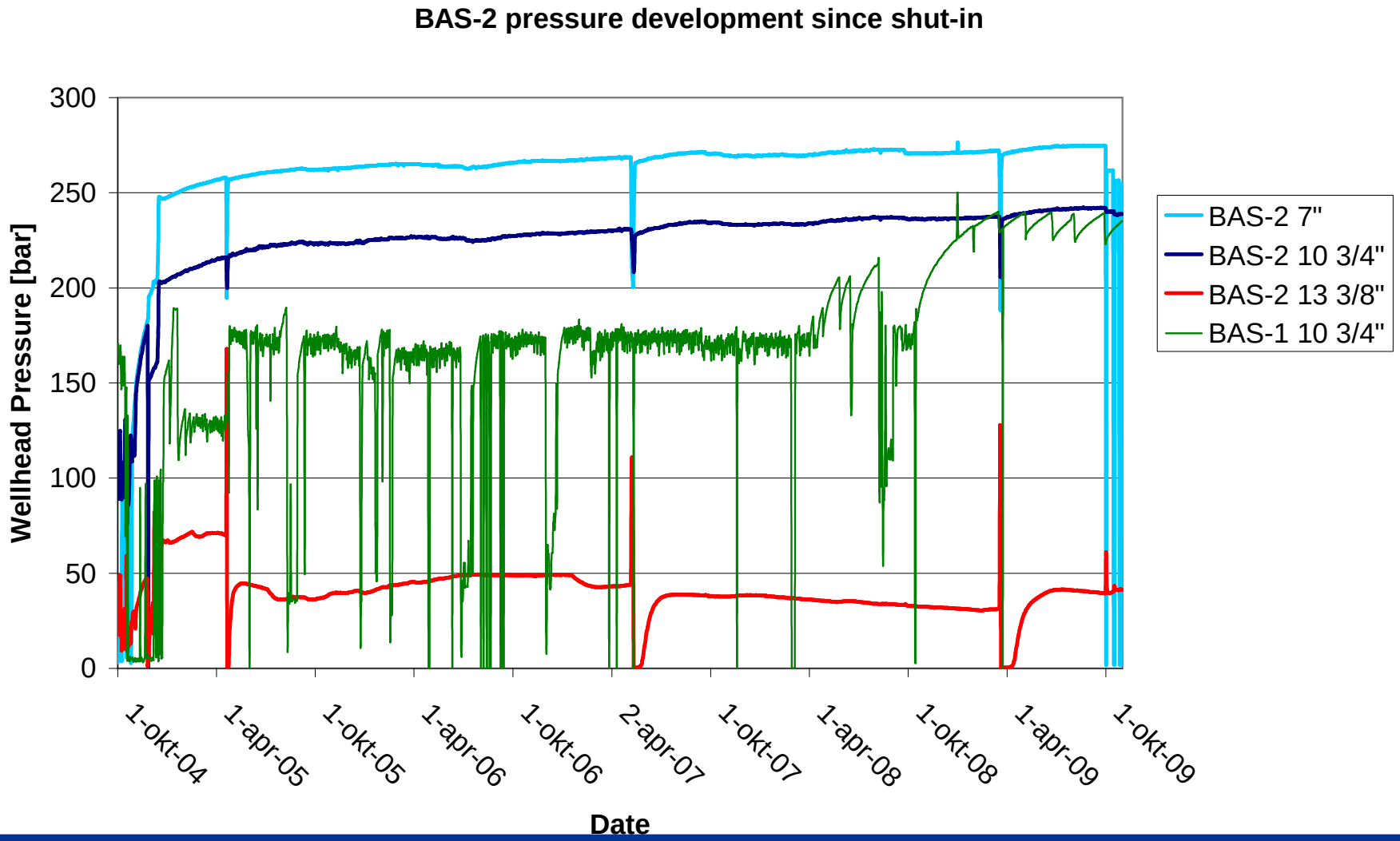
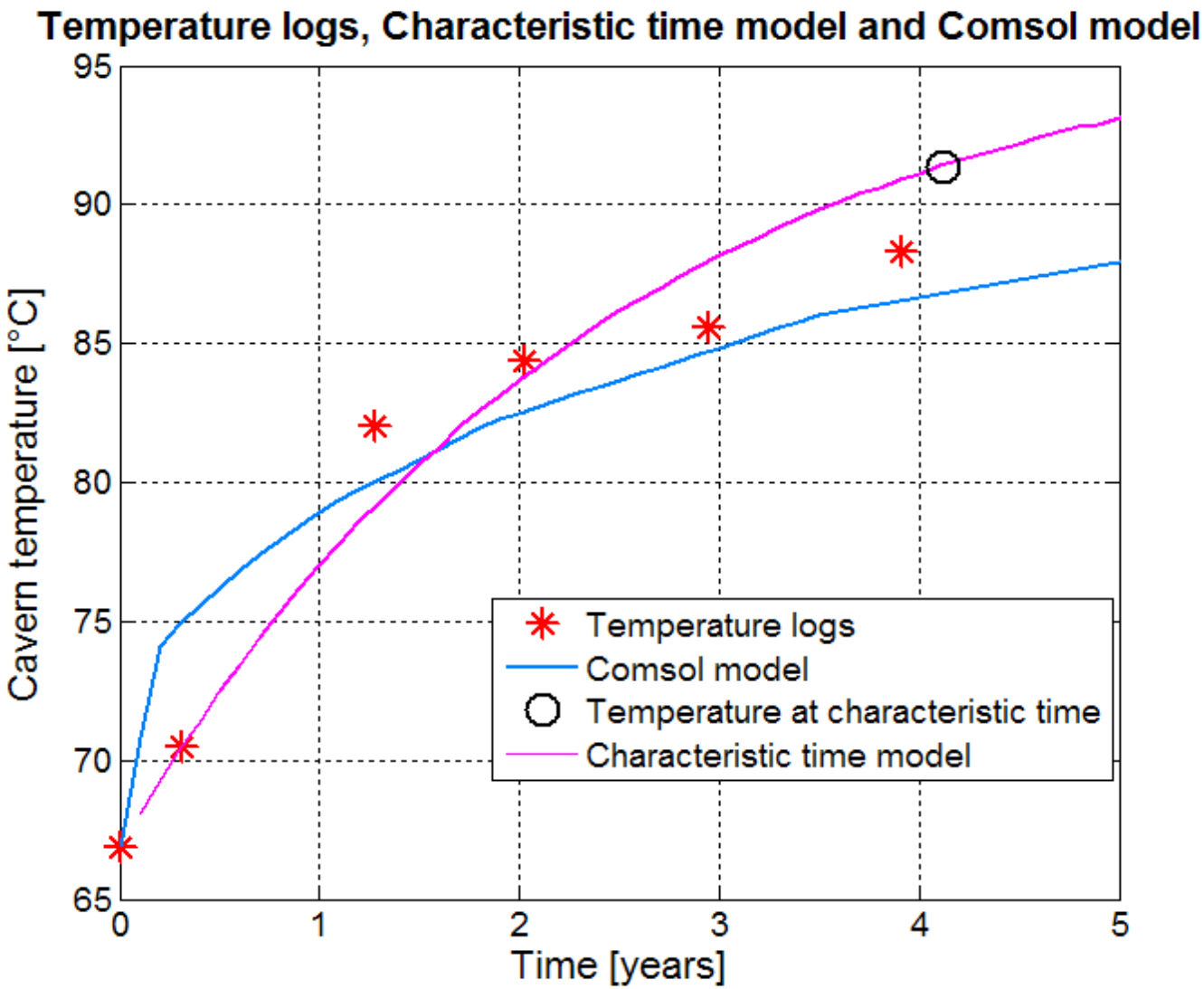
Introduction

- BAS-2 shut-in since November 2004



Introduction



Worst-Worst approach

We have taken a worst case approach for the:

- Hydraulic-mechanical model
- Permeation engine

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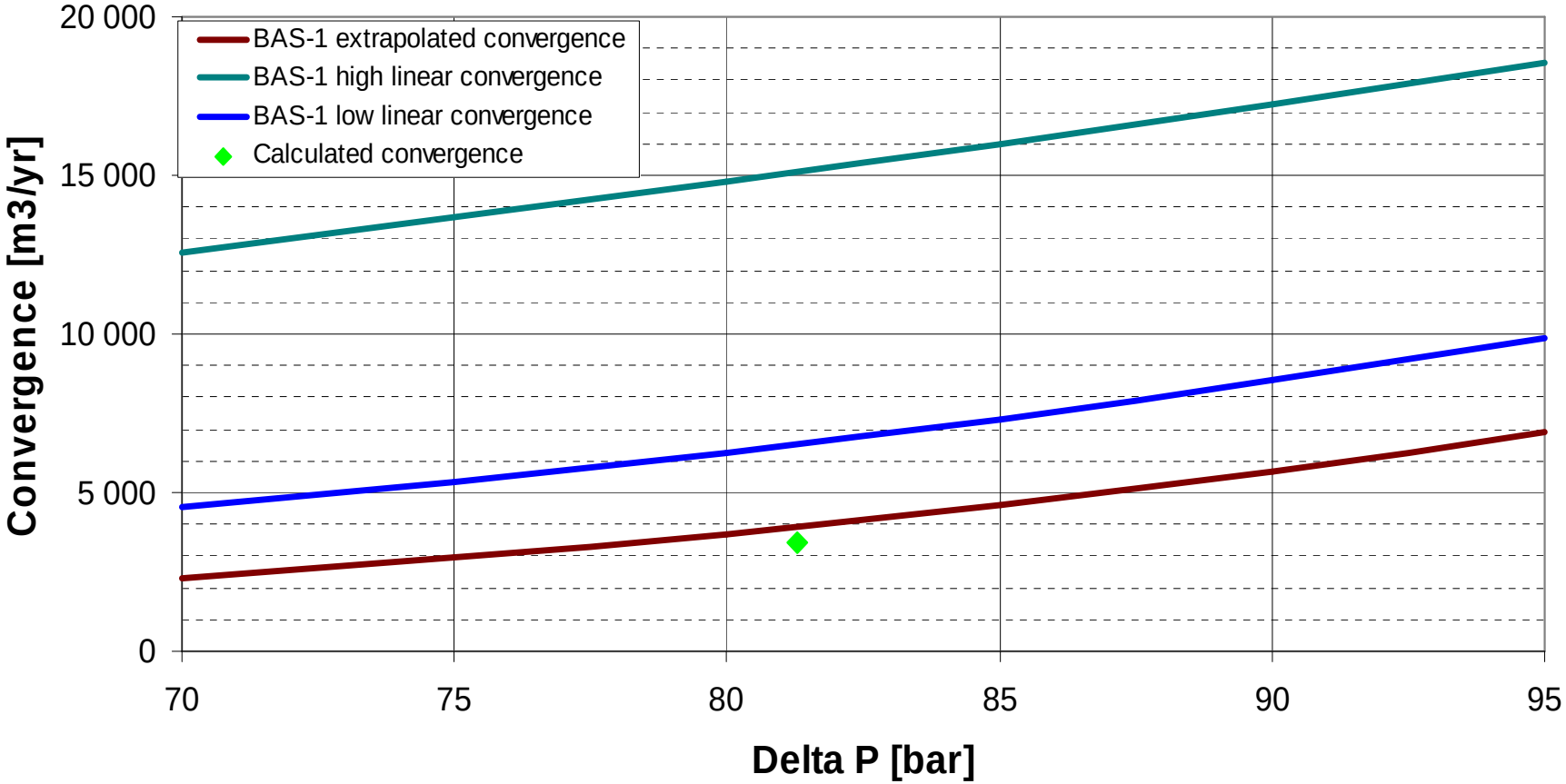
Calibration salt creep parameters

Comparisson BAS-1 pressure build-up with creep models



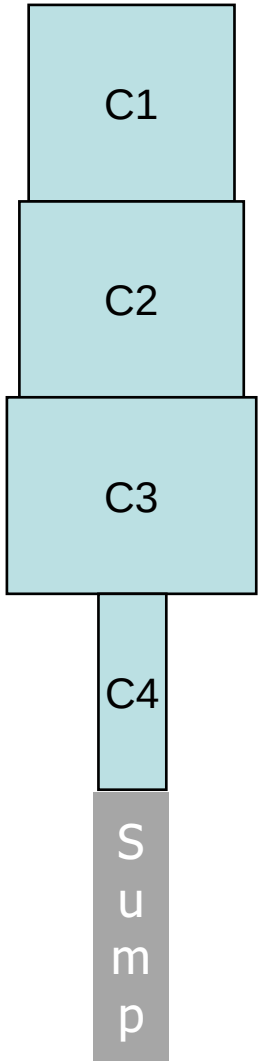
BAS 1 bleed-offs show that predominant creep mechanism is power law.

Convergence rate development

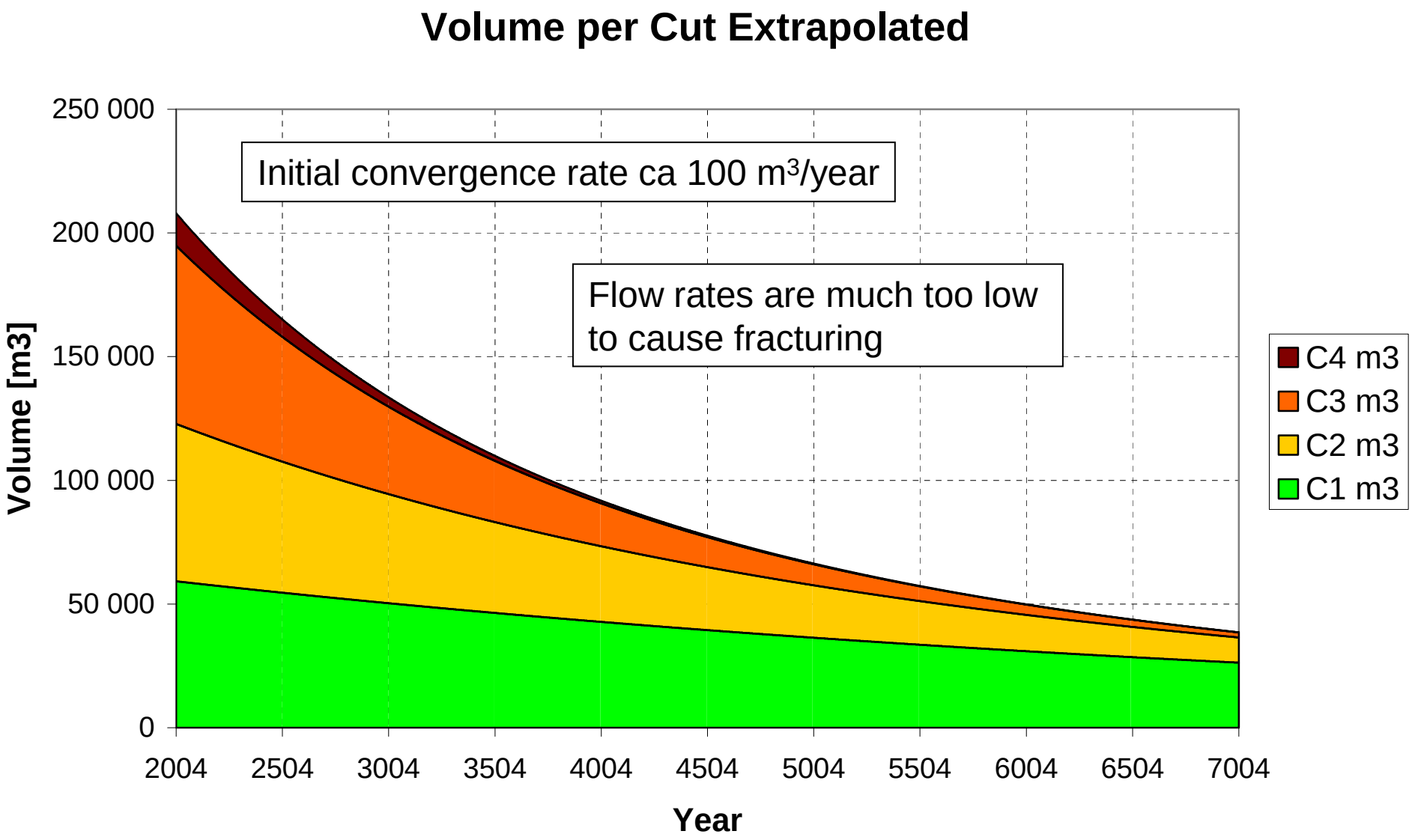
Factors influencing convergence:

- Volume
- Height
- Fluid type e.g. NaCl/Carnallitic brine

Cavern divided in 4 cuts according to the most recent echo survey.



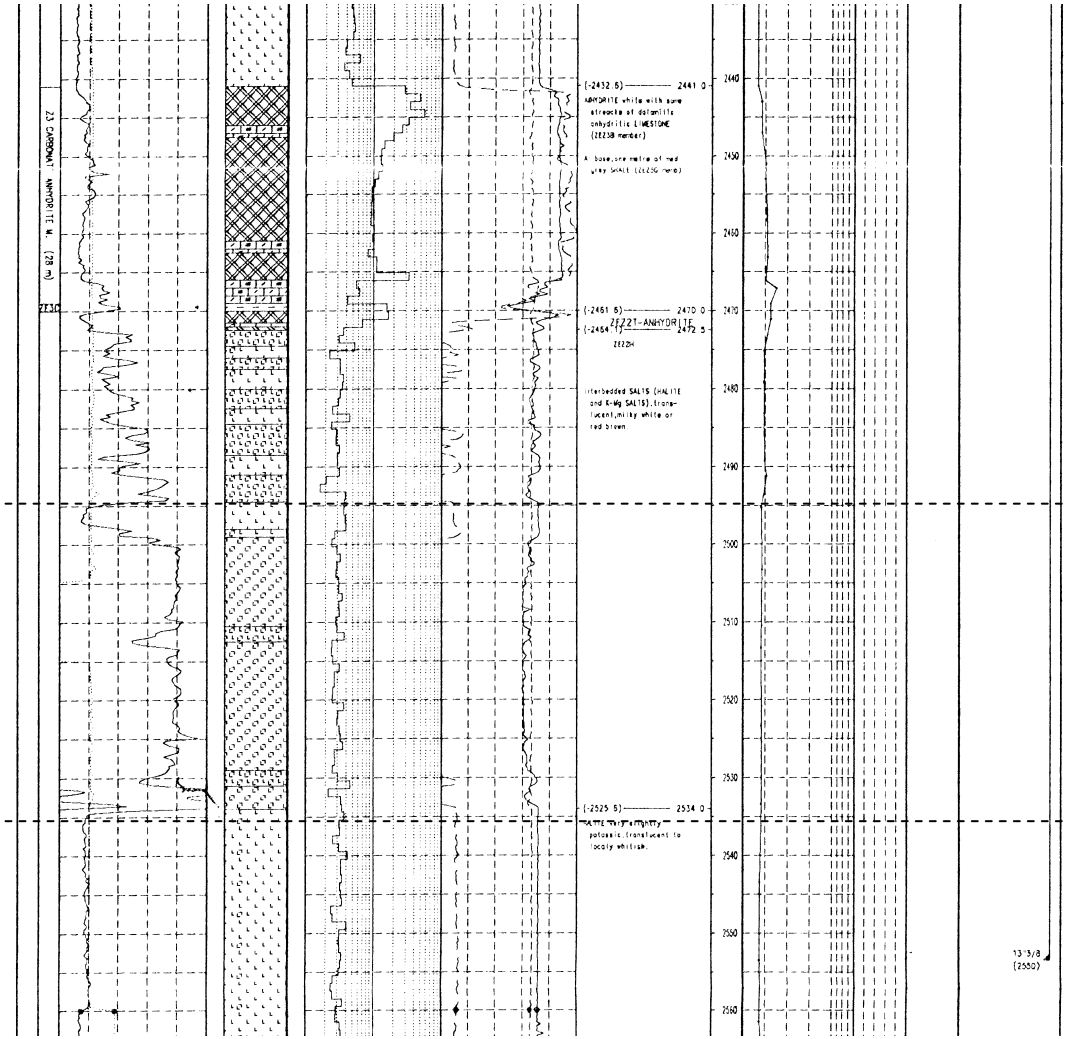
Convergence rate development

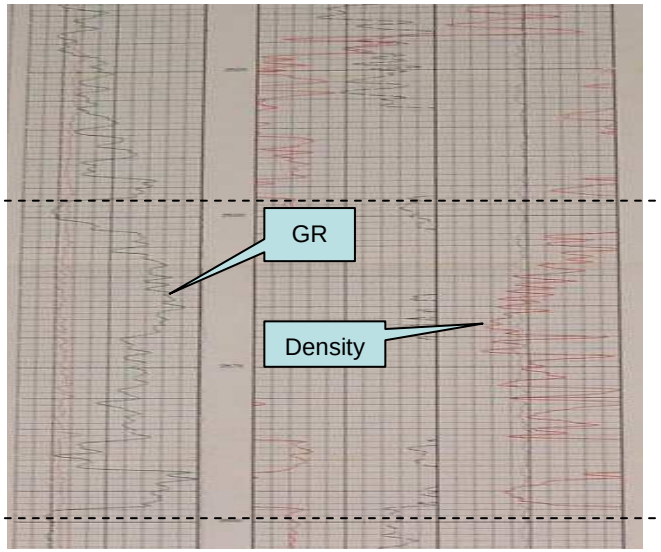


Worst case convergence rate

- The current cavern pressure at the top of the cavern is 20 bars below the estimated theoretical lithostatic pressure.
- The pressure differential between the actual lithostatic and cavern pressure however should be 0 in order for permeation to begin.
- Currently the 20 bars pressure differential at the top is used as driver for the squeeze and therefore permeation, this is a conservative estimation for the permeation rate.

BAS-2 Carnallite Anhydrite section

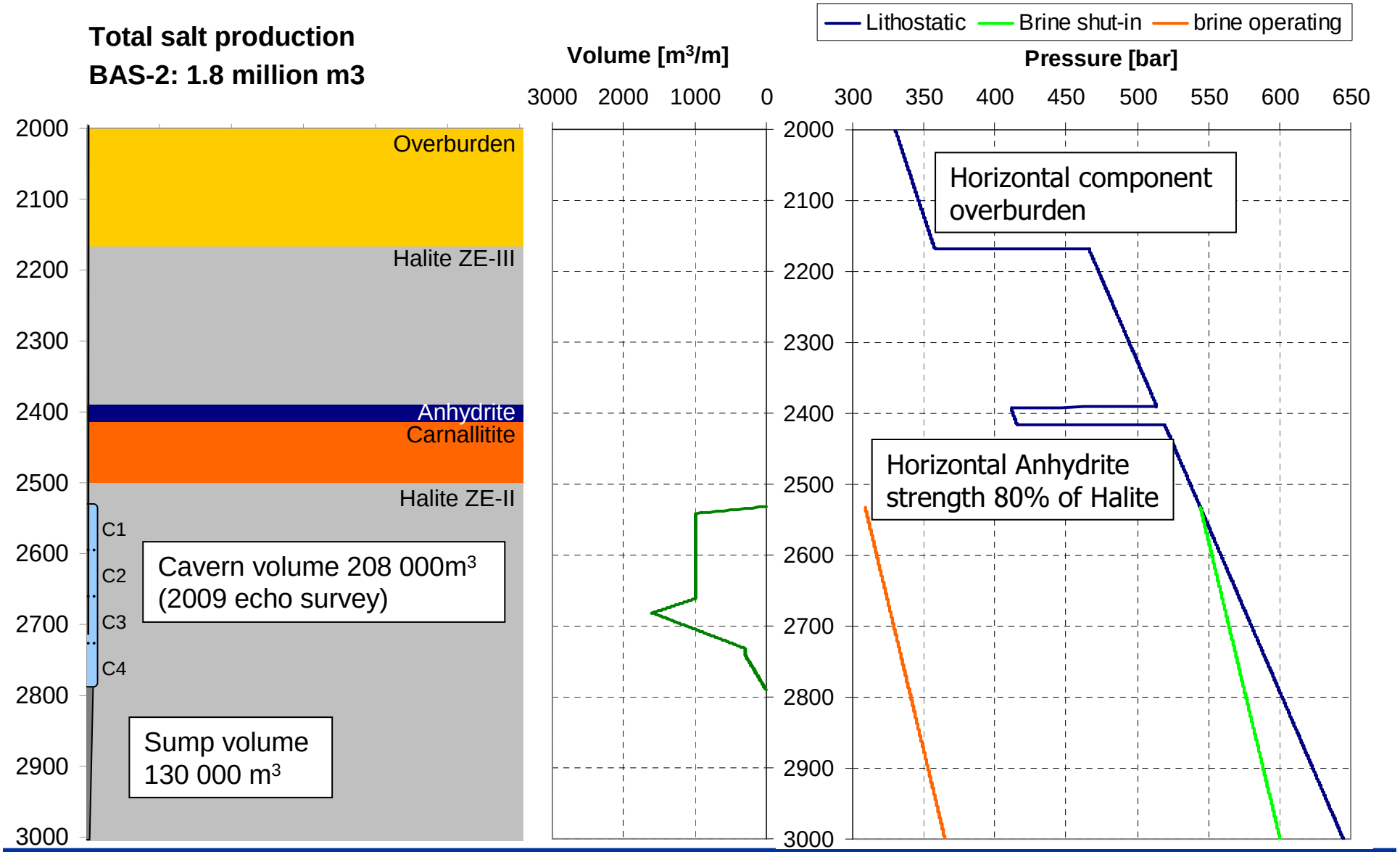




BAS-2 Assumed initial status

Total salt production

BAS-2: 1.8 million m3



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- **Sump compaction**
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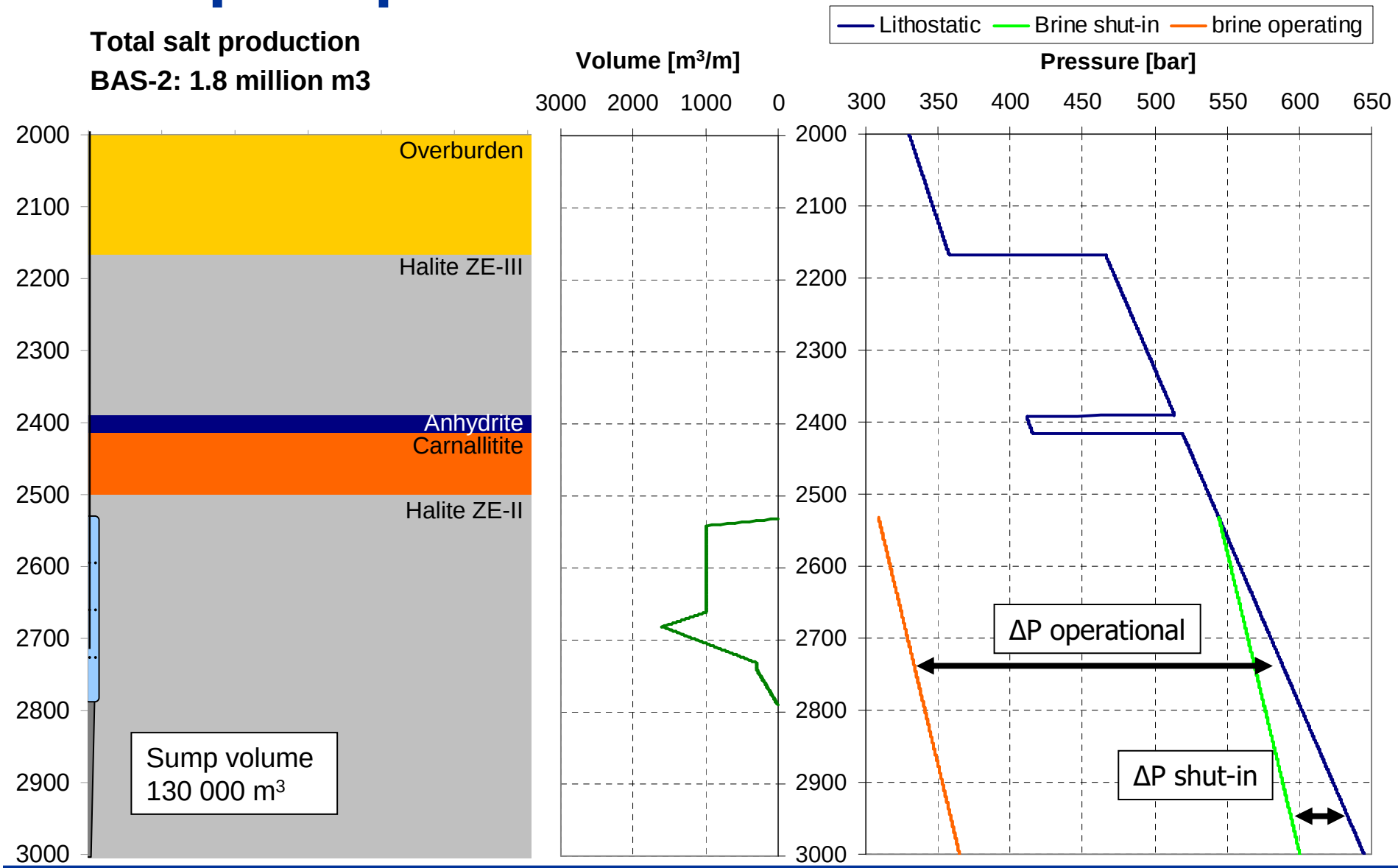
Sump compaction

Total salt production

BAS-2: 1.8 million m3



Sump compaction during operation

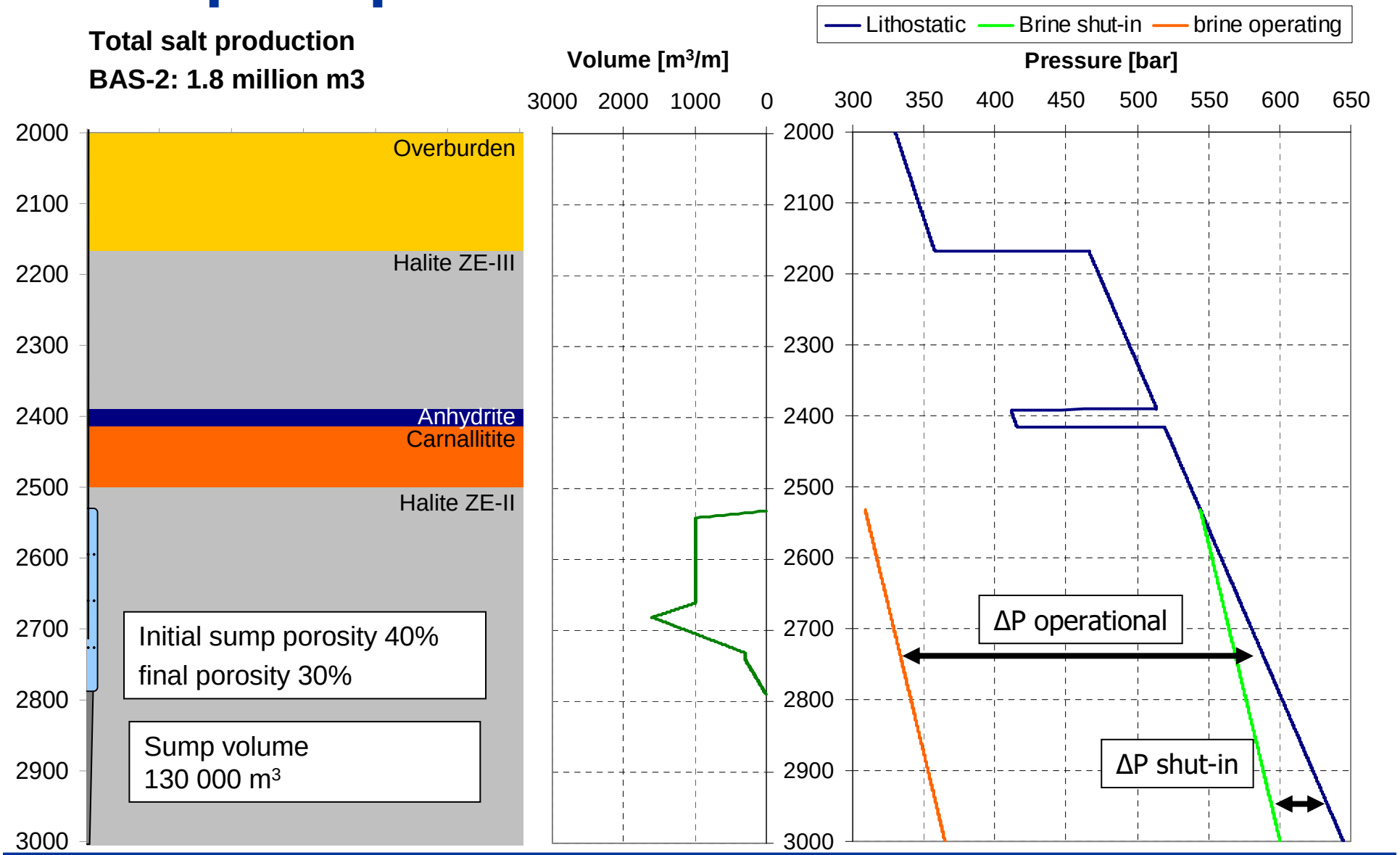
$$\sigma_{total} = \sigma_{grains} + \sigma_{pores}$$

$$\sigma_{grains} = P_{ltihostatic} - P_{cavern}$$

Sump compaction

Total salt production

BAS-2: 1.8 million m3



Content

- Introduction
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- Sump compaction
- **Well integrity**
- Permeation process
  - BAS-2
  - BAS-3

Well integrity

- The primary cementations of Bas-2 and Bas-3 were successful.
- The last cemented 13 3/8" / 14" casing was specifically designed to withstand lithostatic pressure.
- Due arching in the roof seal around the casing has been enhanced over time.
- During the long term observation of BAS-2 no irregularities of the wellbore have been noticed.

From this we conclude that the well is not likely to form a preferential leakpath.

Content

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- **Permeation process**
  - **BAS-2**
  - **BAS-3**

BAS-2 permeation

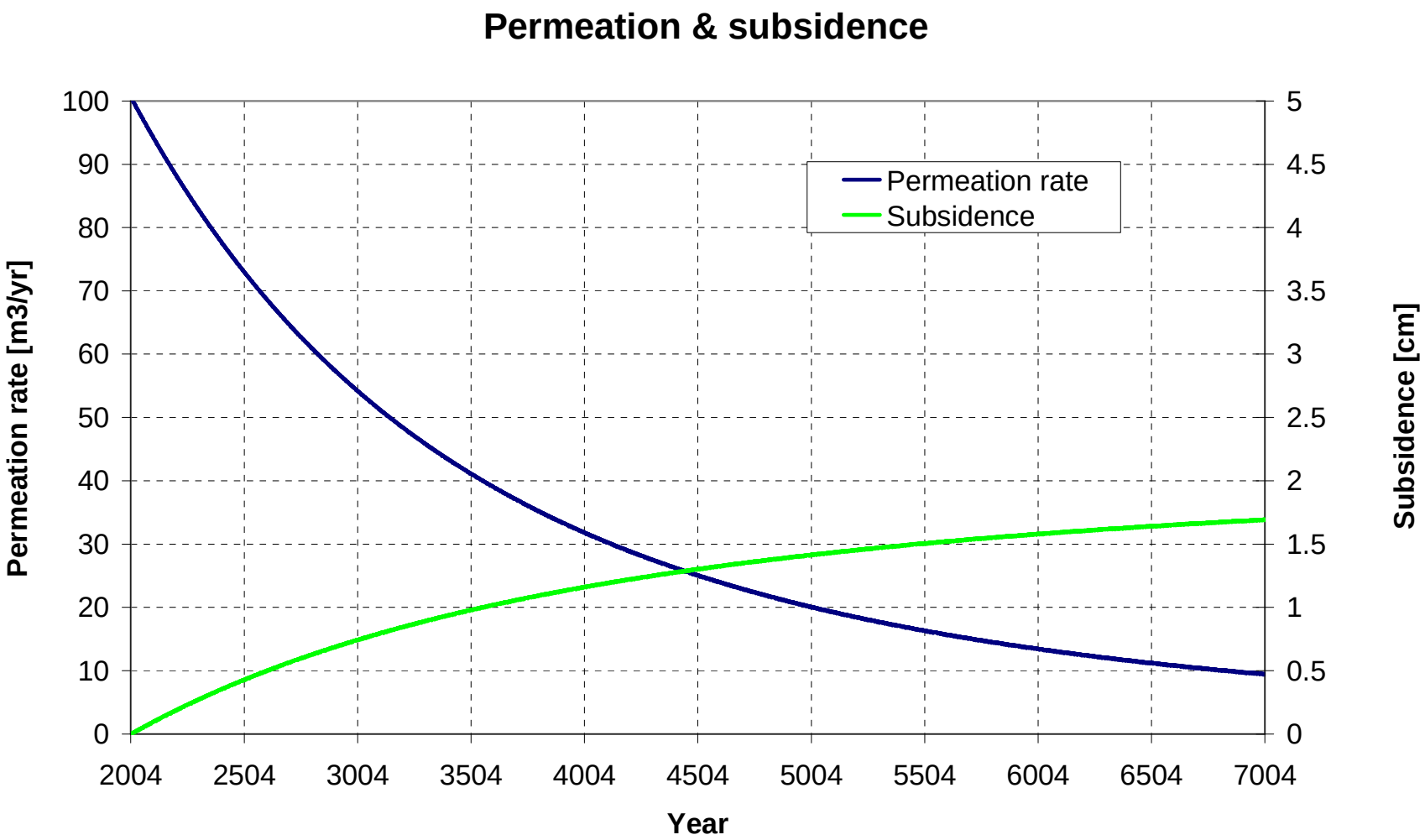
- Worst case
- With brine storage capacity

BAS-2 worst case permeation

Assumptions:

- 1 drop permeating from the cavern leads to 1 drop flowing into the overburden leading directly to subsidence. The primary porosity in the salt layer is brine filled under lithostatic pressure and can not be compressed.
- No secondary porosity is created, all of the fluid leaving the cavern will reach the overburden and lead to subsidence.
- Dynamic pressure loss in the permeation path is neglected while there will be resistance to flow in the narrow and tortuous flowpaths.
- Increased dynamic flow resistance due to recrystallisation of salts caused by cooling is neglected. Recrystallisation will occur in reality for NaCl as well as Carnallitic (Q) brines.
- Anhydrite layers do not have a barrier function.

Permeation leads directly to subsidence

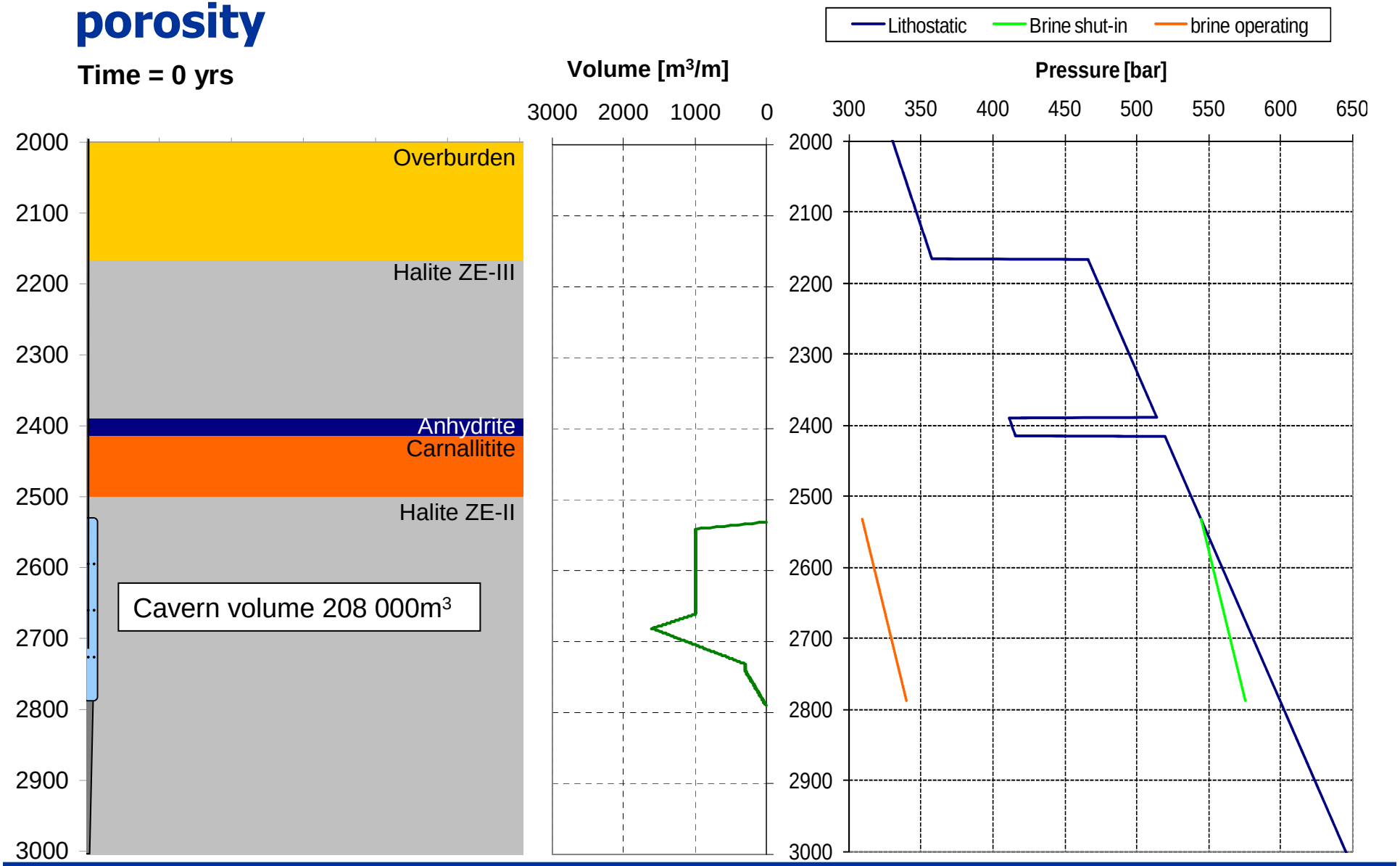


BAS-2 permeation with storage capacity

- Step by step for the 0.2 % secondary porosity scenario.

BAS-2 permeation process creating 0.2% secondary porosity

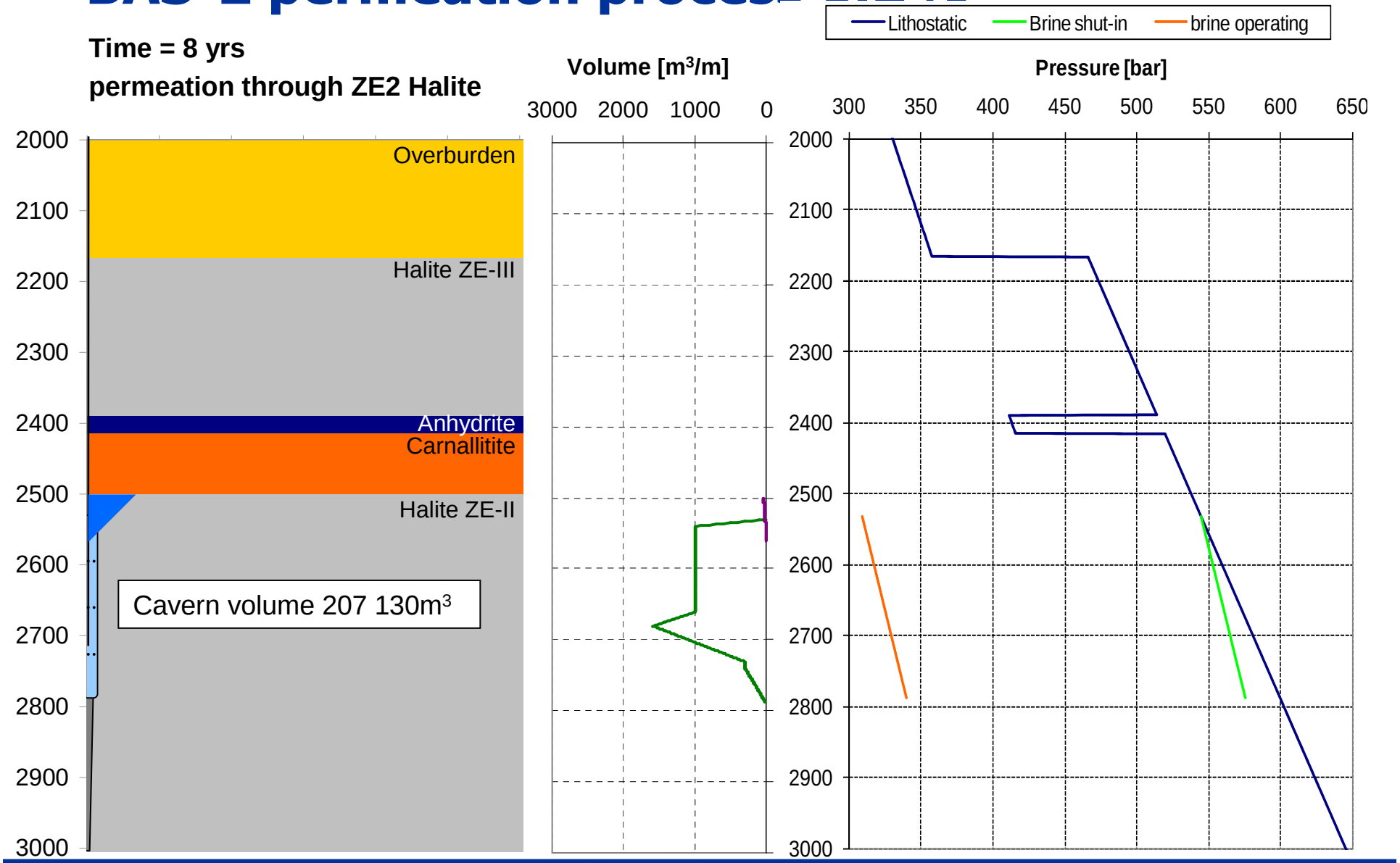
Time = 0 yrs



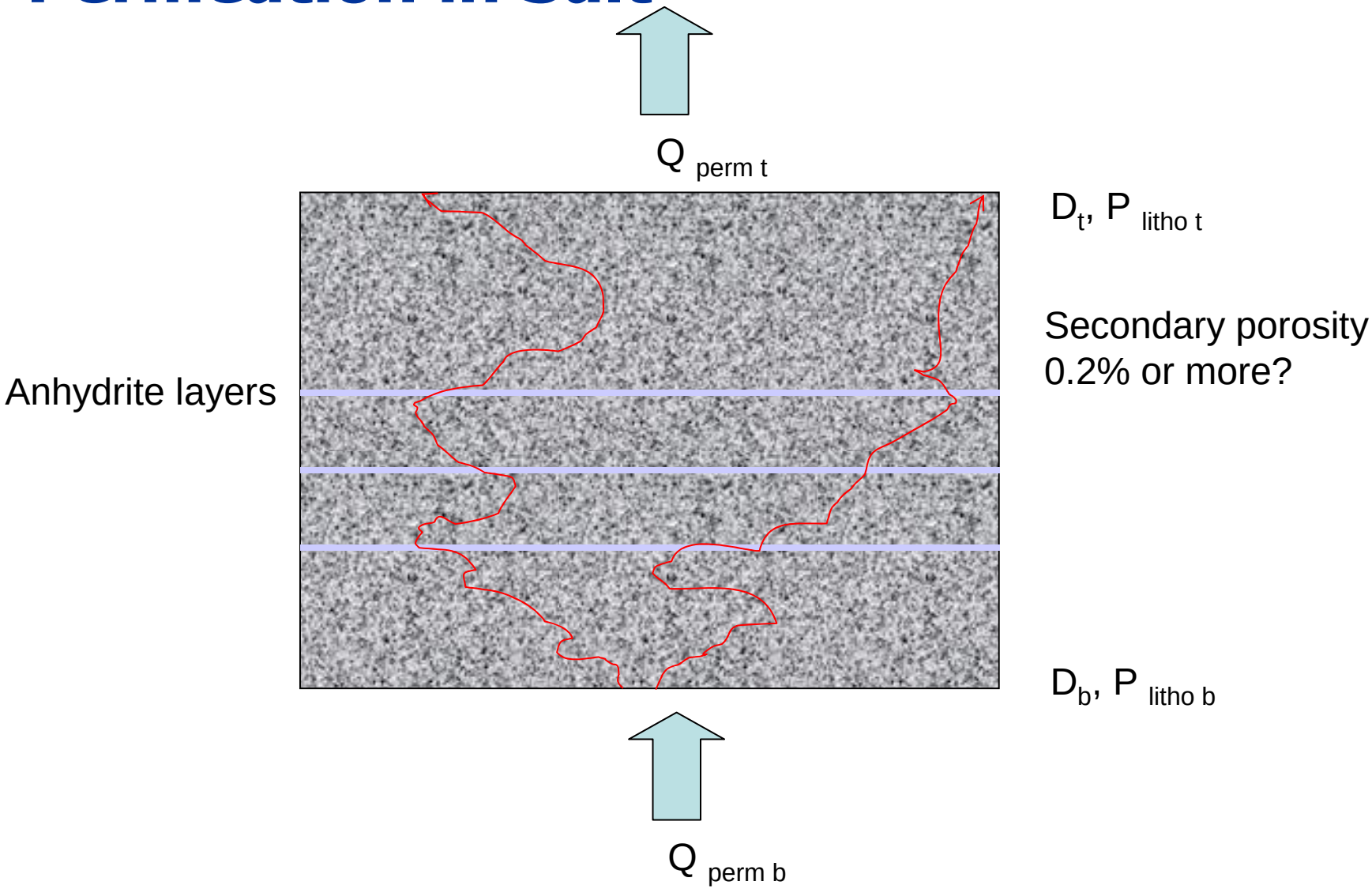
BAS-2 permeation process 0.2%

Time = 8 yrs

permeation through ZE2 Halite



Permeation in Salt



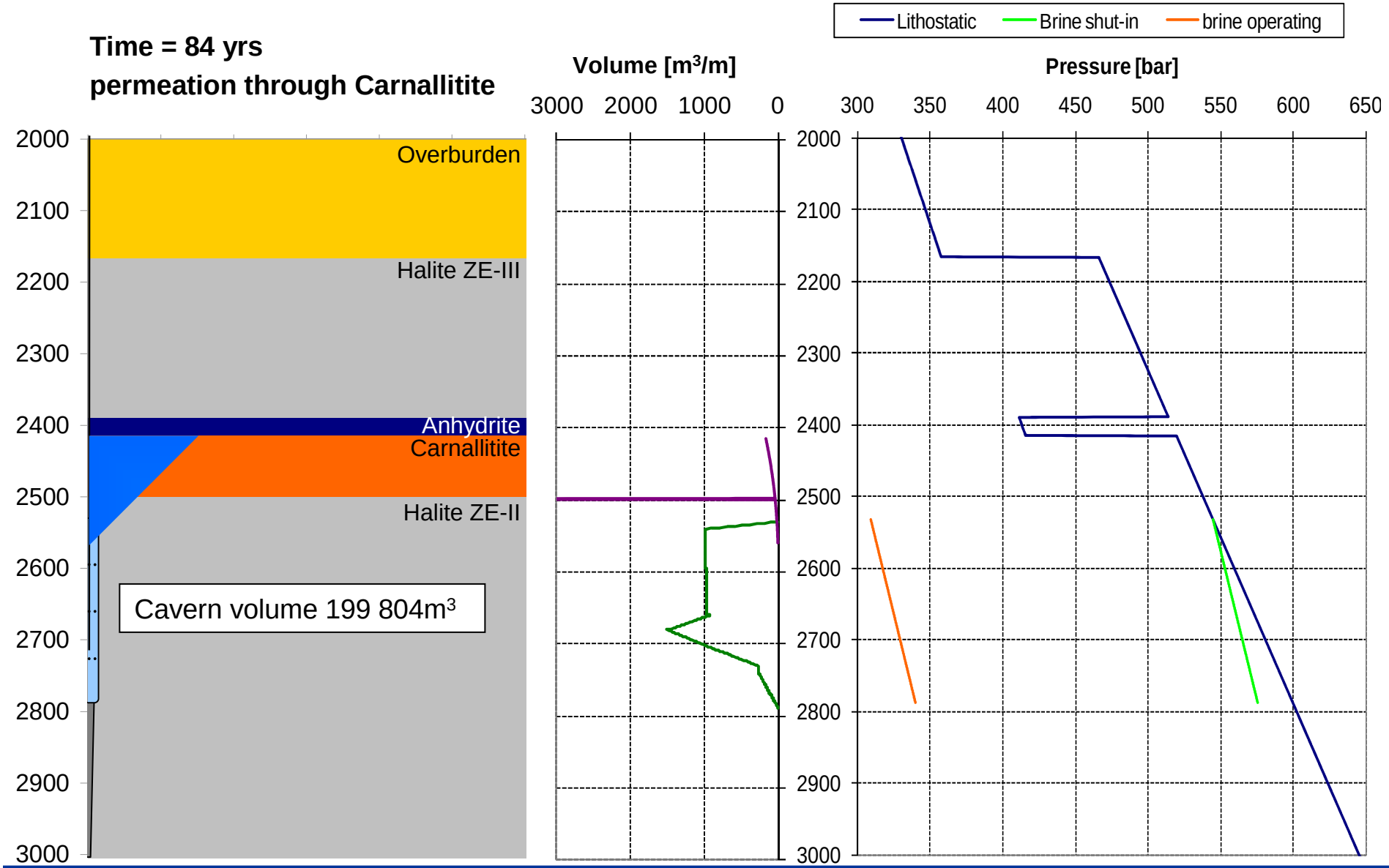
Step by step - Permeation of the roof between top cavern and carnallite

- The brine will start permeating in the top of the cavern with a 45 degree cone upwards.
- It permeates through the ZE2 Halite layer.
- This layer can store about 870 m^3 of brine assuming 0.2 % 'new' porosity (i.e. secondary porosity).
- As the salt mass above the cavern is lithostatically pressurised, the brine will be added to the existing rock volume.
- Volume lost in the cavern will be stored in the rock mass above the cavern, hence no volume reduction will occur.
- Without volume reduction there will be no subsidence.

BAS-2 permeation process 0.2%

Time = 84 yrs

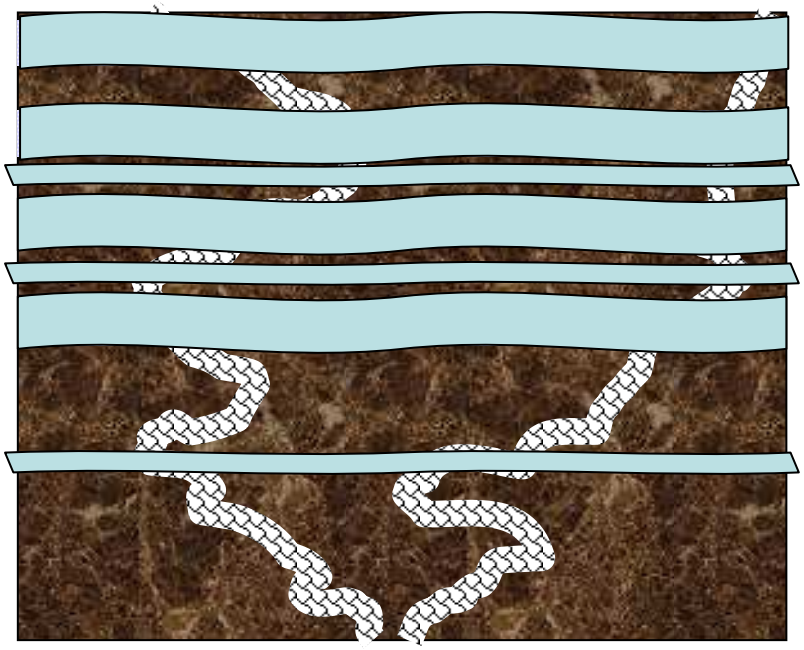
permeation through Carnallitite



Permeation in Carnallitite

$Q_{perm\ t}$

NaCl layers



D_t, $P_{litho\ t}$

Secondary porosity 0.2%?

Free brine volume at lithostatic conditions

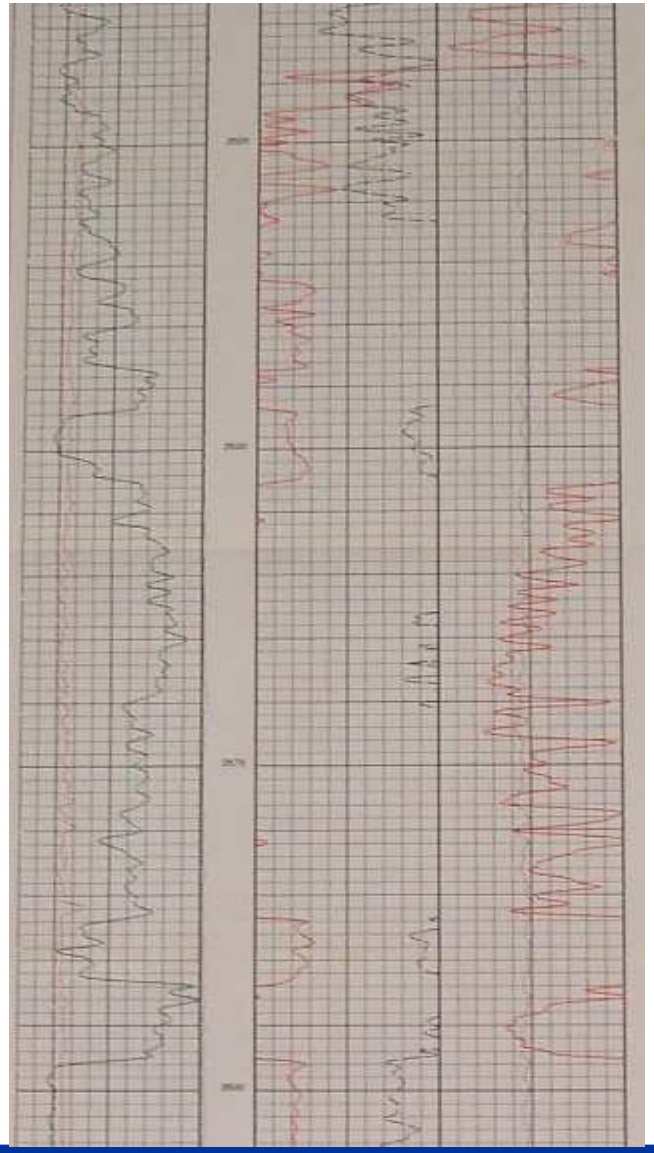
Bulking effect

D_b, $P_{litho\ b}$

$Q_{perm\ b}$

Composition of the Carnallitite

BAS-2 GR & Density >



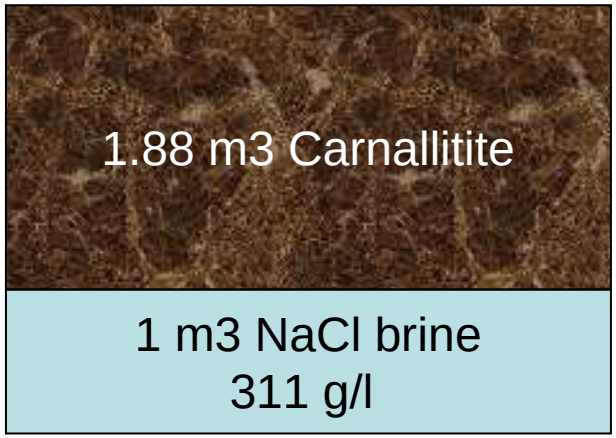
Two types of carnallite sections in the Carnallitite are identified:
•High grade 55% carnallite mineral.
•Low grade 30% carnallite mineral.

These layers are interbedded with NaCl layers.

It can be seen that the high grade layers are at the bottom and the low grade layers at the top.

Source NG

Dissolution of 55% Carnallitite by NaCl brine



Total = 2.88 m^3

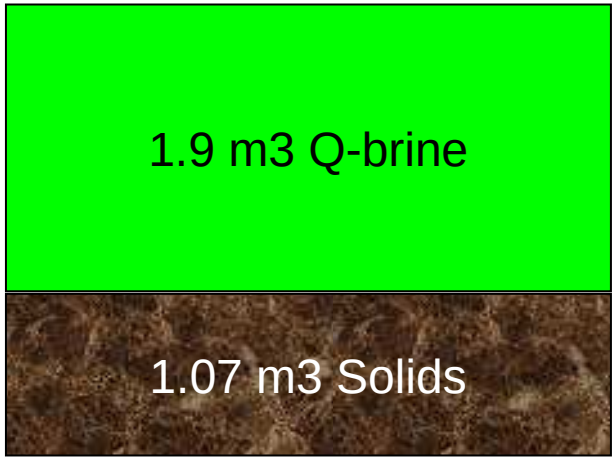
1 m3 NaCl brine affects 1.88 m3 55% Carnallitite @ 85 degC:

Volumetric composition carnallitite:

0.13 m^3	Kieserite ($MgSO_4 \cdot H_2O$)
1.20 m^3	Carnallite ($KMgCl_3 \cdot 6(H_2O)$)
0.04 m^3	Sylvite (KCl)
0.42 m^3	Halite (NaCl)
0.09 m^3	Insolubles (e.g. clays & anhydrite)
total	1.88 m^3

Source NG

Dissolution of 55% Carnallitite by NaCl brine



Total = 2.97 m^3

After complete conversion of NaCl brine into Q-brine @ 85 degC and 55% carnallite content:

Solids
0.28 m^3 Kainite ($MgSO_4 \cdot KCl \cdot 3H_2O$)
0.14 m^3 Sylvite (KCl)
0.56 m^3 Halite (NaCl)
0.09 m^3 Insolubles (e.g. clays & anhydrite)
Subtotal 1.07 m^3

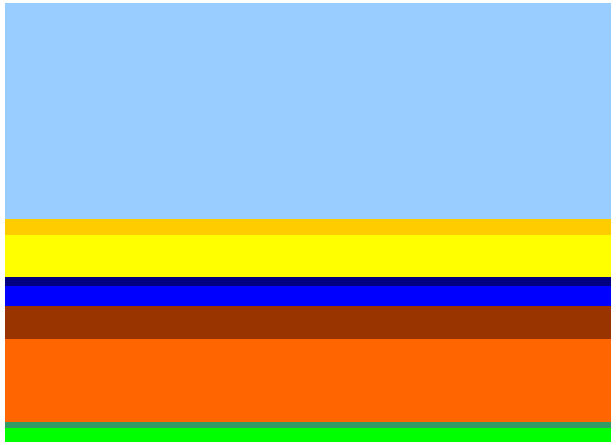
Fluid
1.90 m^3 Q-brine

Total 2.97 m^3

Source NG

Mass balance: new = old
but 0.09 m^3 volume created

Dissolution 55% Carnallitite by NaCl brine



The solids will bulk up and the pores will be filled with brine
Distribution Q brine after conversion

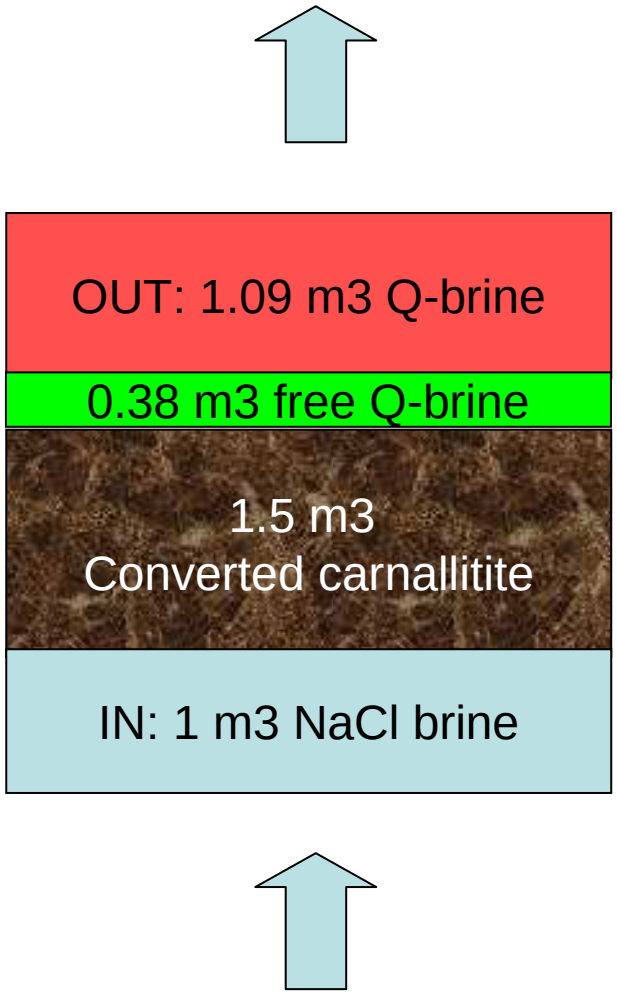
Solids	Bulked	
0.28 m^3	0.39 m^3	Kainite
0.14 m^3	0.20 m^3	Sylvite
0.56 m^3	0.79 m^3	Halite
0.09 m^3	0.12 m^3	Insolubles
1.07 m^3	1.50 m^3	Subtotal

Fluids
1.47 m^3 free Q-brine
0.43 m^3 Q-brine in pores

Total 2.97 m^3

Source NG

Permeation through 55% Carnallitite at lithostatic conditions



Volumetric effects of permeation of NaCl brine through 55% carnallitite @ 85degC at lithostatic conditions :

Solids	Bulked	
0.28 m^3	0.39 m^3	Kainite
0.14 m^3	0.20 m^3	Sylvite
0.56 m^3	0.79 m^3	Halite
0.09 m^3	0.12 m^3	Insolubles
1.07 m^3	1.50 m^3	Subtotal

Fluids

0.38 m3 free Q-brine

0.43 m^3 Q-brine in pores

Total 1.88 m^3

Source NG

BAS-2 total Carnallitite conversion

TOP	Thickness	Carnallitite %	Volume	Carnallite volume	NaCl brine used	Carnallite dissolved	Carnallite left	Insolubles created	Bulked insolubles	Pore volume	Free volume created	Volume permeating further	Volume stored in Carnallite
[m] TVD	[m]		m3	m3	m3	m3	m3	m3	m3	m3	m3	m3	m3
2415	5	30%	400	400	0	0	400	0	0	0	0	0	0
2420	5	0%	375	0	0	0	0	0	0	0	0	0	0
2425	15	30%	985	985	0	0	985	0	0	0	0	0	0
2440	5	0%	284	0	0	0	0	0	0	0	0	0	0
2445	5	55%	263	263	0	0	263	0	0	0	0	0	0
2450	5	0%	244	0	0	0	0	0	0	0	0	0	0
2455	35	55%	1212	1212	145	273	939	218	281	63	214	158	118
2490	5	0%	112	0	0	0	0	0	0	0	0	0	0
2495	6	55%	118	118	63	118	0	94	121	27	92	68	51
SUM	86		3992	2978	208	391	2587	312	401	89	306	227	0

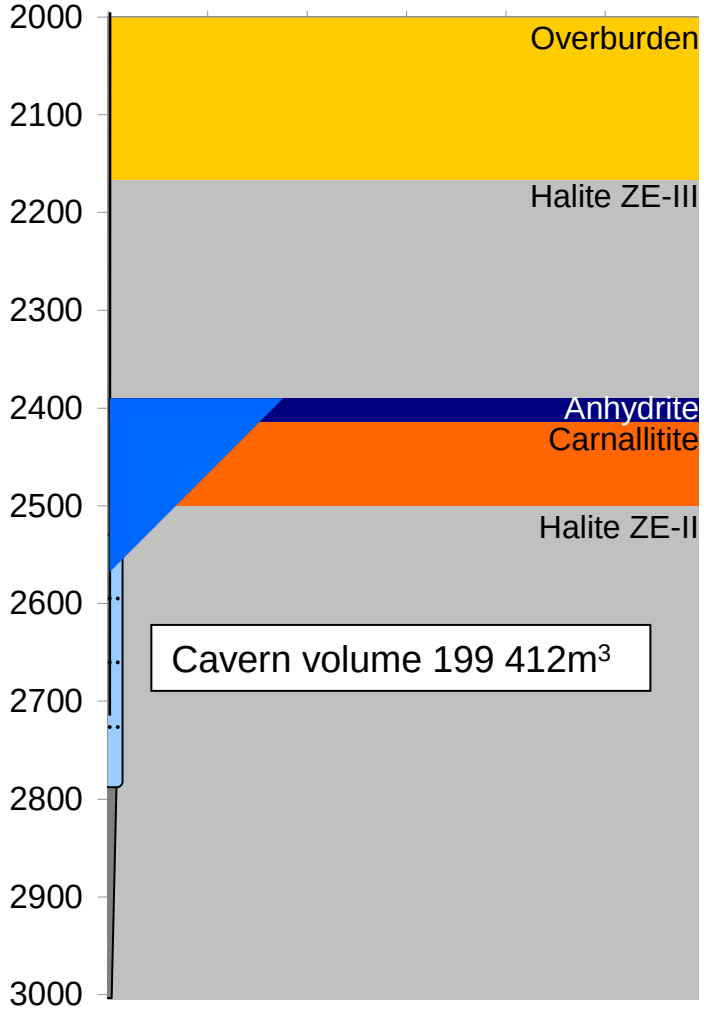
Step by step

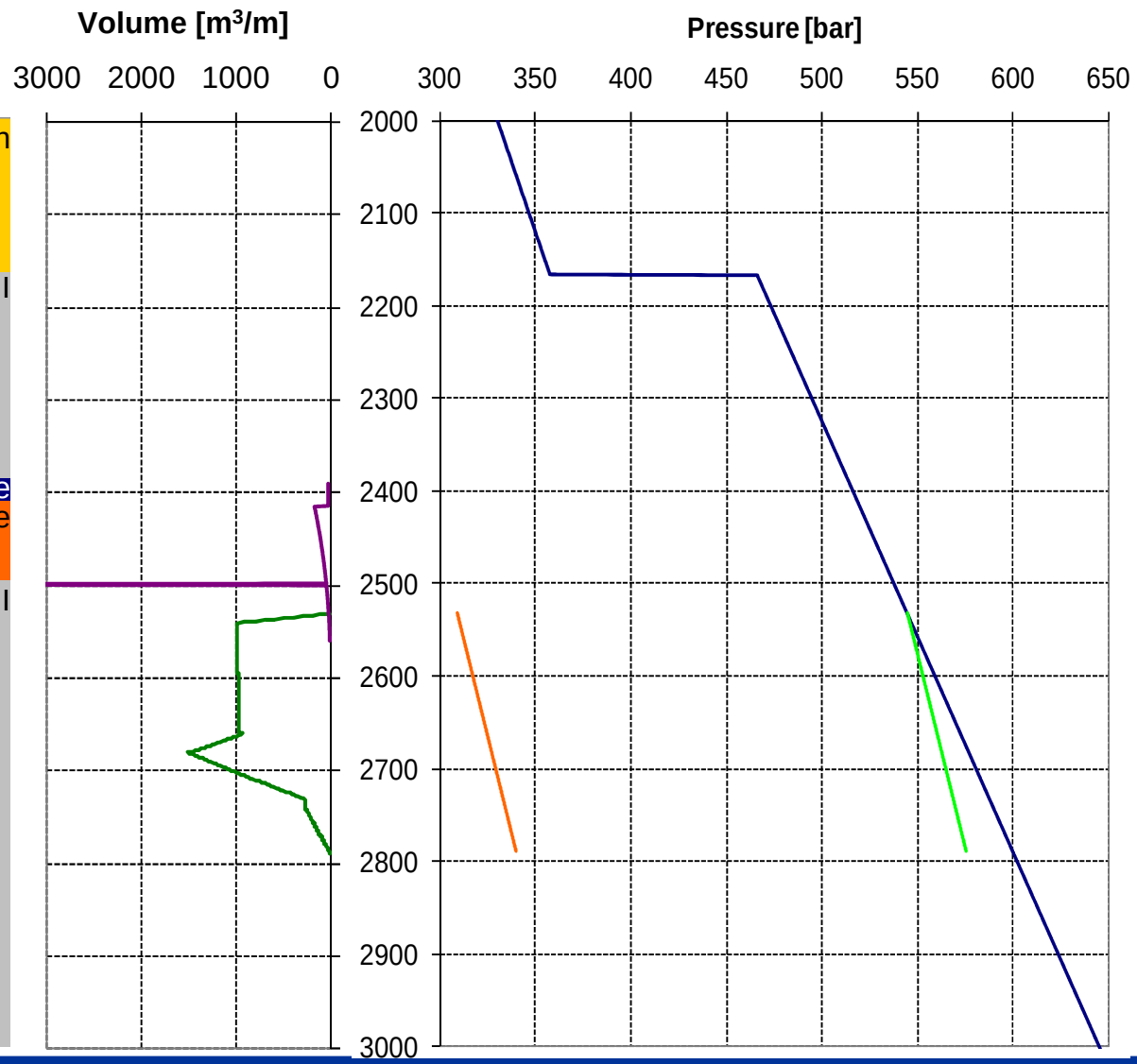
- The brine will continue permeating through the carnallitite layer.
- The NaCl brine is transformed into Q brine.
- There is a net volume increase of 9% this will lead to extra permeation.
- There is enough Carnallite available to transform the complete cavern volume into Q brine.
- Formed Q-brine will stay in the carnallite partially in the pore space and partially as free volume. This free volume has little height and therefore hardly any drive for further permeation.
- This layer can store about 8000 m^3 of brine assuming a 0.2% porosity on top of the created pore space and free volume.

BAS-2 permeation process 0.2%

Time = 88 yrs

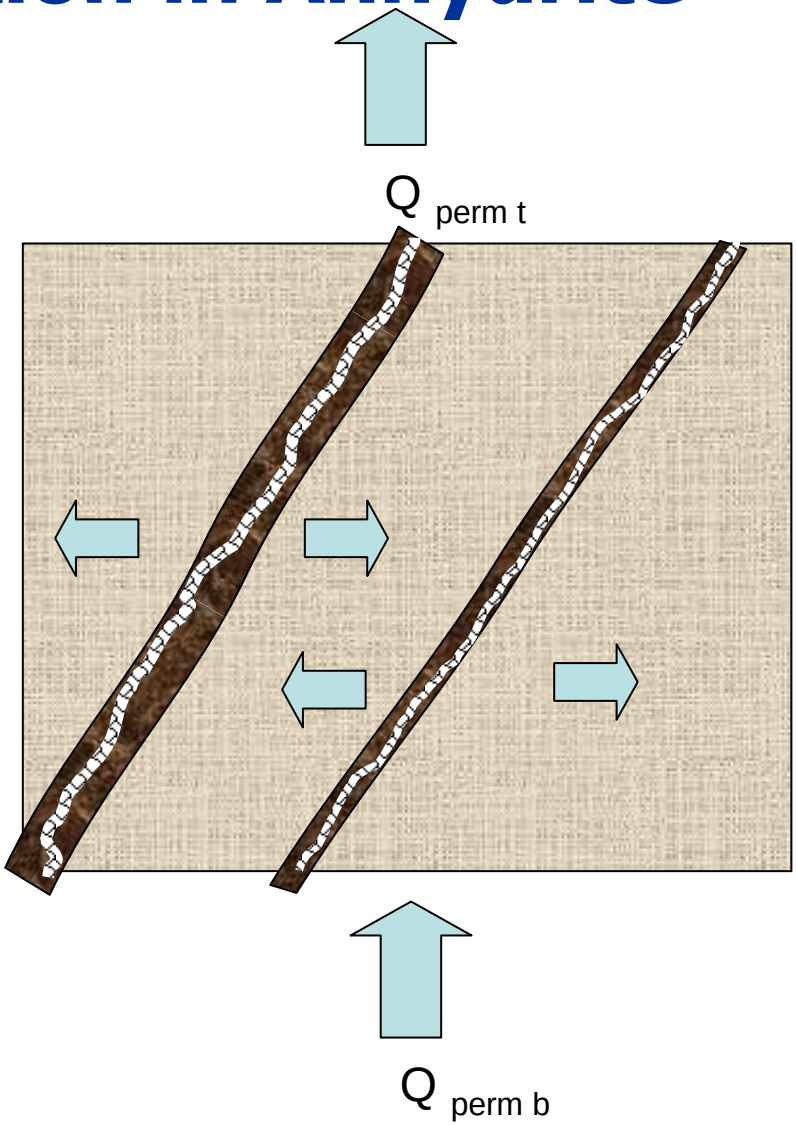
Compressing Anhydrite





Permeation in Anhydrite

Carnallite intrusions



D_t, $P_{v,\ litho\ t}$

Secondary porosity negligible

$P_h < P_v$

Flow resistance high?

Bulking effect negligible

D_b, $P_{v,\ litho\ b}$

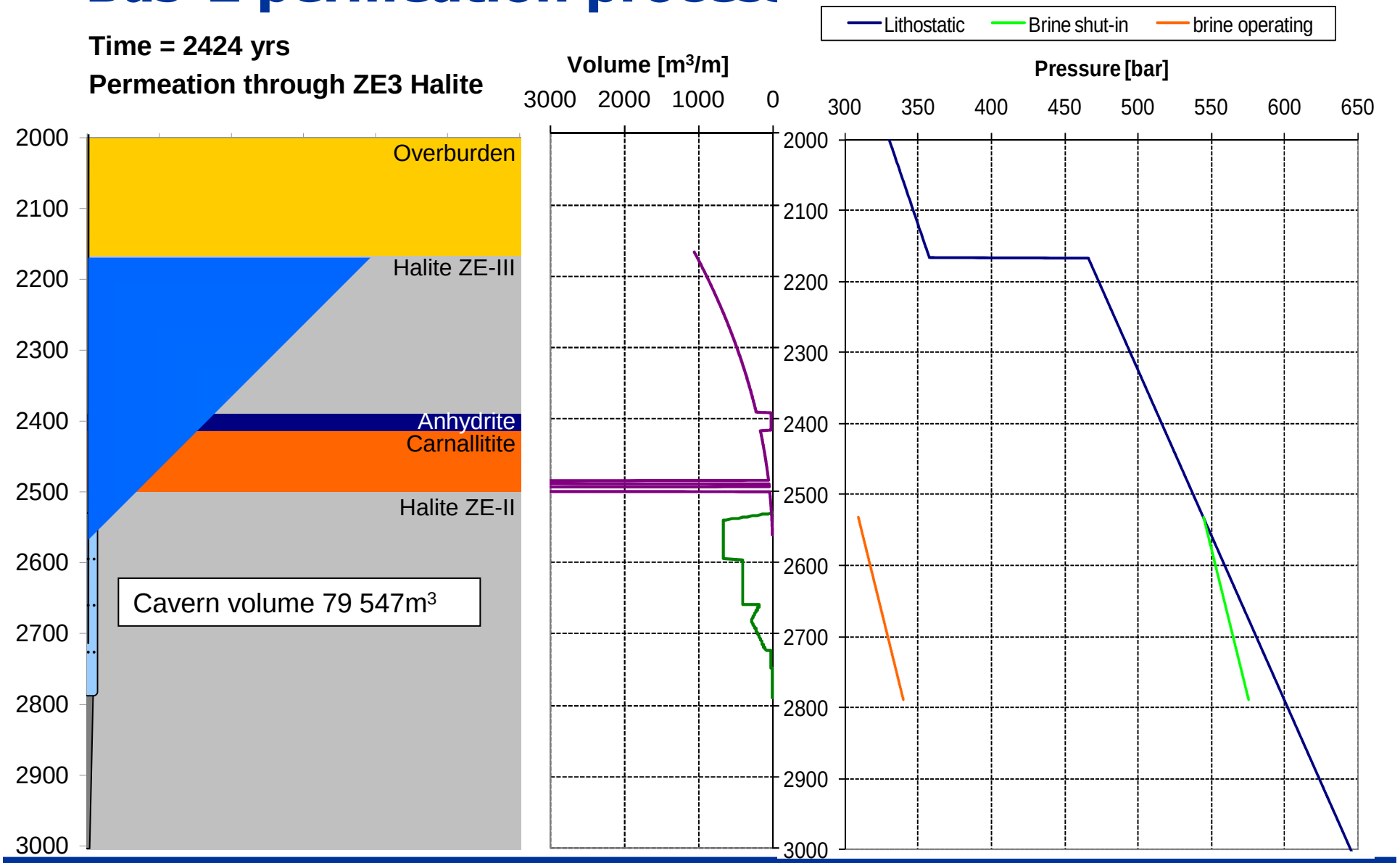
Step by step

- The brine will continue permeate through the cracks in the Anhydrite.
- This layer does not have a porosity but can store 430m^3 of brine due to compression of the anhydrite.

Bas-2 permeation process 0.2%

Time = 2424 yrs

Permeation through ZE3 Halite



Step by step

- The brine will continue permeating through the ZE3 Halite layer.
- This layer can store about 130 000 m^3 of brine assuming a 0.2 % secondary porosity.

BAS-2 summary table volumes 0.2%

	Time	Convergence	Caverne volume	ZE-2 NaCl pores	Undisolved Carnallitite secondary pores	Carnallitite pores and free volume	Anhydrite	ZE-3 pores	Overburden	NaCl brine	Carnallitic brine	Total fluid volume	Subsidence
Initial	0	0	208	0	0	0	0	0	0	208	0	208	0.0
Untill Carnalite	8	1	207	0.9	0	0	0	0	0	208	0	208	0.0
Untill anhydrite	84	8	200	0.9	7.8	6	0	0	0	201	14	214	0.0
Untill Z3	88	9	199	0.9	7.8	6	0.4	0	0	200	14	215	0.0
untill Overburden	2424	128	80	0.9	7.4	103	0.4	131	0	80	242	322	0.0
Final	5000	169	39	0.9	7.3	137	0.4	131	45	39	320	360	0.5

Time in years, volumes in 1000 m3 and subsidence in cm

Higher secondary porosity

- If a higher secondary porosity is used for instance 1% or 2% the brine will not reach the overburden.
- When the brine does not reach the overburden, there will be no subsidence.

Higher secondary porosity

0.2%, 1% and 2% after 5000 yrs

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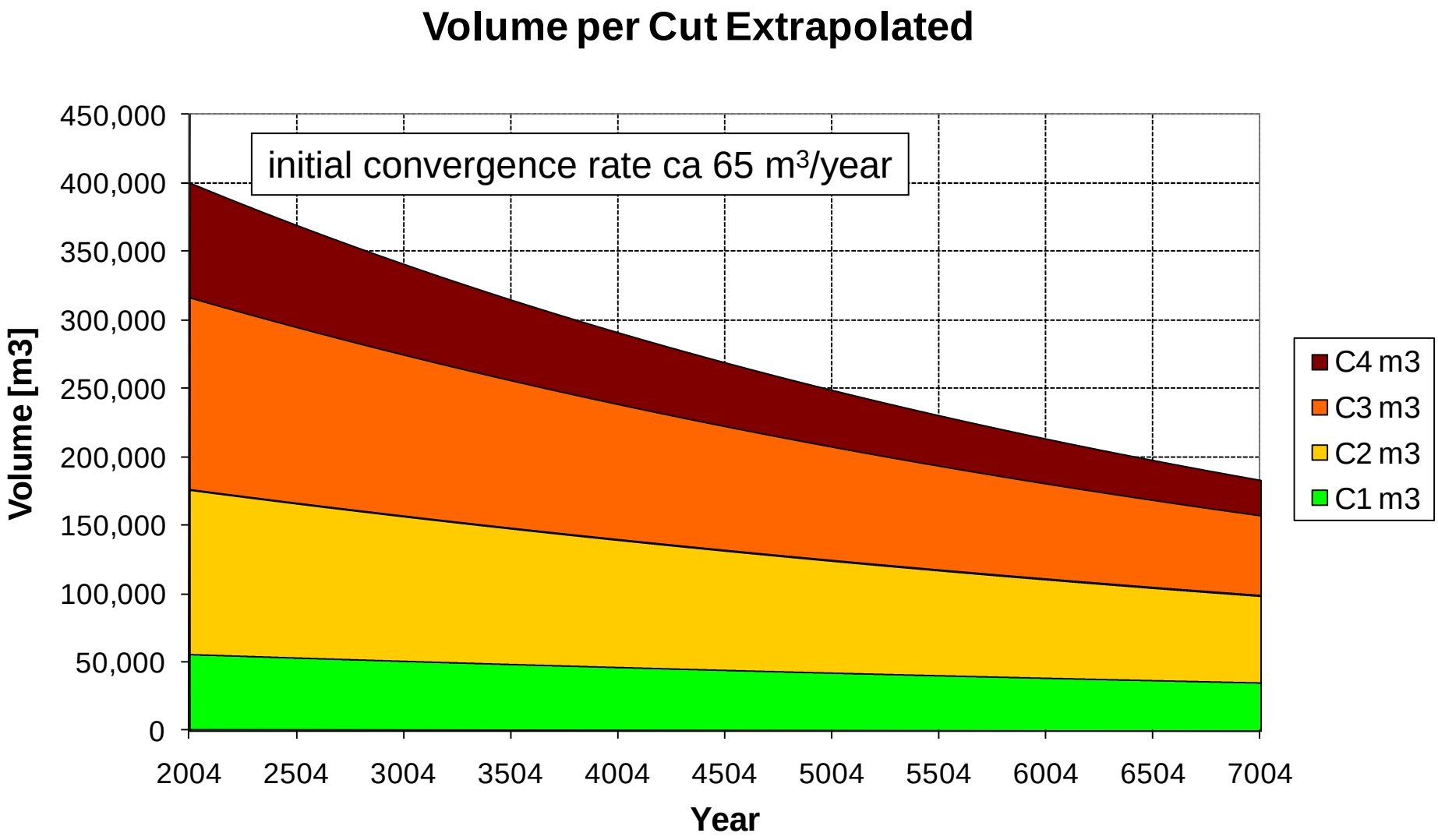
  - **BAS-3**

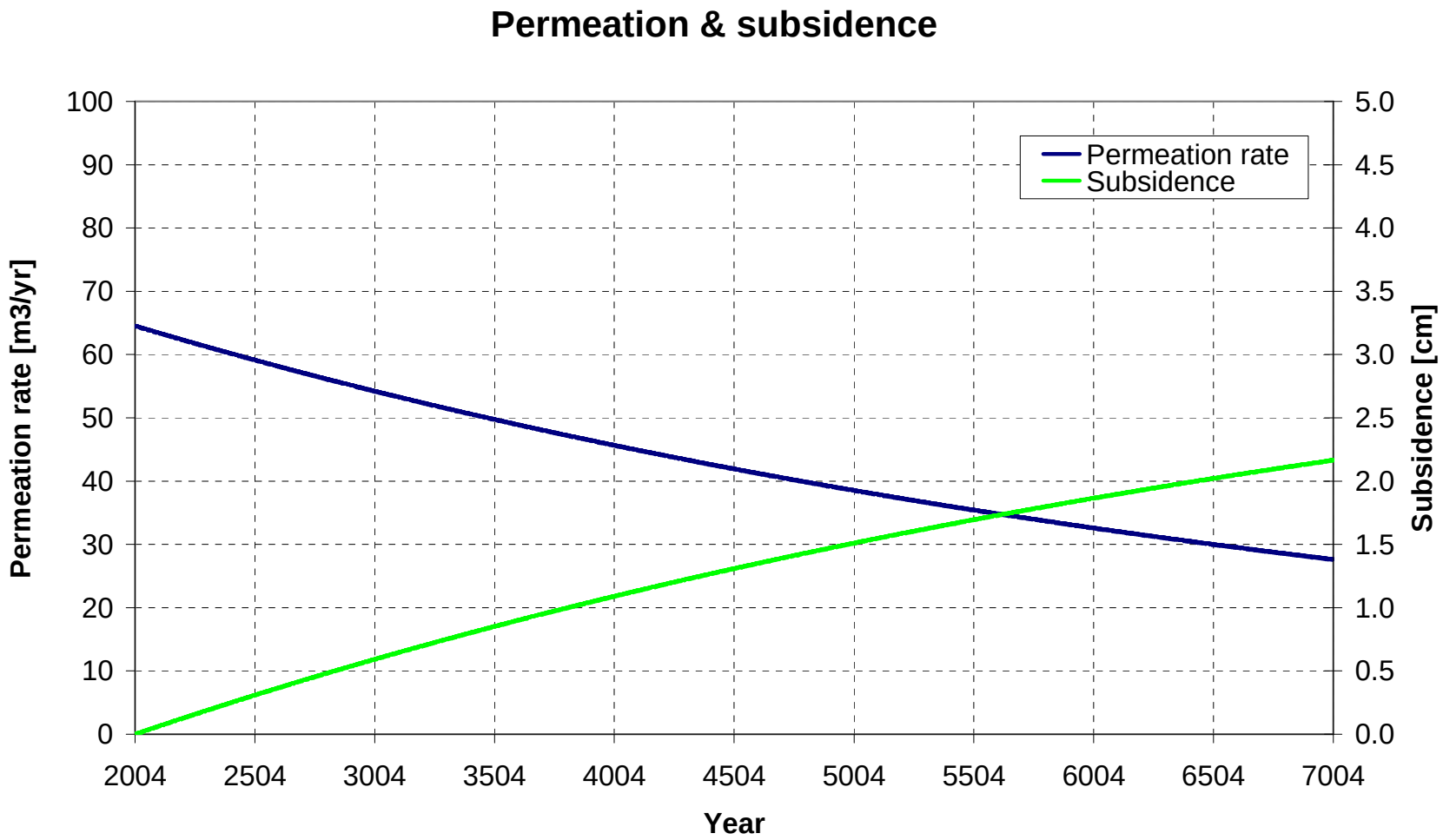
BAS-3 permeation scenario 0.2% secondary porosity

- Process identical to BAS-2, same worst case approach and a scenario with 0.2% secondary porosity.
- The convergence rate is slower than BAS-2 due to higher position and less cavern height. This can not be compensated by the bigger volume (almost 2 x BAS-2).

Convergence rate development

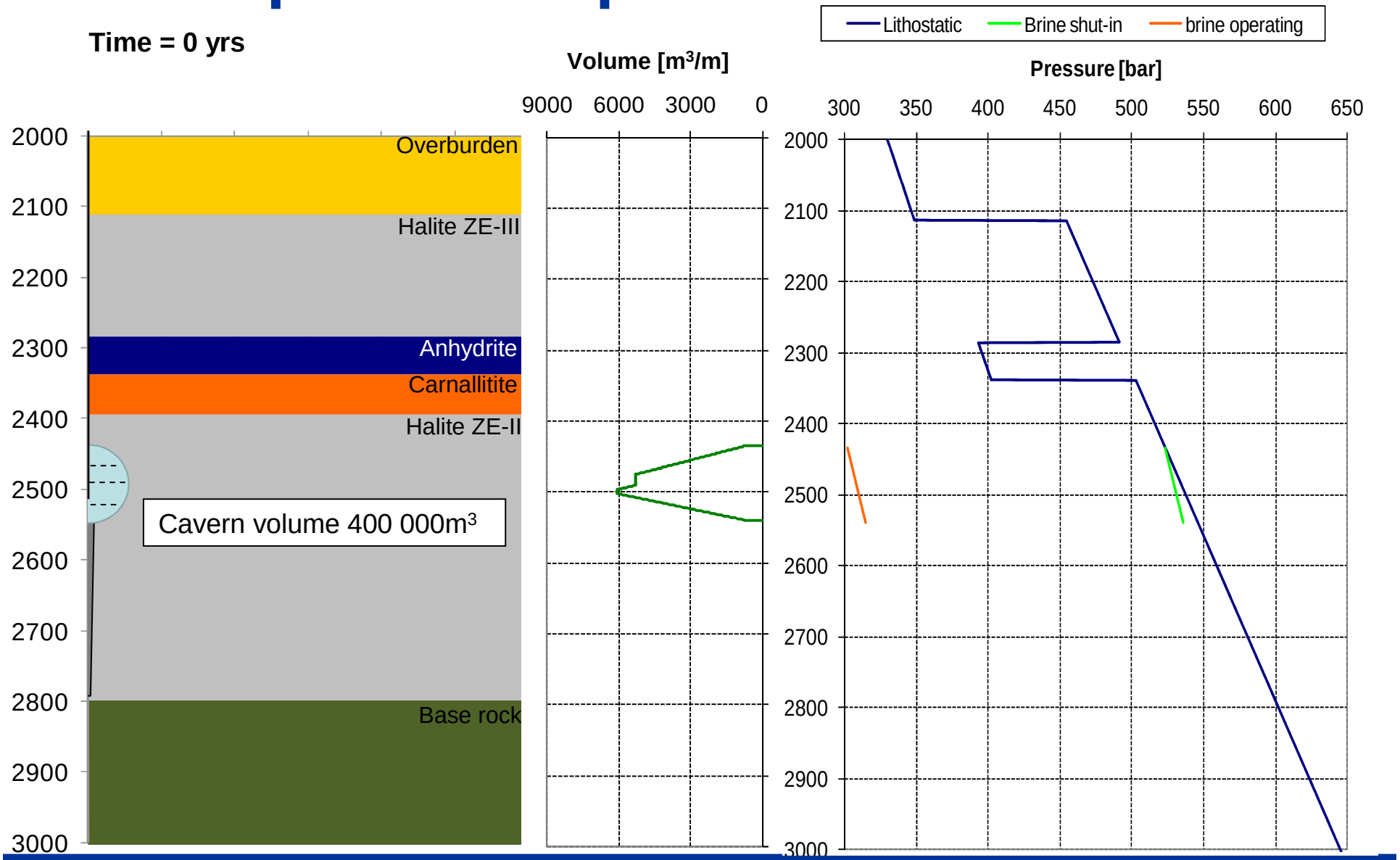


Permeation leads directly to subsidence



BAS-3 permeation process 0.2%

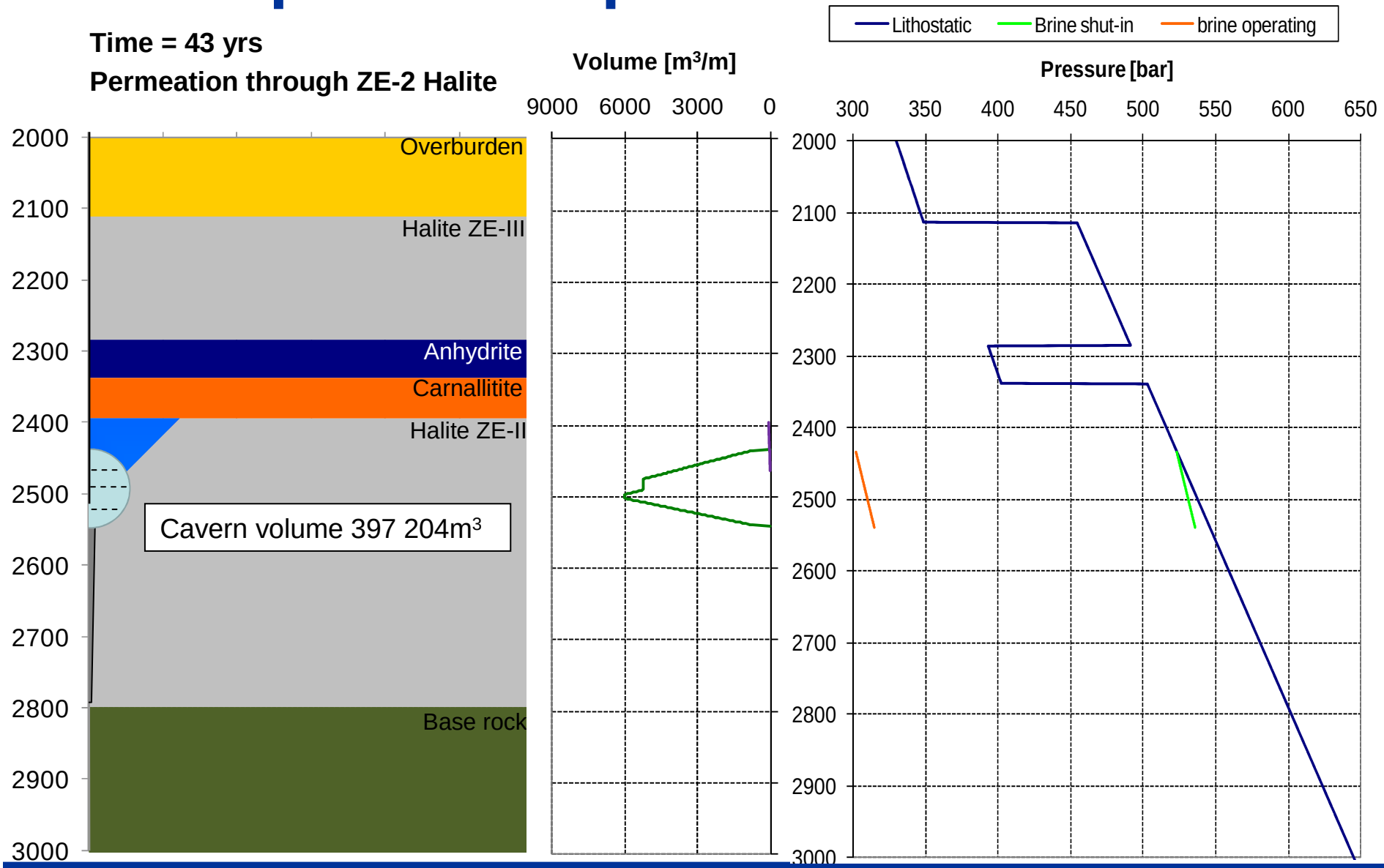
Time = 0 yrs



BAS-3 permeation process 0.2%

Time = 43 yrs

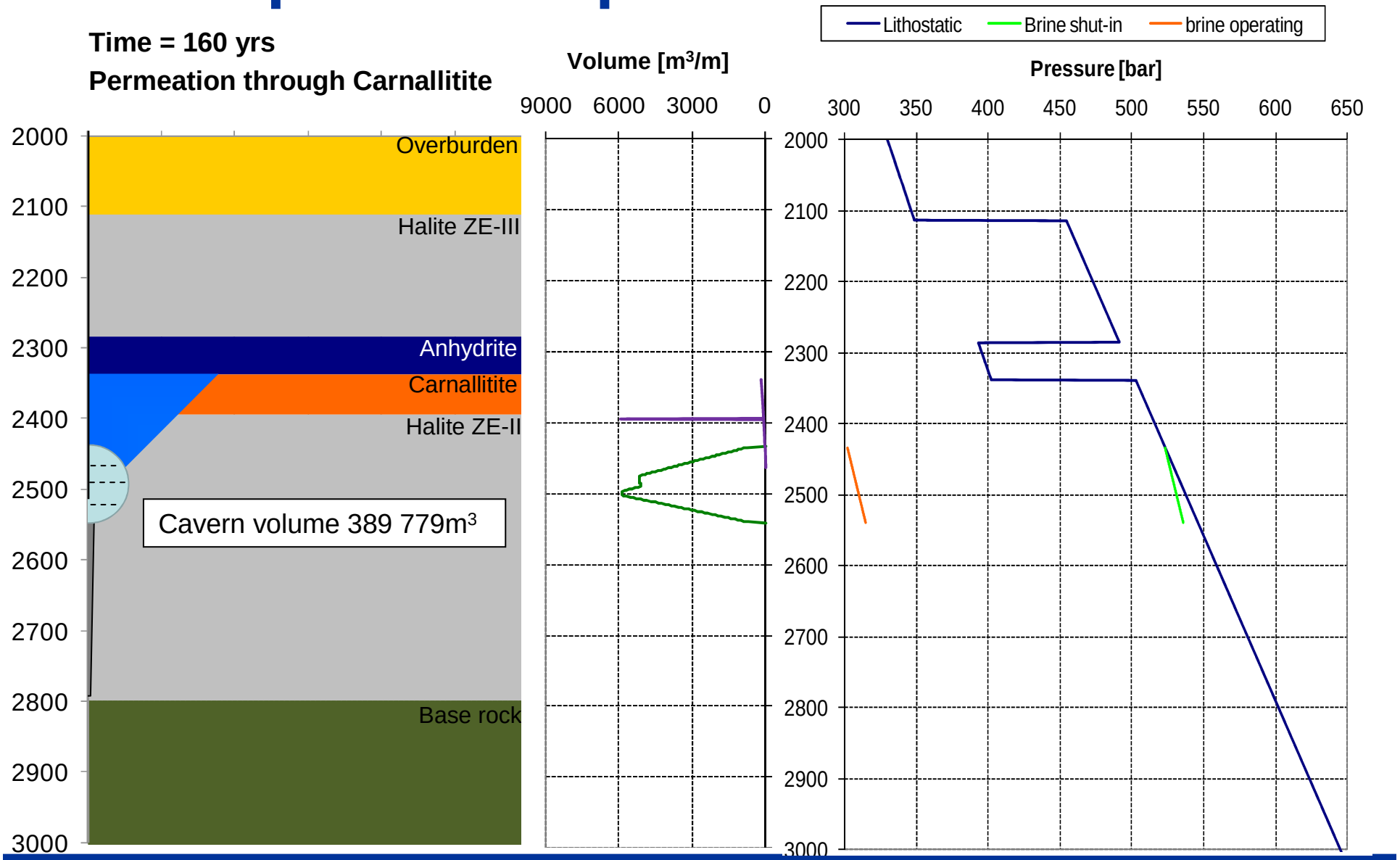
Permeation through ZE-2 Halite



BAS-3 permeation process 0.2%

Time = 160 yrs

Permeation through Carnallitite



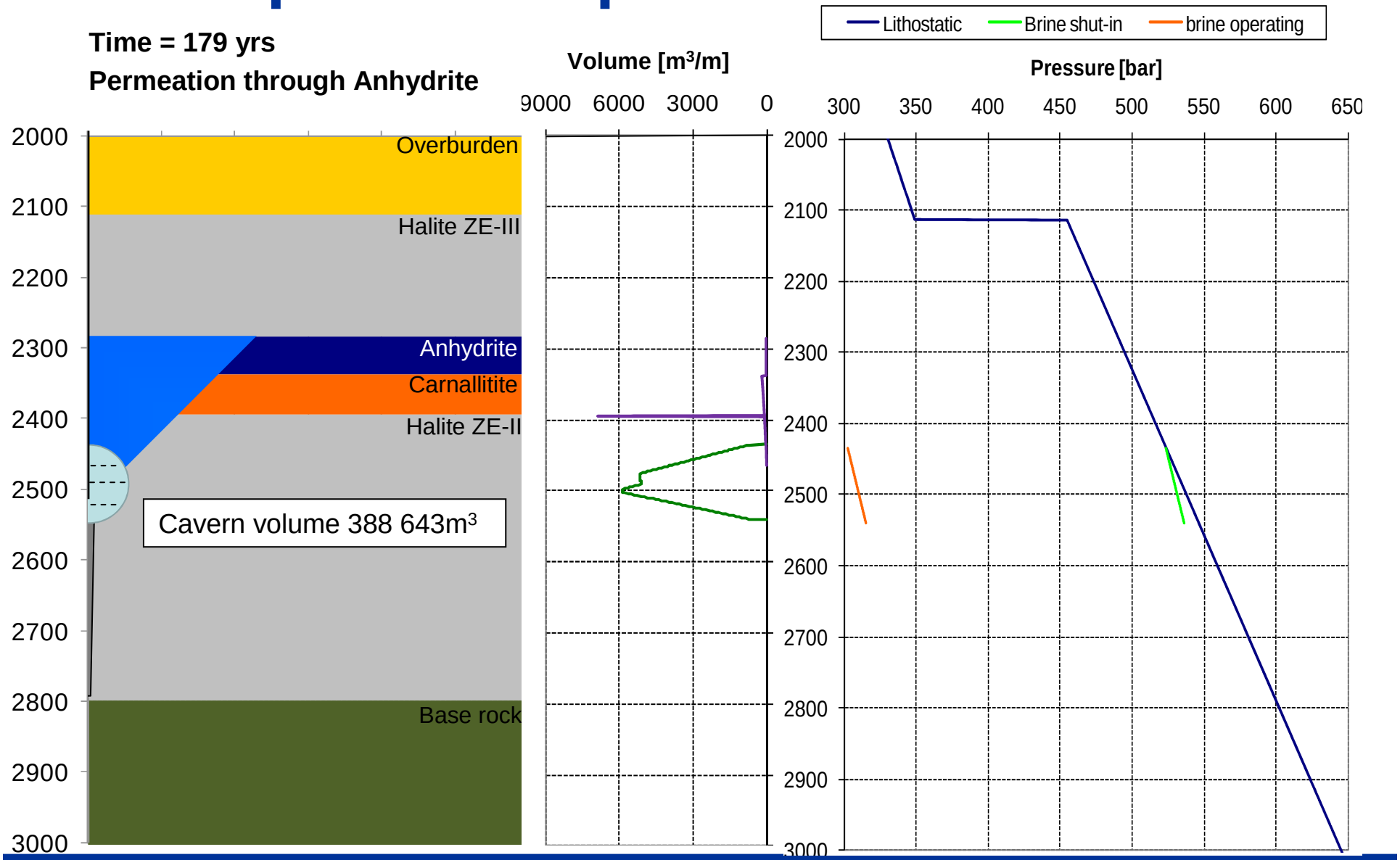
BAS-3 total carnallite conversion

TOP	Thickness	Carnallitite %	Volume	Carnallite volume	NaCl brine used	Carnallite dissolved	Carnallite left	Insolubles created	Bulked insolubles	Pore volume	Free volume created	Volume permeating further	Volume stored in Carnallite
[m] TVD	[m]		m3	m3	m3	m3	m3	m3	m3	m3	m3	m3	m3
2415	7	0%	662	0	0	0	0	0	0	0	0	0	0
2420	20	30%	1611	1611	0	0	0	0	0	0	0	0	0
2425	5	0%	342	0	0	0	0	0	0	0	0	0	0
2440	25	55%	1383	1383	400	752	631	600	772	172	588	436	324
SUM	57		3997	2994	400	752	631	600	772	172	588	436	324

BAS-3 permeation process 0.2%

Time = 179 yrs

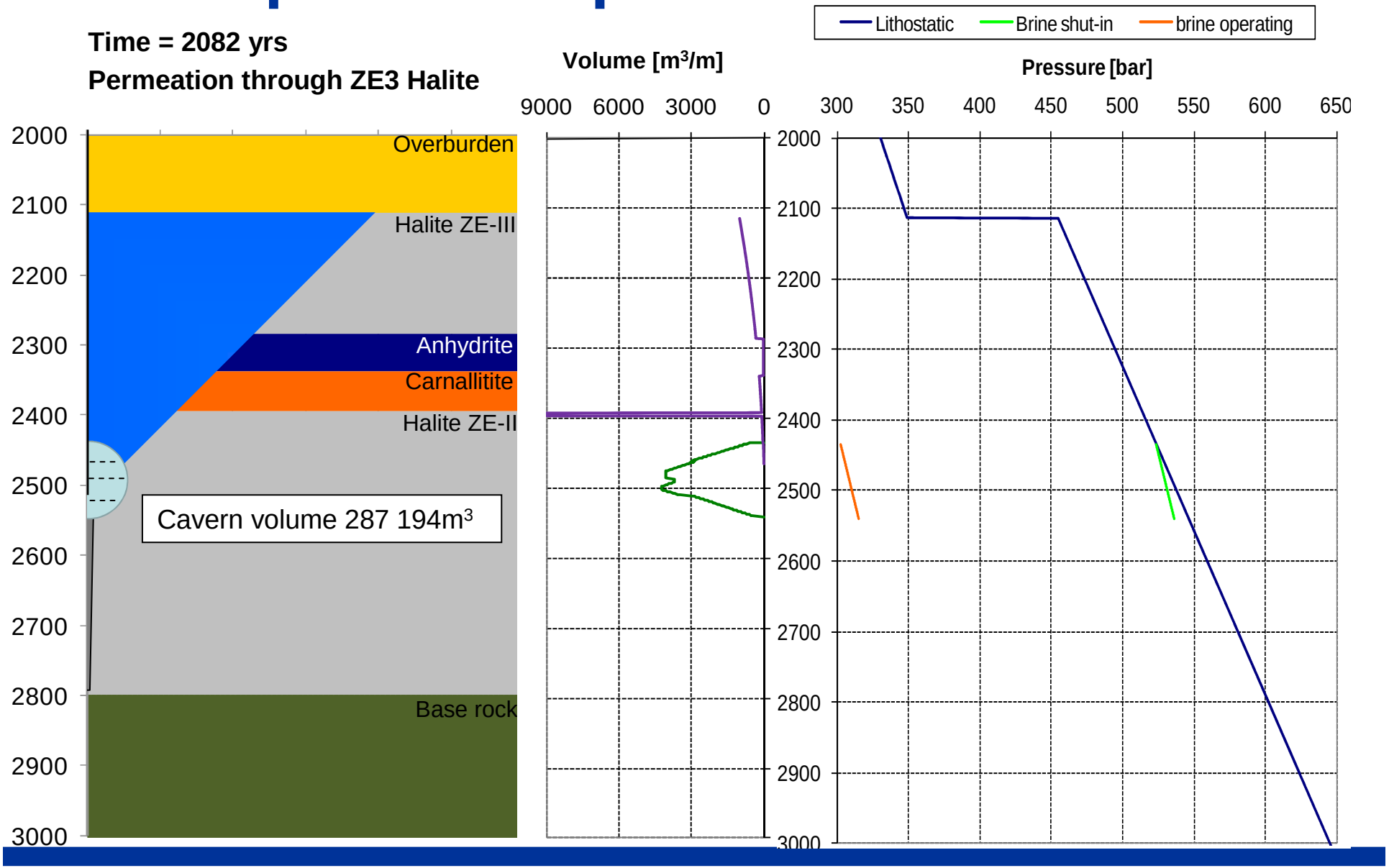
Permeation through Anhydrite



BAS-3 permeation process 0.2%

Time = 2082 yrs

Permeation through ZE3 Halite



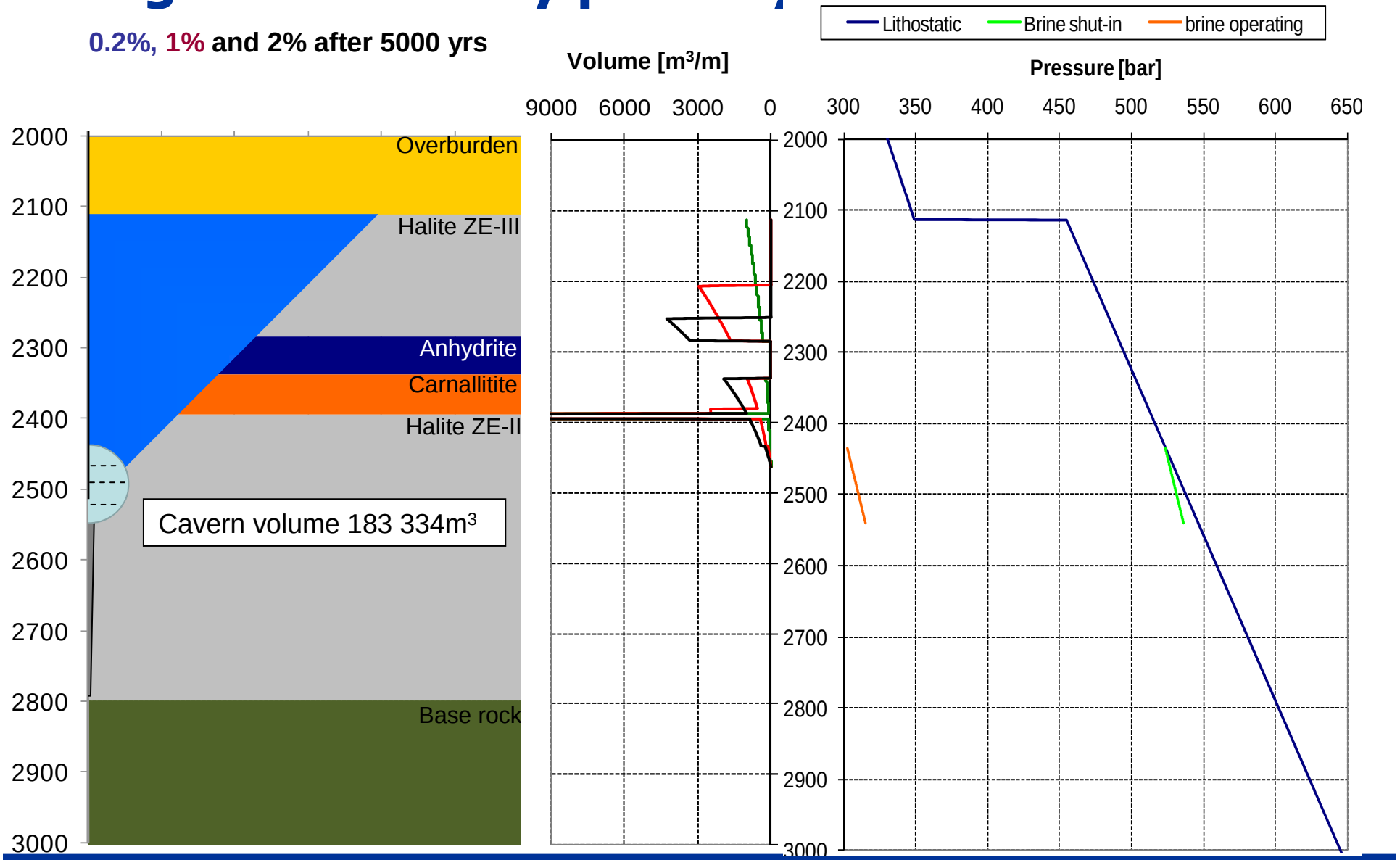
BAS-3 Summary table volumes 0.2%

	Time	Convergence	Caverne volume	ZE-2 NaCl pores	Undisolved Carnallitite secondary pores	Carnallitite pores and free volume	Anhydrite	ZE-3 pores	Overburden	NaCl brine	Carnallitic brine	Total fluid volume	Subsidence
Initial	0	0	400	0	0	0	0	0	0	400	0	400	0.0
Untill Carnalite	8	3	397	2.8	0	0	0	0	0	400	0	400	0.0
Untill anhydrite	160	10	390	2.8	7.8	6	0	0	0	393	14	406	0.0
Untill Z3	179	11	389	2.8	7.8	7	1.2	0	0	391	16	407	0.0
untill Overburden	2082	113	287	2.8	7.5	89	1.2	110	0	290	208	498	0.0
Final	5000	217	183	2.8	7.1	173	1.2	110	115	186	406	592	1.1

Time in years, volumes in 1000 m3 and subsidence in cm.

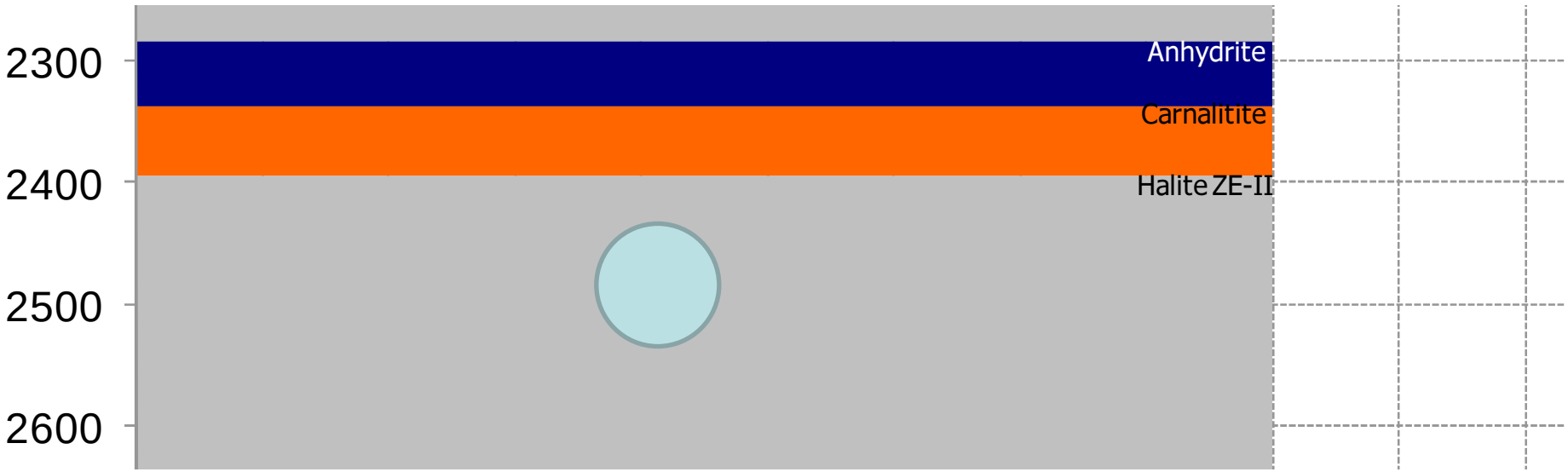
Higher secondary porosity

0.2%, 1% and 2% after 5000 yrs



BAS-3 roof collapse scenario spherical cavern

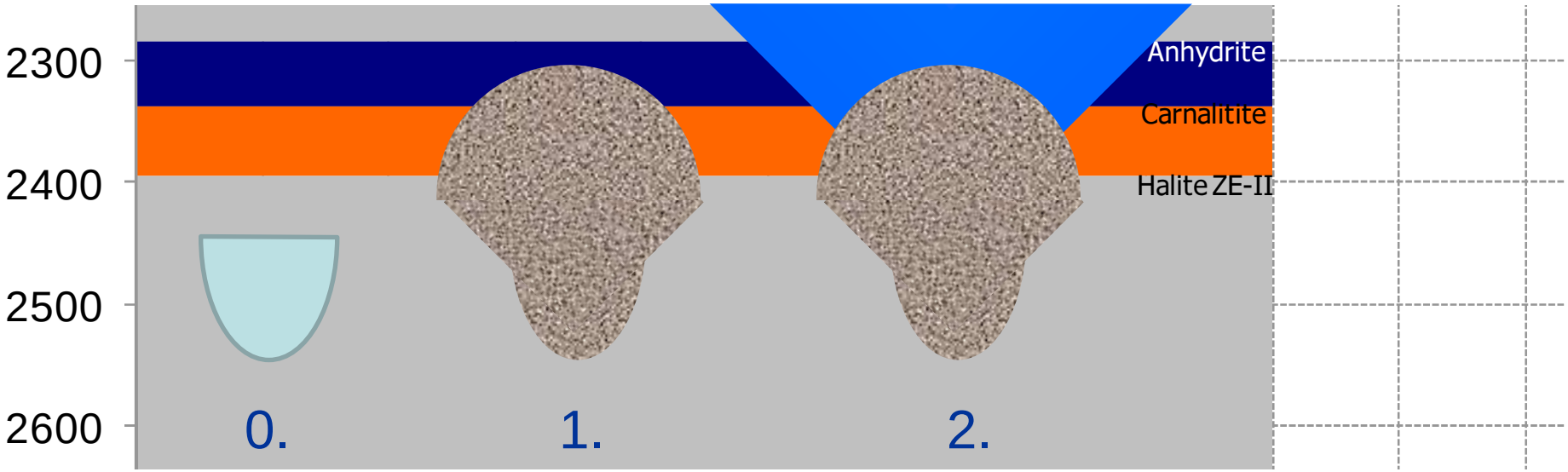
According to Deltares 2009 a cylindrical cavern with a 50 m radius is stable under near lithostatic conditions. Hence roof collapse is not likely and a permeation scenario is expected.



Sphere with a flat roof

1. Roof span with this geometry collapses => Cavern fills itself with NaCl, Carnallitite and anhydrite from the roof. This converts to Q-brine and the insolubles bulk up.
2. Due to the volume increase 36 000 m^3 of Q-brine permeates into the overlying strata. This can be stored assuming 0.2%, 1% and 2% secondary porosity.

NaCl brine	Q-brine	Permeating	Pores	Bulked volume
m^3	m^3	m^3	m^3	m^3
400 000	760 000	36 000	724 000	2 534 000



Final storage

- The excess brine will finally end up in the overburden that consists of several sand and clay formations.

Other confinement zones