APPENDIX C
Nedmag TR2 brine leakage study
Base case and sensitivities

Panterra Geoconsultants

Scope of Work

- Carry out fracture propagation study in order to improve understanding of what happened during leakage event on 20 April 2018

Modeling Approach

- Simulation of water injection-driven hydraulic fracture propagation
- **Two** different models (simulators) are used (complementing each other):

1. **Model 1**: Fractured water injection model
   - *Used for prediction and management of waterfloods and water disposal operations under induced fracturing conditions*
   - ***PLUS**: Leak-off / flow in the reservoir is properly modeled*
   - ***PLUS**: Numerical stability, works well in connection with 3D reservoir simulator*
   - ***MINUS**: The model uses an assumed fracture shape (two half-ellipses)*

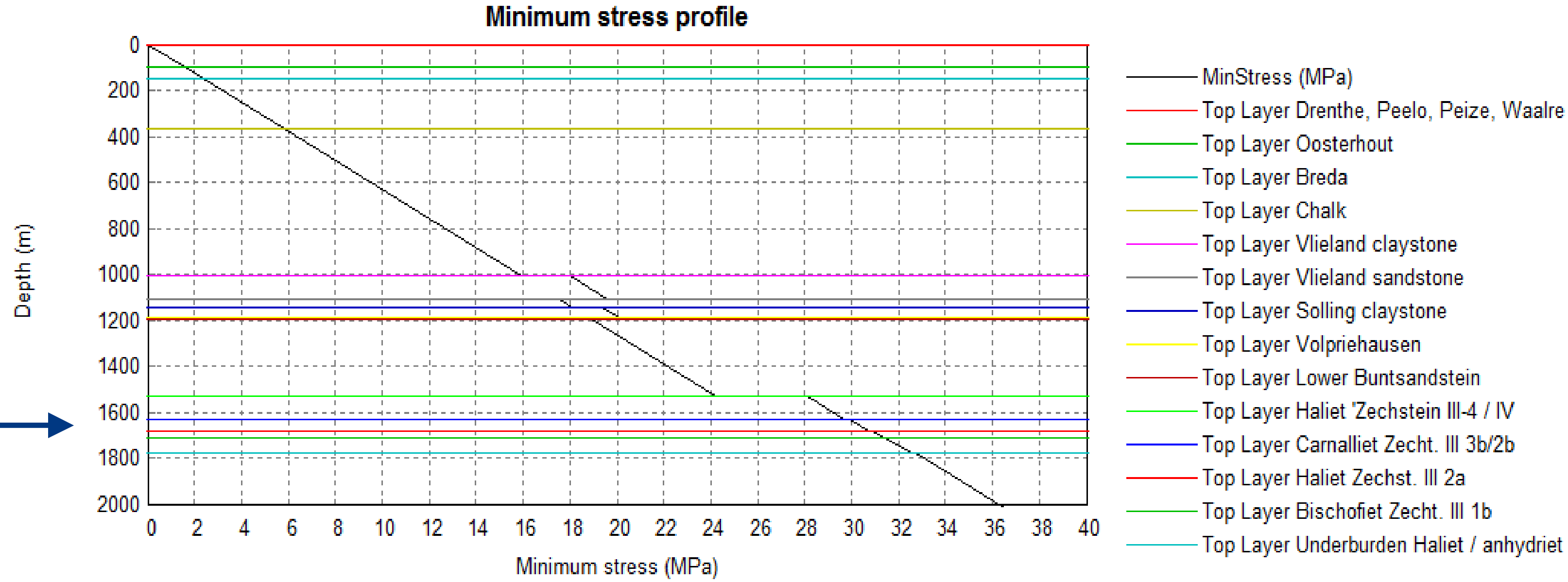
2. **Model 2:** Boundary Element Model (BEM), in which the **fracture is subdivided in a grid**
   - *Used for predictions and designs of pump (proppant) schedules in hydraulic fracture stimulation and for predictions in cuttings re-injection*
   - ***PLUS**: Good (more detailed) description of the shape of the fracture (because of the gridding) and its evolution during injection. Therefore better in modelling the details of fracture geometry (horizontal, vertical) per layer.*
   - ***MINUS**: Program has been built for modeling hydraulic fracture stimulation and cuttings re-injection, where leak-off rates are relatively low. Therefore, it is unsuited for modelling situations with (relatively) high leak-off, such as most cases of water injection.*
   - ***MINUS**: The physical process of fracture propagation is extremely difficult to describe on a grid, and therefore such simulation programs are often numerically fairly unstable.*

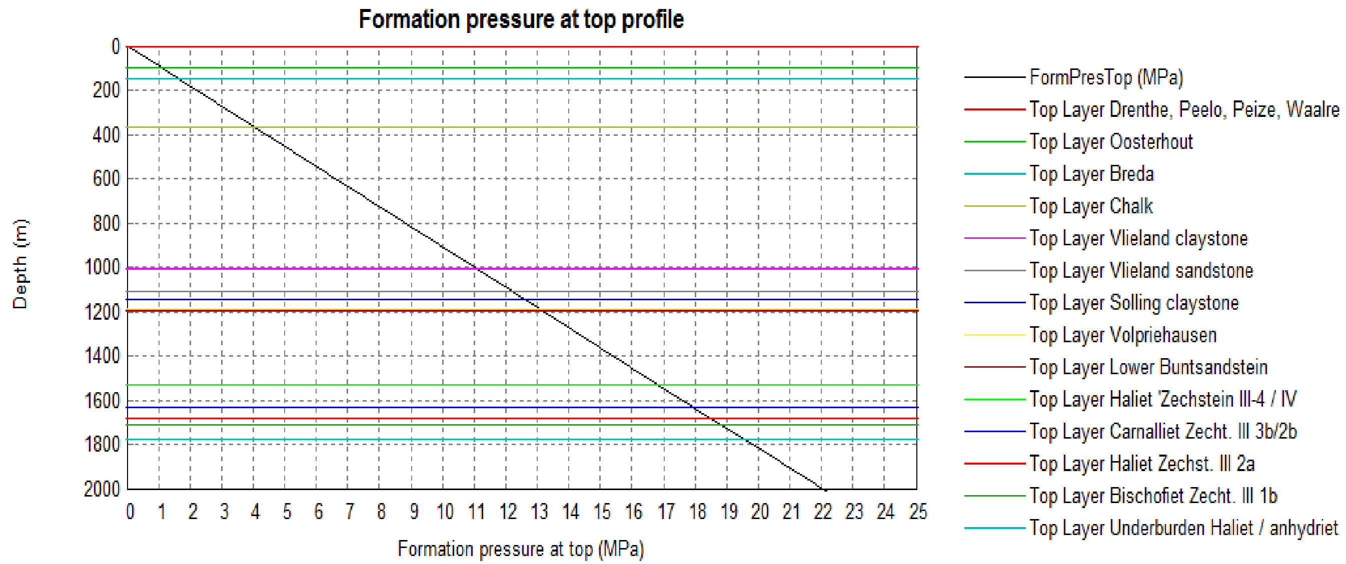
Description of base case

- Simple geological layer-cake model – geology provided by Nedmag
- Minimum horizontal in-situ stresses based on well-known geomechanical correlations (differences between salts, shales, and sands)
- Hydrostatic formation pressure gradient
- Because (except for the highly permeable shallow sands) the Vlieland sandstone absorps most of the brine leakage, the storage capacity of this formation was looked at in more detail, with the following main findings:
  - *The Vlieland sandstone in the Veendam area is laterally continuous over large distances (tens of kilometers)*
  - *Its thickness is approximately constant (~ 35 m)*
  - *It is intersected by NE-SW oriented sealing faults (perpendicular to the orientation of the fractured induced by brine injection)*
  - *However, these fault networks are not connected and therefore we expect a good lateral connectivity.*
  - *Therefore, in our base case we modeled the Vlieland sandstone as a laterally continuous formation with a constant pressure boundary at 10 km ("very far") from the injection well.*

Layers in the model

injection

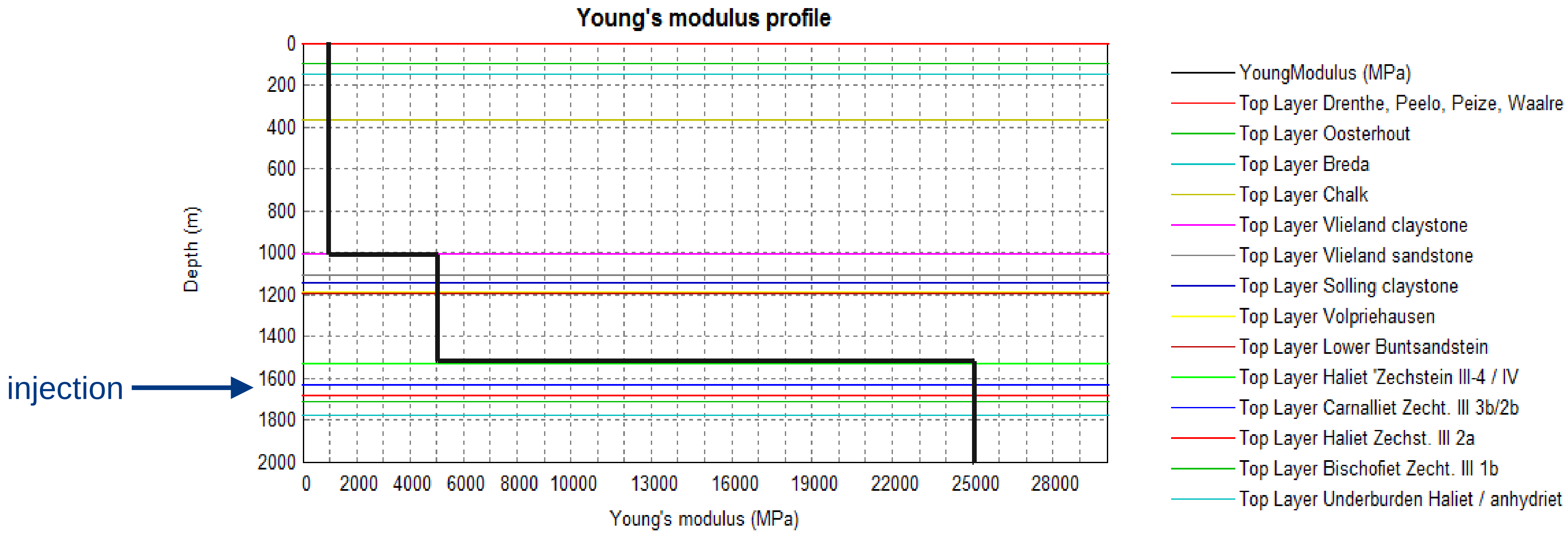


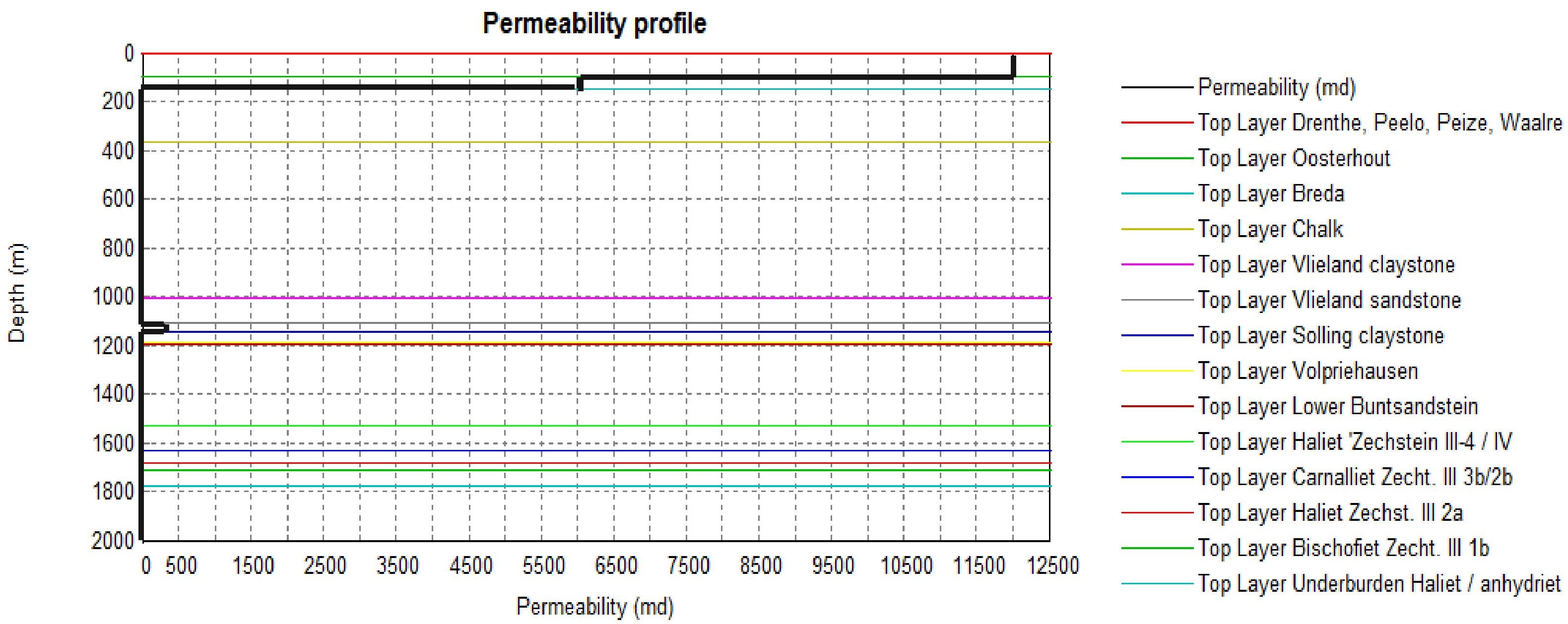


Description of base case (cont’d)

- Simple geological layer-cake model – geology provided by Nedmag
- Minimum horizontal in-situ stresses based on wellknown geomechanical correlations (differences between salts, shales, and sands)
- Hydrostatic formation pressure gradient
- Rock stiffness parameters (Young’s modulus, Poisson’s ratio) based on general geomechanical correlations
- Permeability estimates provided by Nedmag

Layers in the model





Description of base case (cont'd)

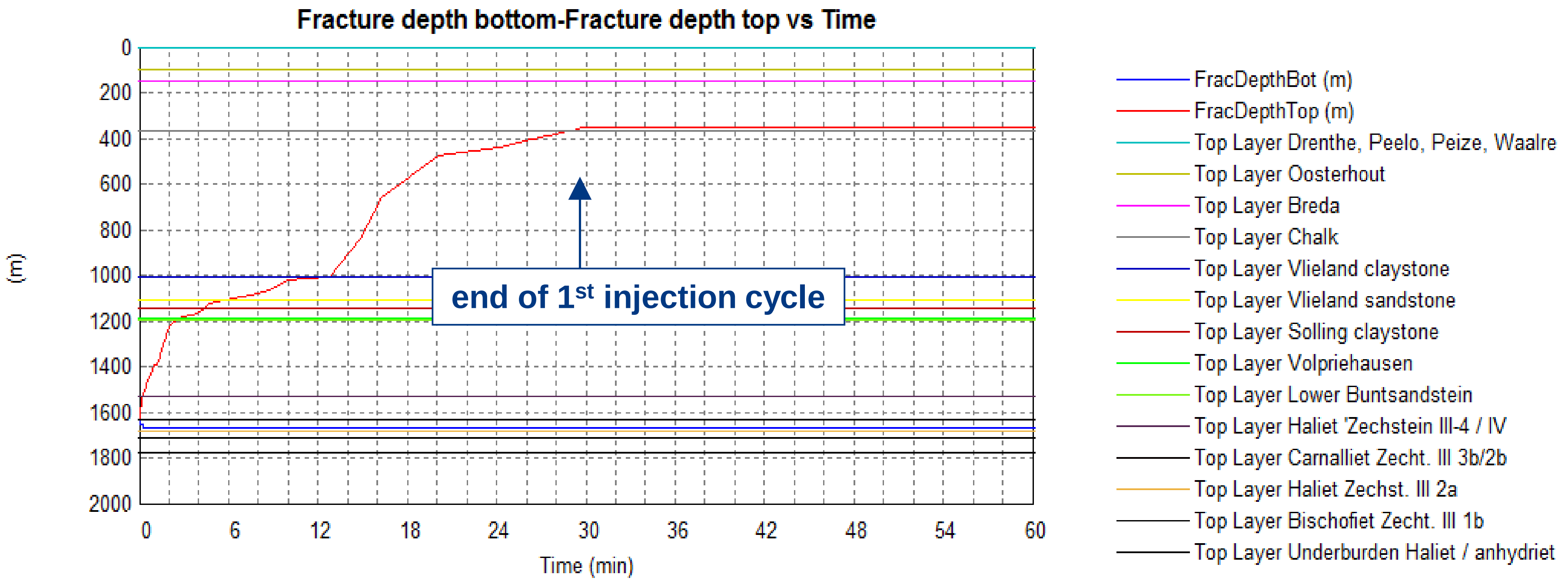
- Simple geological layer-cake model – geology provided by Nedmag
- Minimum horizontal in-situ stresses based on wellknown geomechanical correlations (differences between salts, shales, and sands)
- Hydrostatic formation pressure gradient
- Rock stiffness parameters (Young's modulus, Poisson's ratio) based on general geomechanical correlations
- Permeability estimates provided by Nedmag
- Injection takes place from top Carnalite
- Leakage incident is modeled by three **subsequent** injection cycles:

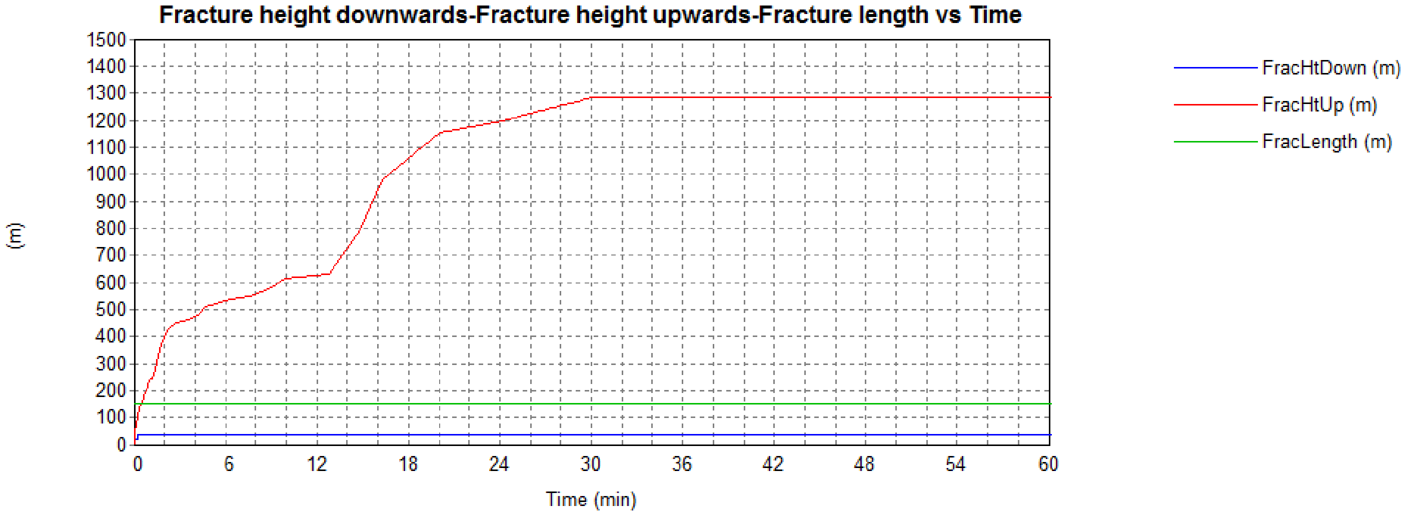
1. *Very high rate (50000 m^3/h) during 30 minutes*
2. *High rate (1050 m^3/h) during 47,5 hours*
3. *'Medium' rate (100 m^3/h) during 30 days*

RESULTS

Base case

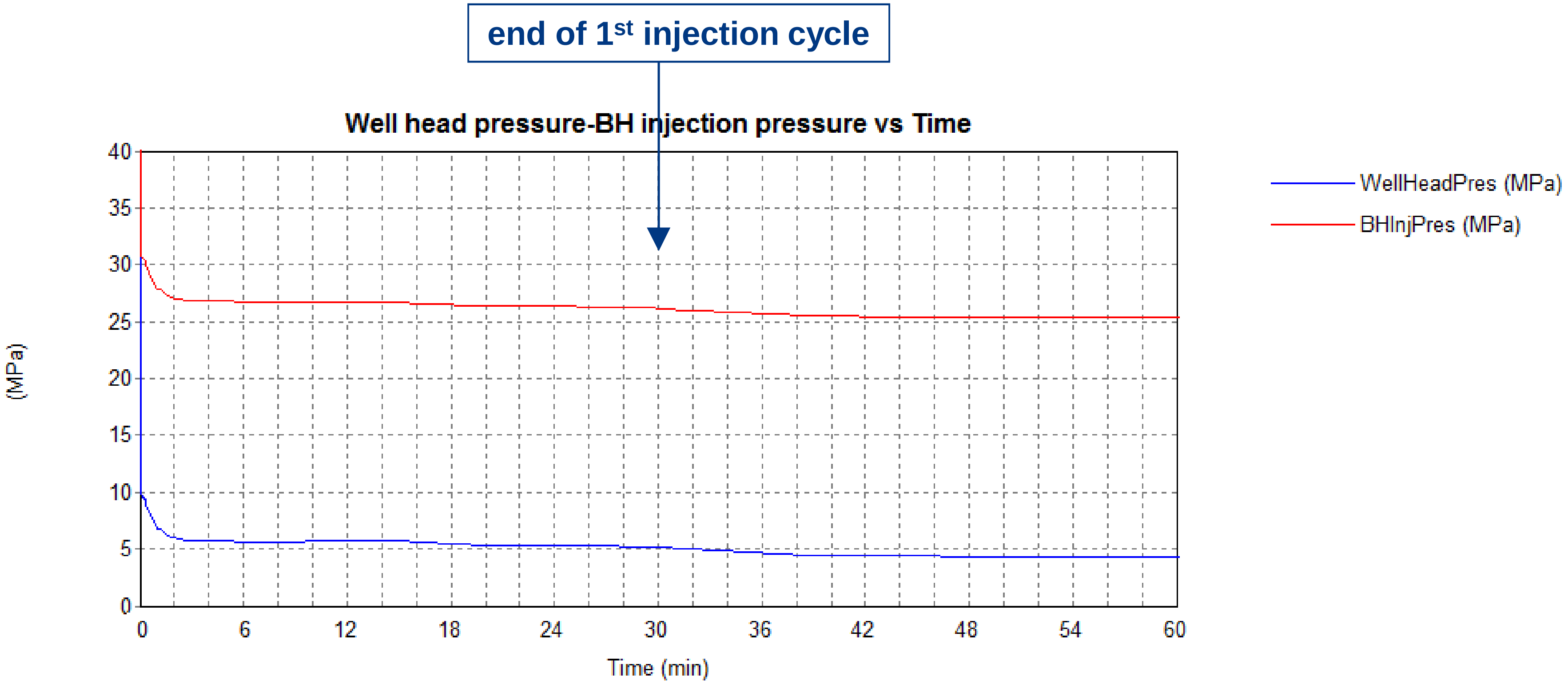
Results after 1 hour of injection





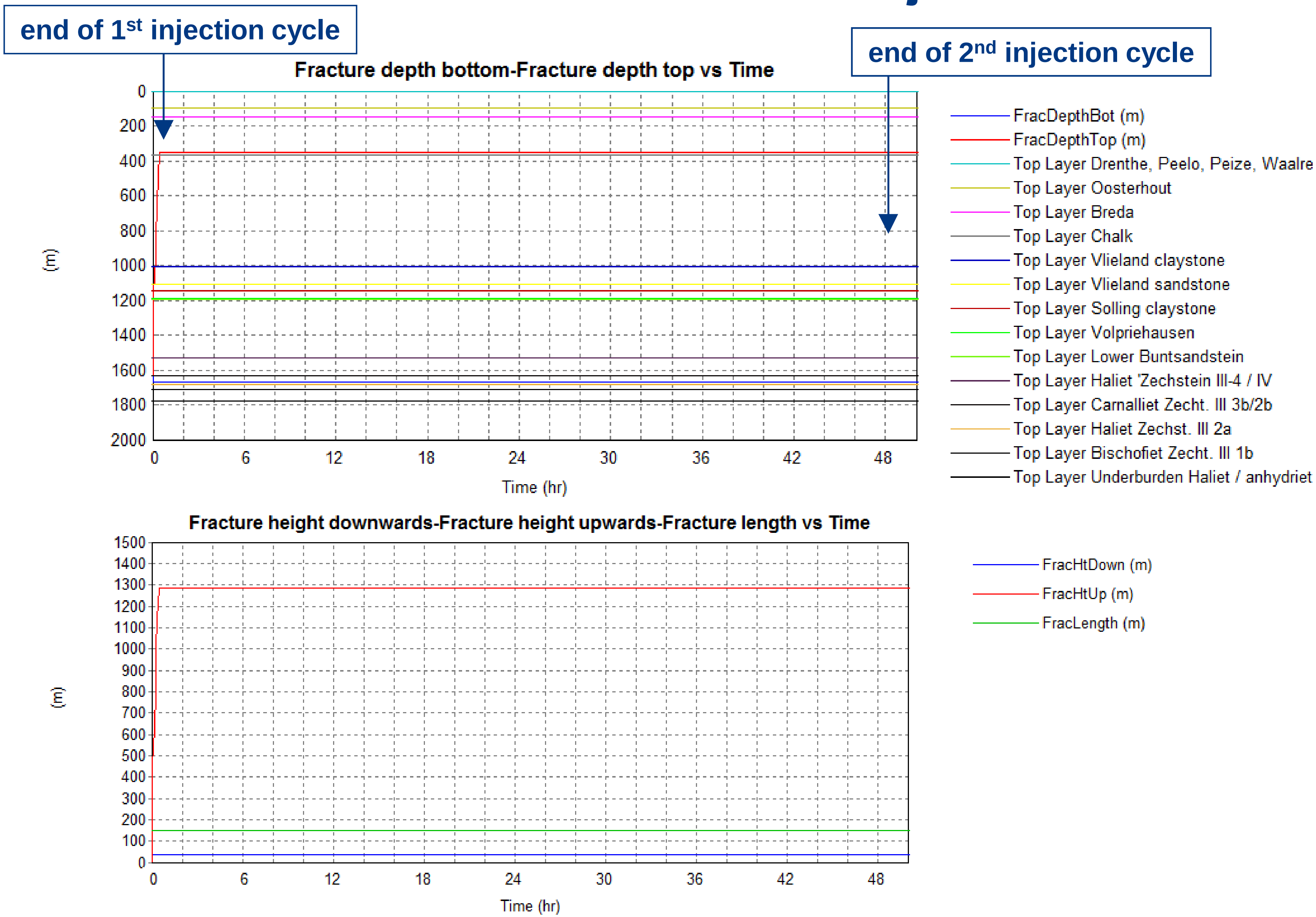
Base case

Results after 1 hour of injection



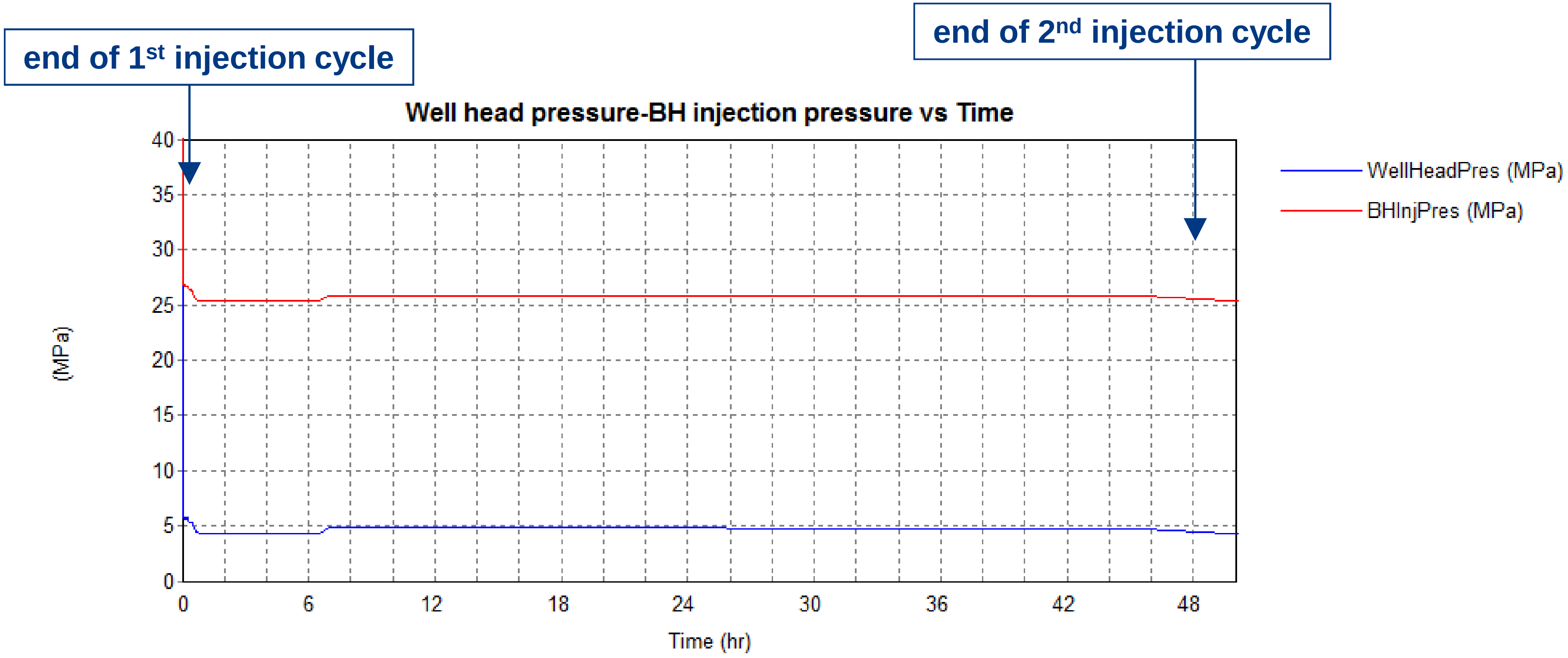
Base case

Results after 50 hours of injection



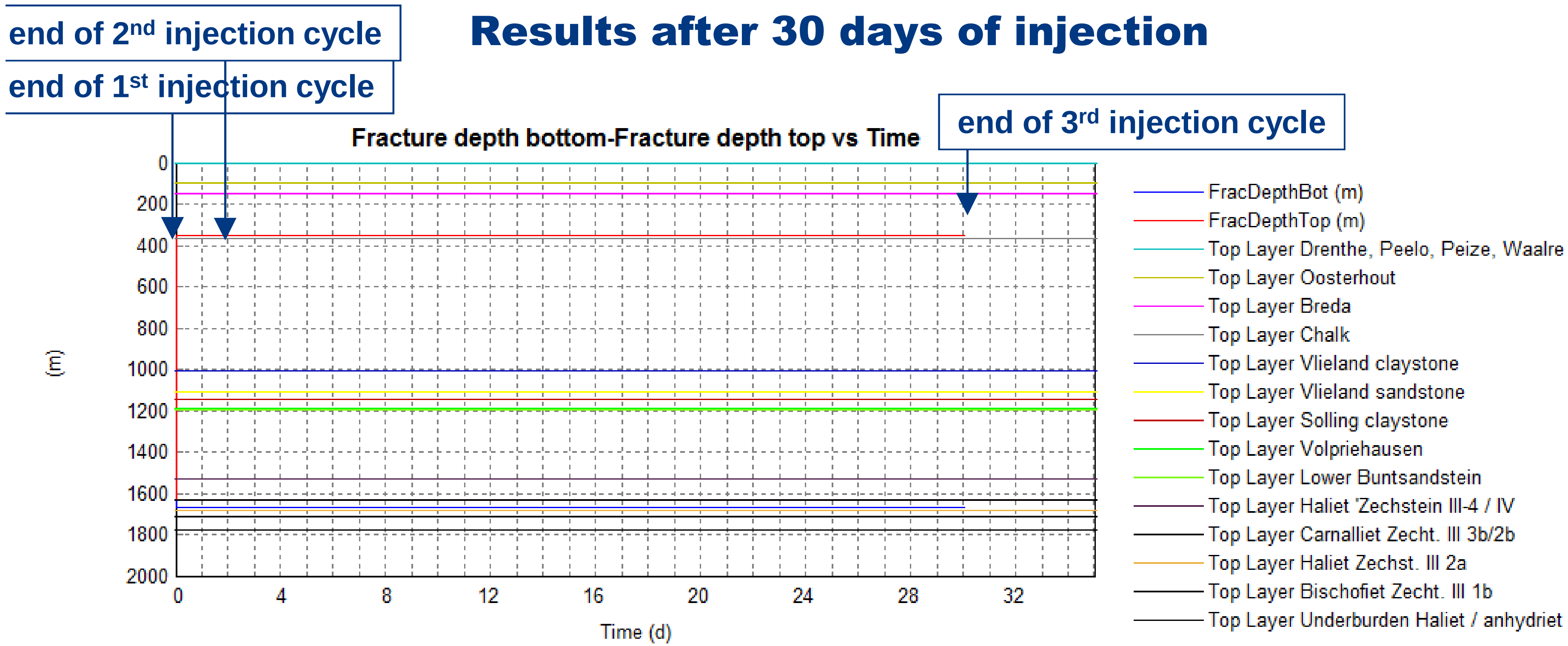
Base case

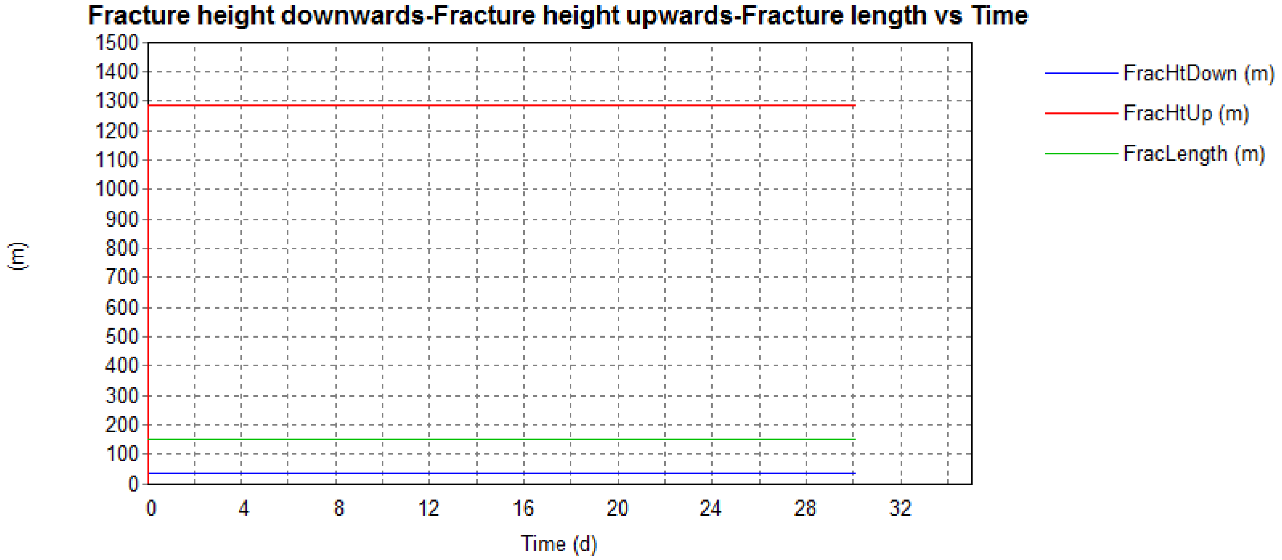
Results after 50 hours of injection



Base case

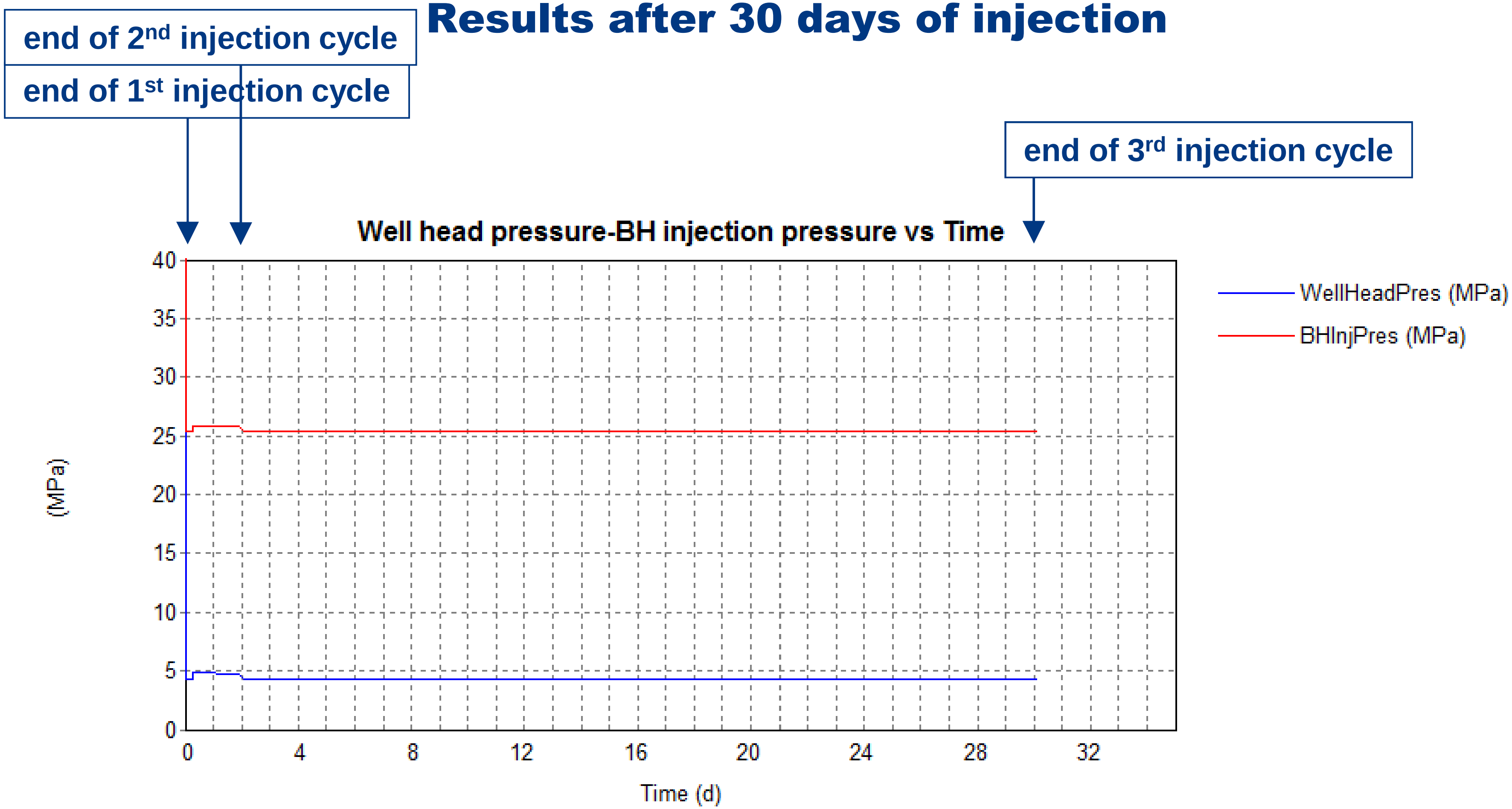
Results after 30 days of injection





Base case

Results after 30 days of injection

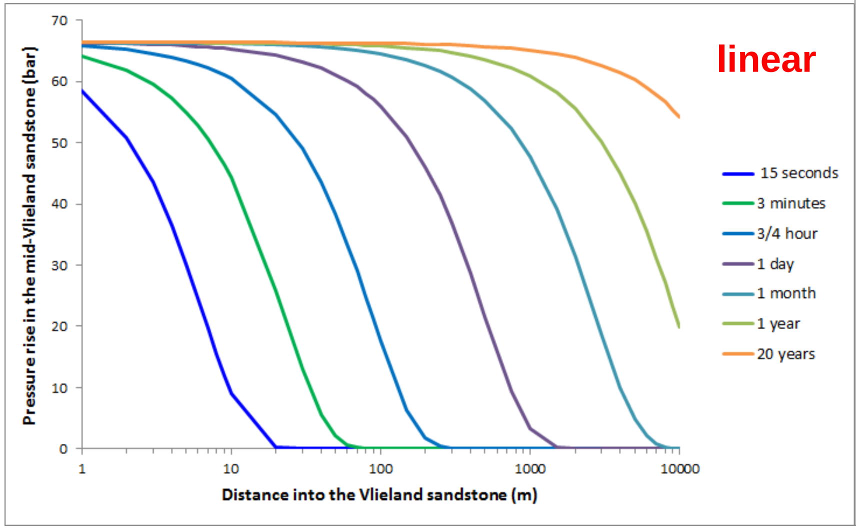


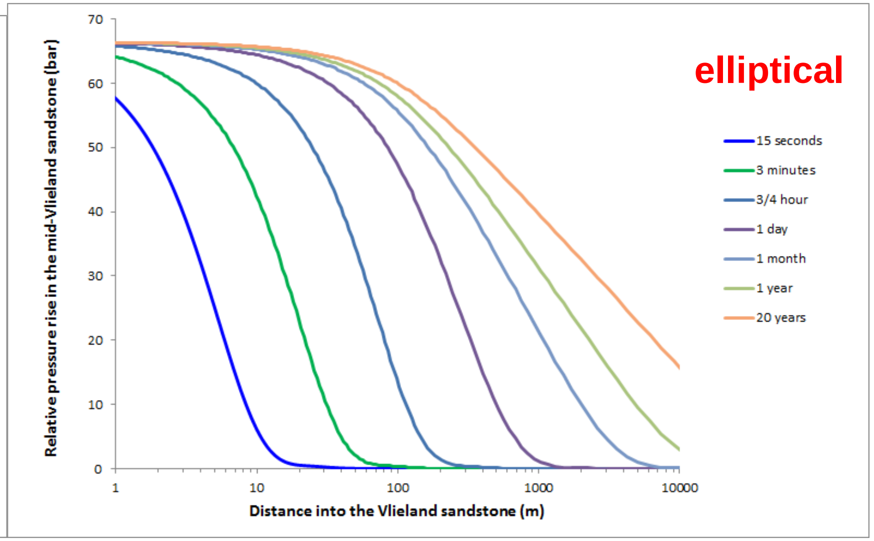
Discussion of base case results

- During the first (high-rate) injection cycle of 30 minutes, a large fracture is created which grows upwards to about 350 m depth in the Breda formation
- During the second cycle, injection rate is much lower. Because the fractures are leak-off driven it is possible that the injection pressure drops below the fracture closure pressure leading to partial fracture closure, i.e. shrinkage. This is in line with general experience from waterflooding operations
- Unfortunately, the waterflood fracture simulation model (model 1) cannot handle **shrinking** fractures, only **stationary** and **growing** fractures.
- In this case, we see that lowering the injection rate in the 2nd injection cycle is predicted to result in only a modest drop in injection pressure (~ 1 MPa) for a stationary fracture.
- Therefore, the injection pressure does not appear to drop below the closure pressure and the fracture likely stays open over its entire length and height.
- During the 2nd injection cycle, the injection pressure is seen to rise slightly again, but not beyond the propagation pressure.
- In the 3rd injection cycle, the injection pressure again shows a modest drop.
- In the 2nd and 3rd injection cycles, the fracture does not grow beyond its size resulting from the 1st injection cycle.

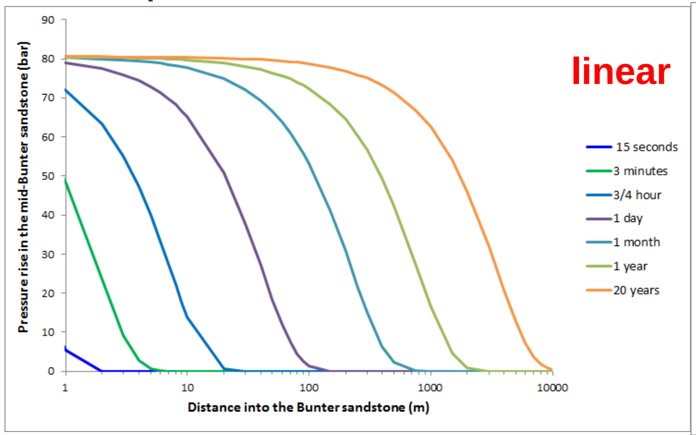
Pore pressure penetration

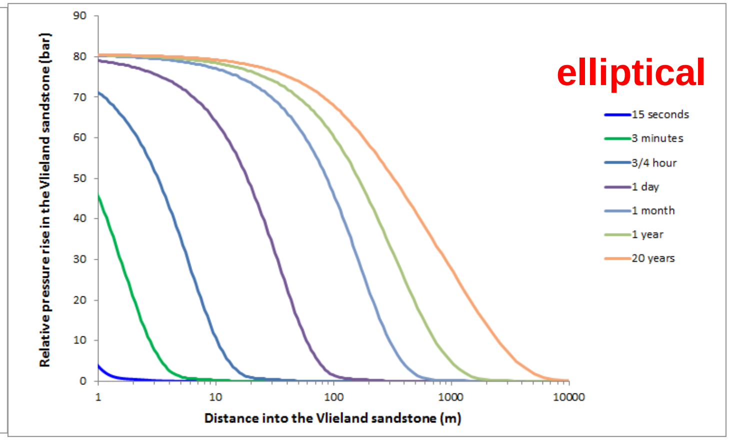
- Pore pressure penetration into the Vlieland sandstone (into which most of the brine leaks away) assuming a linear (conservative) / elliptical (more realistic) pore pressure front





- Pore pressure penetration into the Bunter sandstone





Cum. brine volumes leaked away

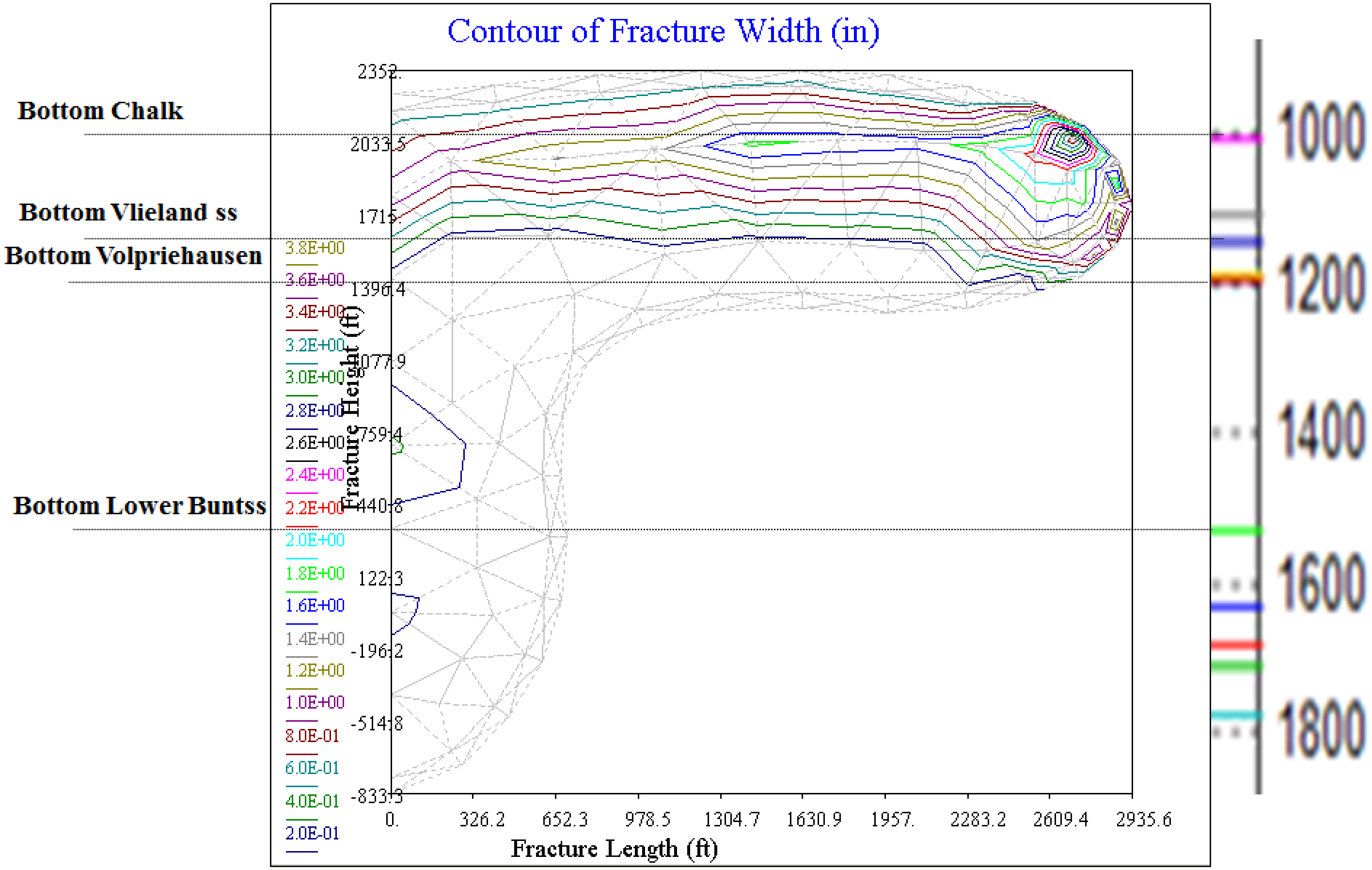
- In total, about 146000 m^3 has been leaked away during the first month
- In total, about 438000 m^3 leaks away per year, assuming a constant leakage rate of about 50 m^3/hr
- The highest volumes (about 90% of total) leak into the Vlieland sandstone
- PLEASE NOTE: The pressure penetration front is far ahead of the brine penetration front!

Formation	Brine volume leaked away (m^3)	Brine penetration front (m)
Chalk	5600	0,54
Vlieland sandstone	132000	39
Volpriehausen	4400	6,7
Lower Bunter	4300	0,27
TOTAL in first month	~146000	
Total in a year assuming a constant rate of 50 m^3/hr	~ 438000	

Injection duration	Brine penetration front into Vlieland sandstone (m)
1 month	39
1 year	110
2 years	176
3 years	220
5 years	290
10 years	417
20 years	595

Boundary Element Model

- First injection cycle (50000 m^3/h during 30 minutes) with stress contrasts between sandstones and clays (base case)
- Fracture grows up to +/- 900 m depth (100 m into the Chalk) which is +/- 500 m deeper than predicted by the other model



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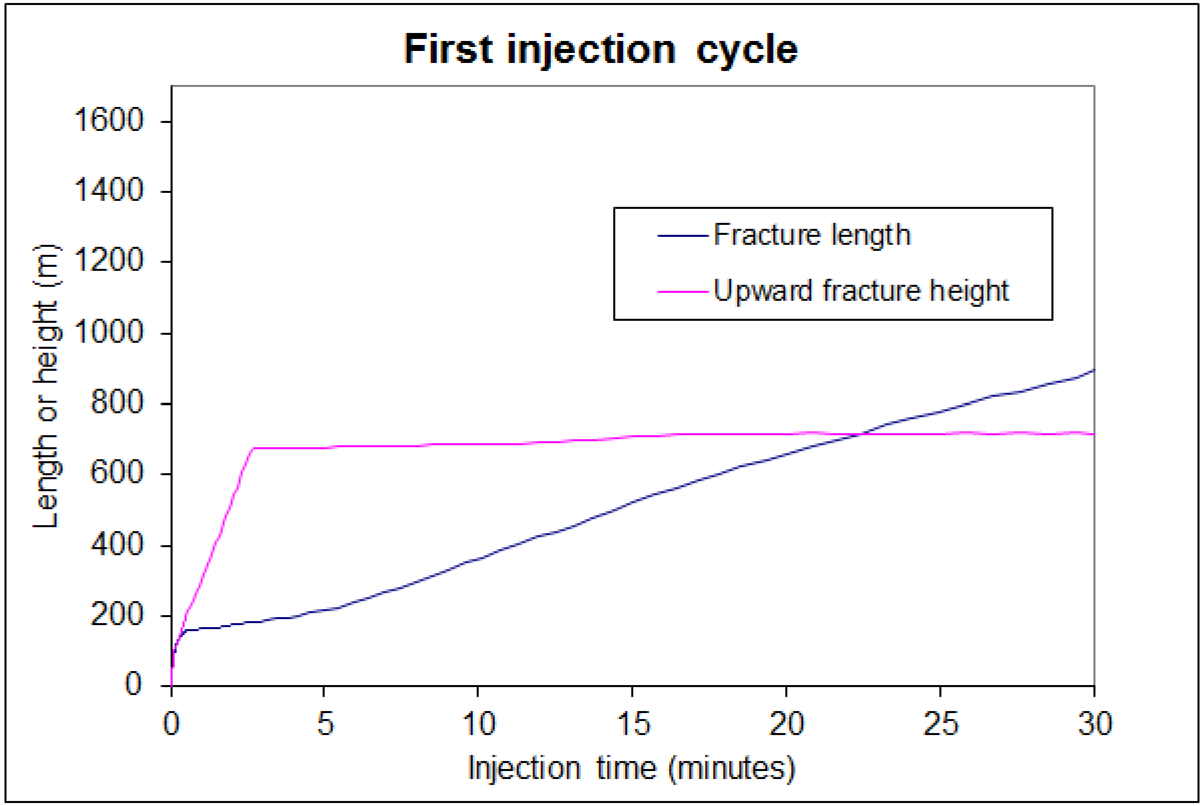


Conclusions from Base Case (1)

- Simple geological model
- Data from Nedmag + estimates (correlations, ‘ballpark figures’)
- Darcy sands in the shallow subsurface included in this study
- Observed trends in injection pressure can be reasonably well reproduced
- The Leakage incident is modeled by three **subsequent** injection cycles:
  1. *Very high rate (50000 m^3/h) during 30 minutes*
  2. *High rate (1050 m^3/h) during 47,5 hours*
  3. *‘Medium’ rate (100 m^3/h) during 30 days*
- For this entire sequence of 3 injection cycles, the induced fracture does not reach the high-permeability shallow sands (Oosterhout and upwards)
- The fracture reaches its maximum upwards extent (just above the top of the chalk) at the end of the first injection cycle, after which no further upward growth takes place.

Conclusions from Base Case (2)

- Numerical BEM model:
    - This model yields a more realistic shape of the fracture. It predicts more horizontal fracture growth.
    - In the presence of stress contrasts between the clay layers and sand layers the fracture does not reach the shallow sand layers, but remains contained to the Vlieland formation.
    - Because the BEM model cannot handle high leak-off (as compared to injection rate), it was only possible to QC the results of the other model for first injection cycle with very high injection rate (50000 m^3/h)
- Based on currently known geological data (global NW-SE for the maximum horizontal in-situ stress in NW Europe), it is expected that the fracture grows in a NW-SE oriented plane.

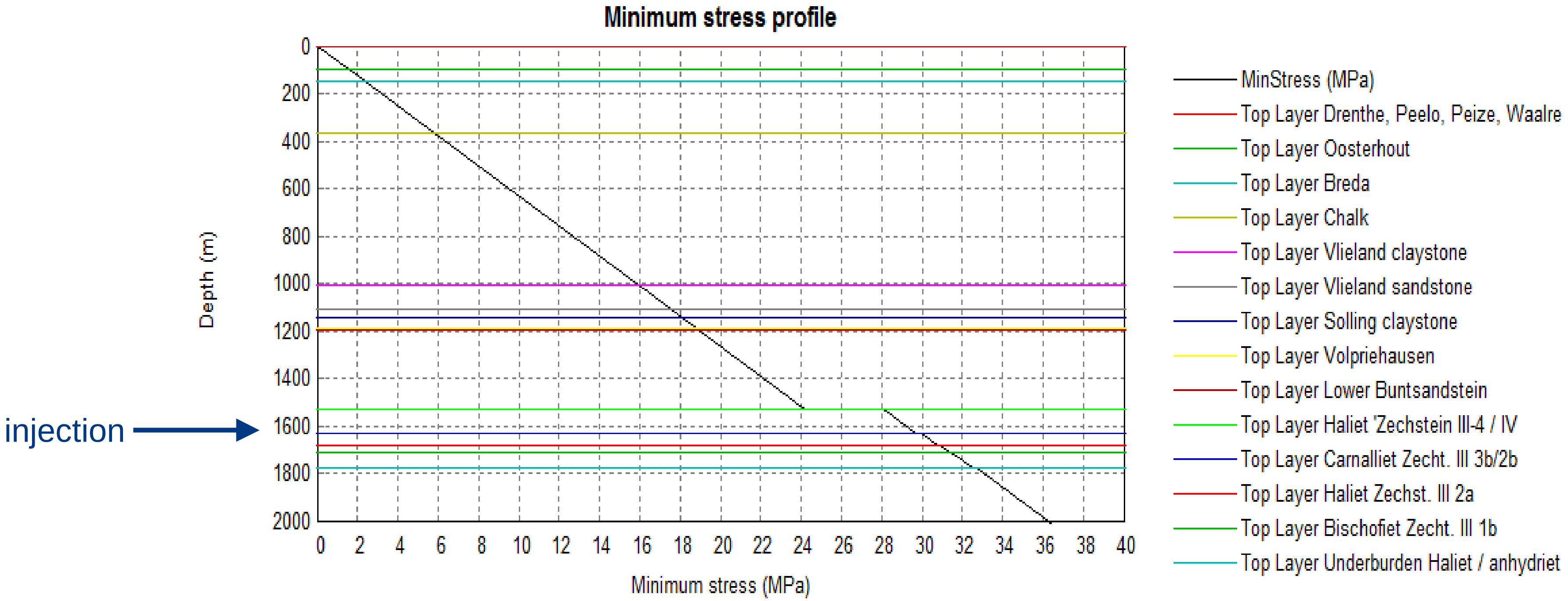
SENSITIVITY ANALYSIS

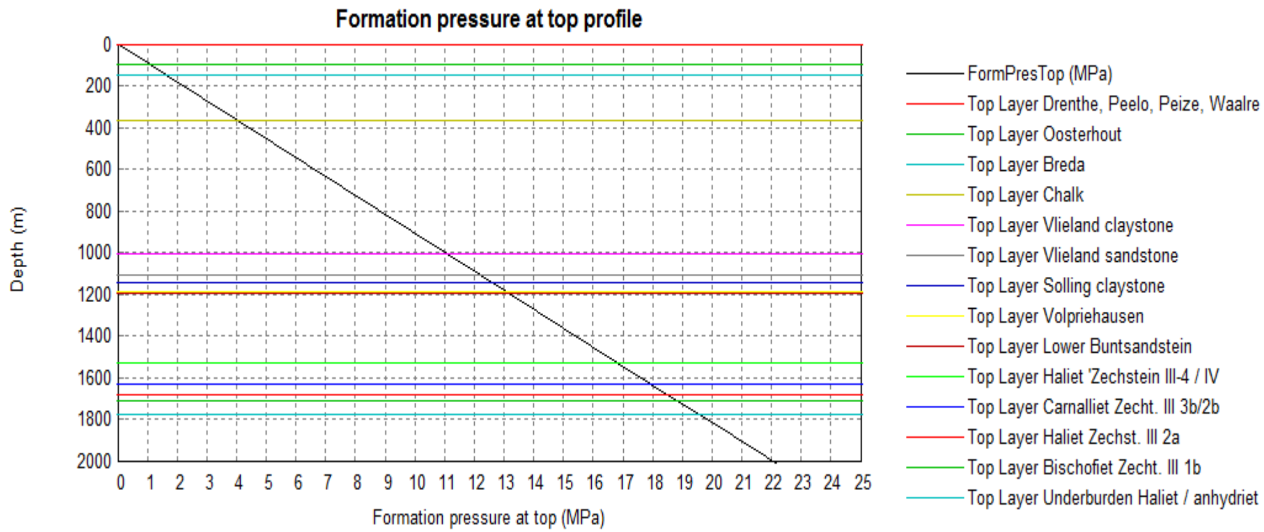
Overview of sensitivity analysis

No	Description	Possibly in combination with			
		a	b	c	d
1	No stress contrasts between sands and clays	Low E (0.1 GPa) in top sands	No stress contrasts only between Vlieland sands and clays	Low stress contrasts only between Vlieland sands and clays	High stress contrasts only between Vlieland sands and clays
2	Injection point in top Halite				
3	Low $k_{Vlieland}$ (30 mD)				
4	High $k_{Vlieland}$ (3000 mD)				
5	High injection rates	Low E (0.1 GPa) in top sands	High injection rate first cycle (BEM)		
6	Low injection rates				
7	Low k_{Bunter} (0.1 mD)				
8	High k_{Bunter} (10 mD)				
9	All k divided by 3				
10	All k multiplied by 3				
11	Initial fracture length 100 m				
12	Initial fracture length 50 m				

Sensitivity 1:

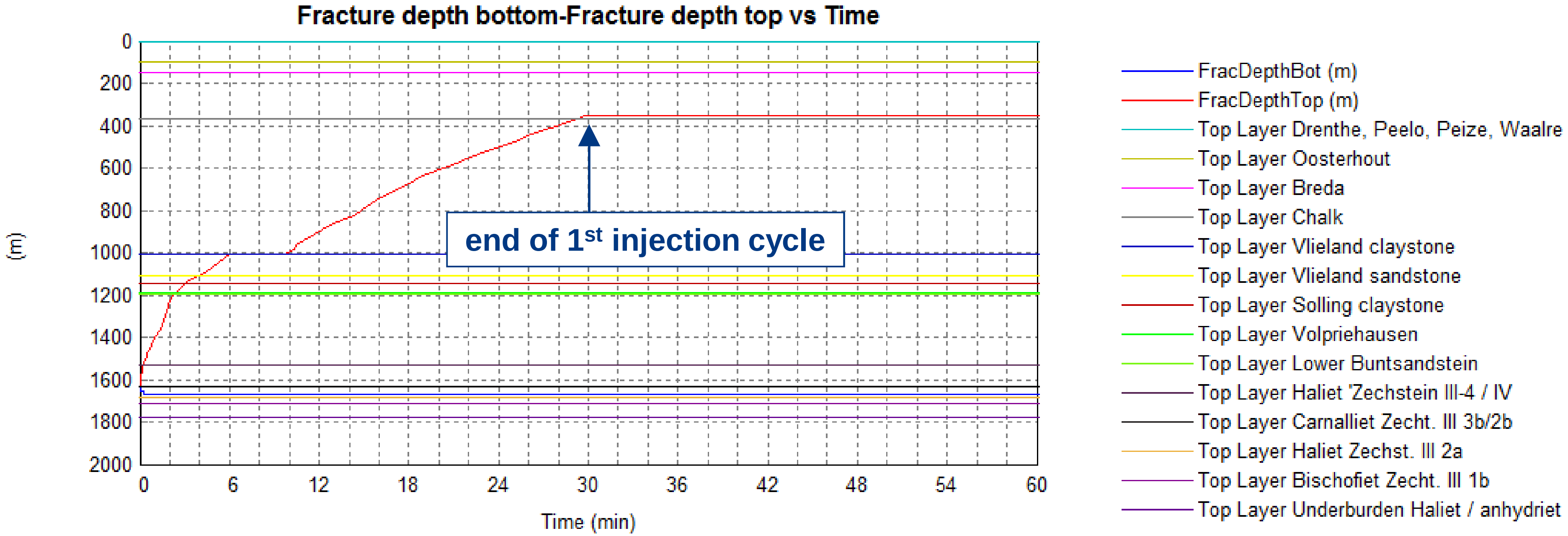
No stress contrasts between sands and clays

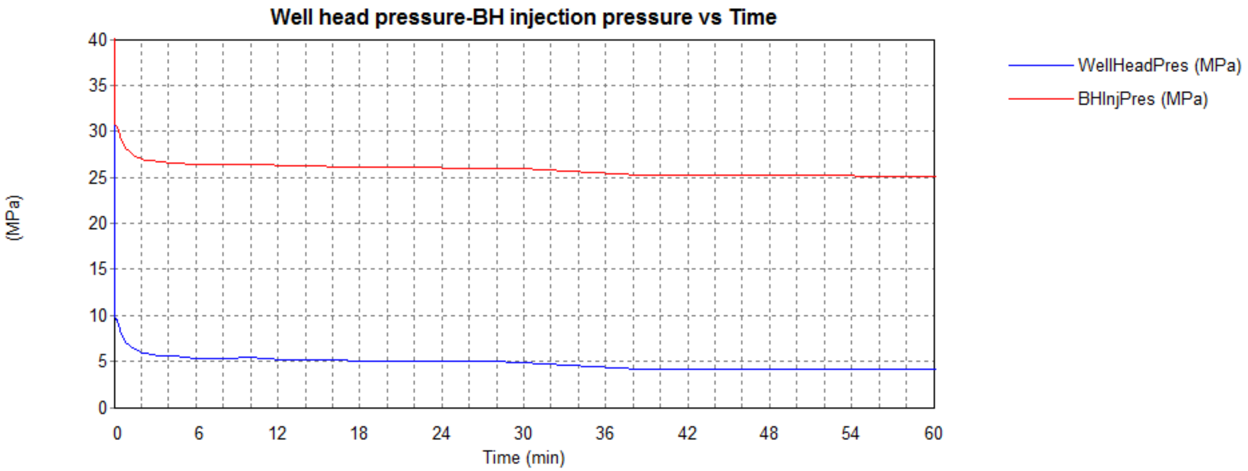




Sensitivity 1: no stress contrasts sand/clay

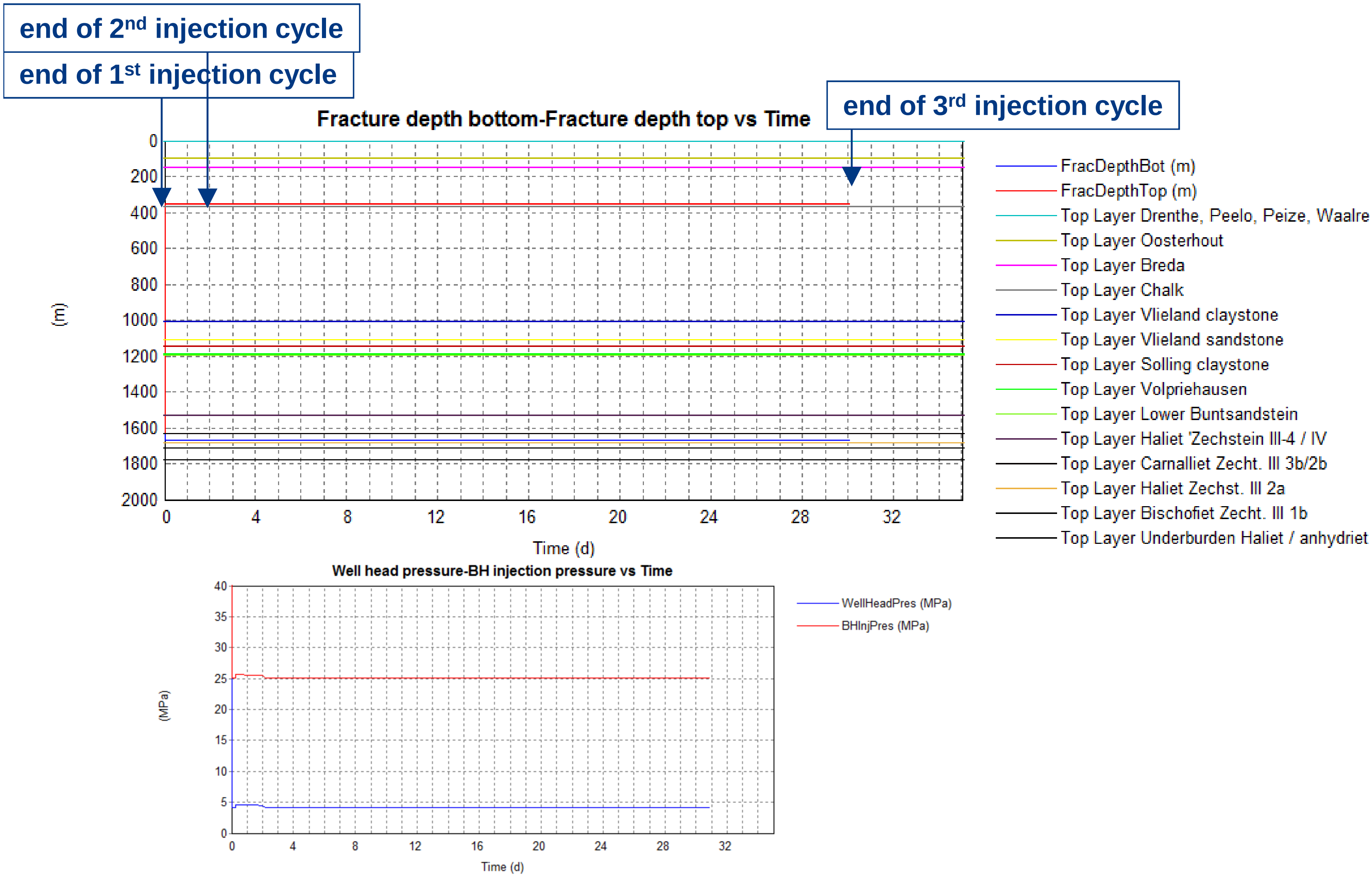
Results after 1 hour of injection





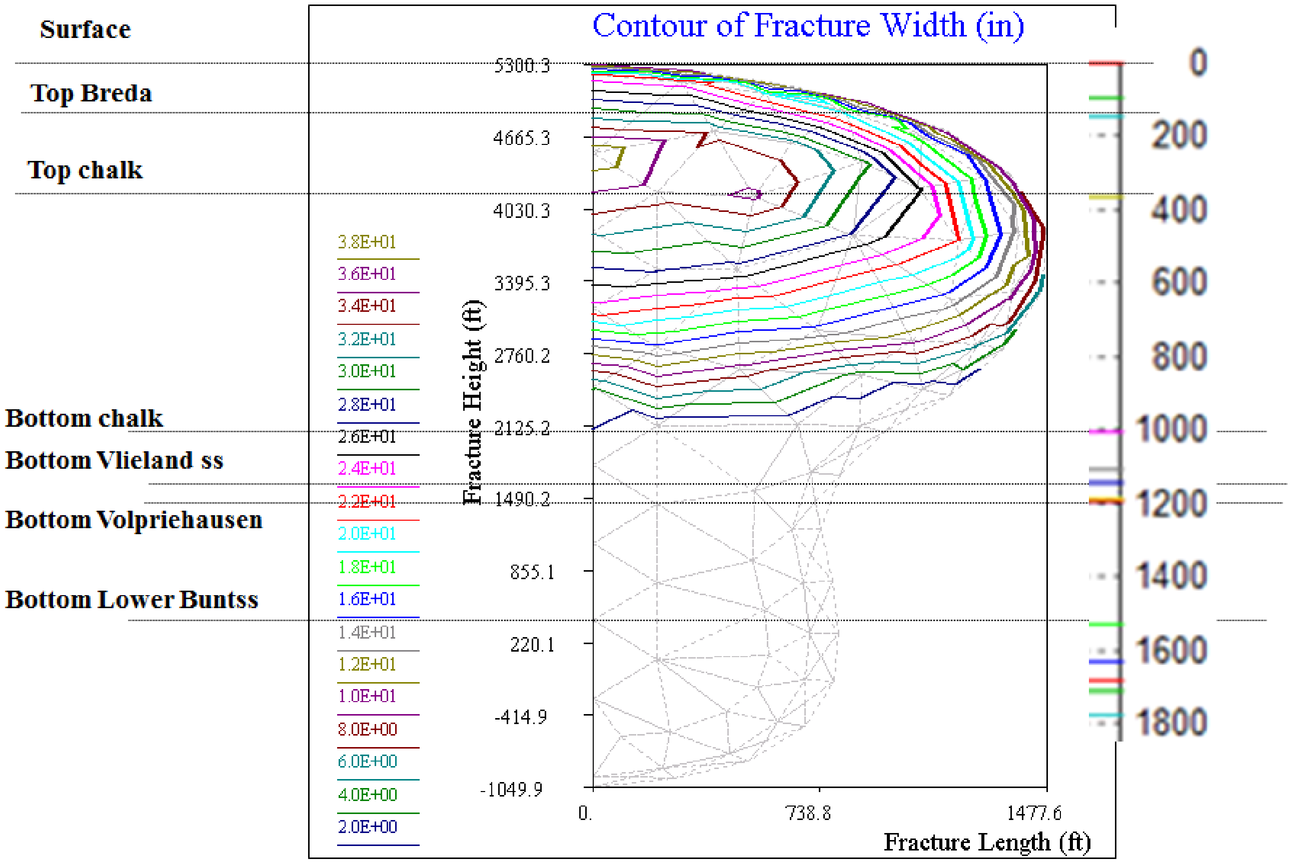
Sensitivity 1: no stress contrasts sand/clay

Results after 30 days of injection



Sensitivity 1: no stress contrasts sands/clays (BEM)

- First injection cycle (50000 m3/h during 30 minutes) **without** stress contrasts between sandstones and clays
- Fracture reaches surface after 28 minutes of injection despite shallow high-permeability sands



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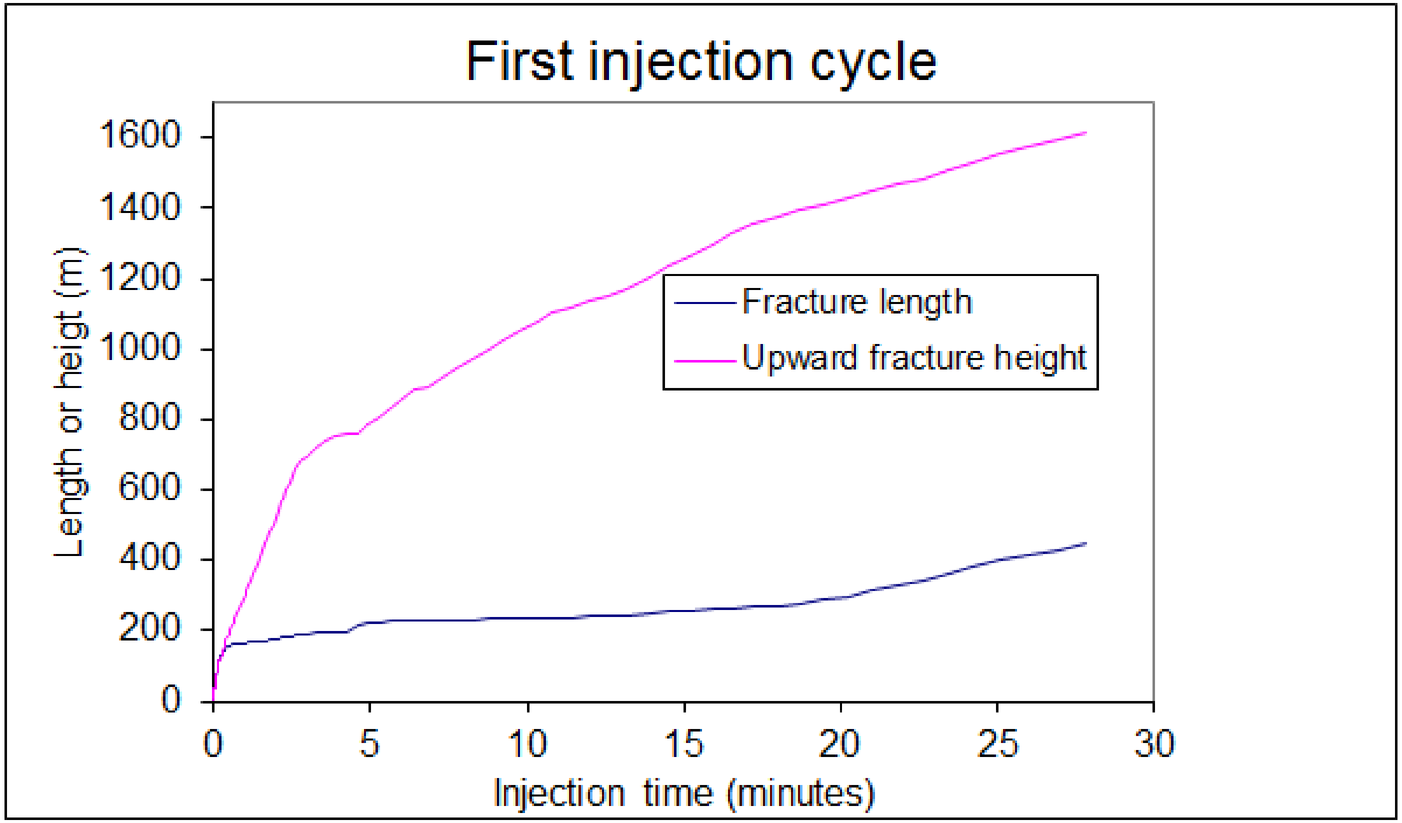
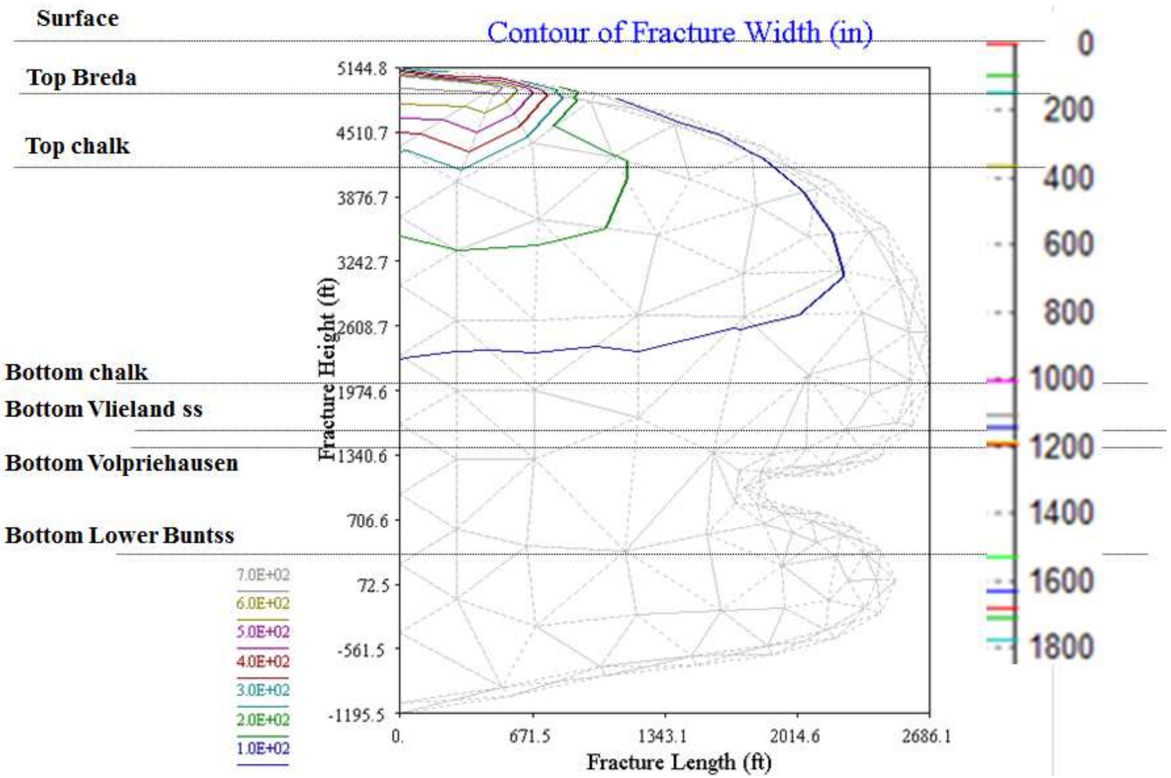


Sensitivity 1a: no stress contrasts sands/clays (BEM) & low E top sands (0.1 GPa)

- First injection cycle (50000 m3/h during 30 minutes) **without** stress contrasts between sandstones and clays & low Young's modulus in high-k top sands
- Fracture does not reach surface after 30 minutes of injection though it does penetrate into shallow high-permeability sands



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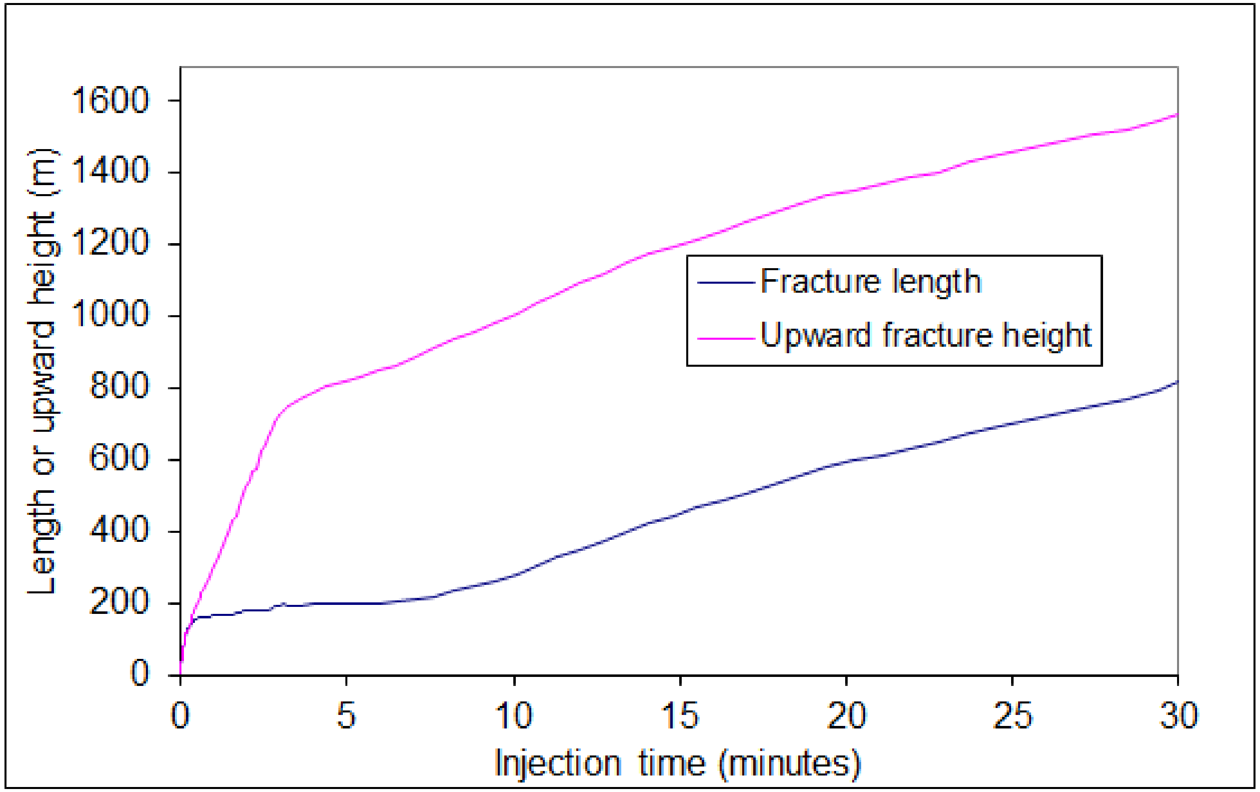
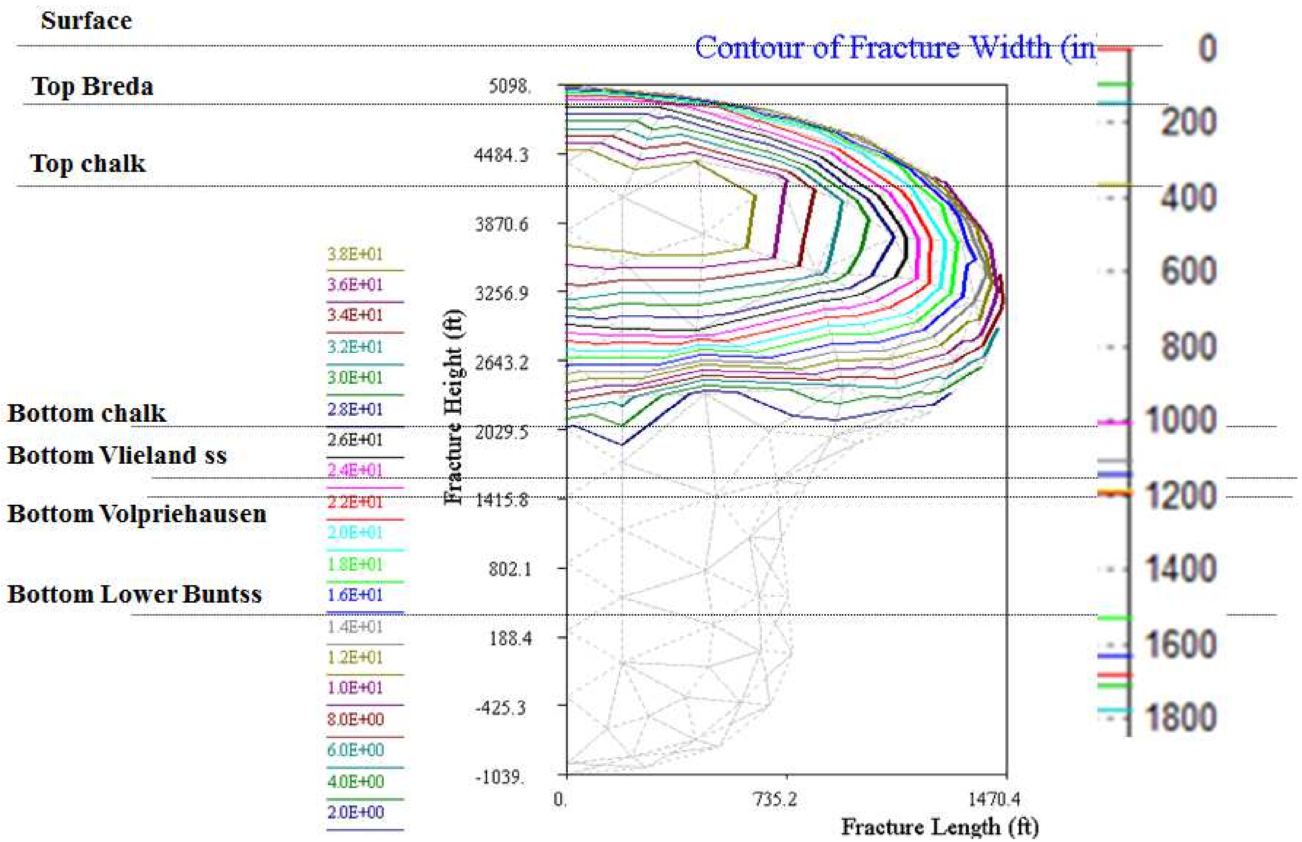


Sensitivity 1b: no stress contrasts Vlieland sand/clay (BEM)

- First injection cycle (50000 m3/h during 30 minutes) **without** stress contrasts only between Vlieland sandstone and Vlieland clay
- Fracture does not reach surface after 30 minutes of injection though it does penetrate into shallow high-permeability sands



Sensitivity 1b: no stress contrasts Vlieland sand/clay(BEM)

- First injection cycle (50000 m3/h during 30 minutes) **without** stress contrasts between Vlieland sandstone and Vlieland clay
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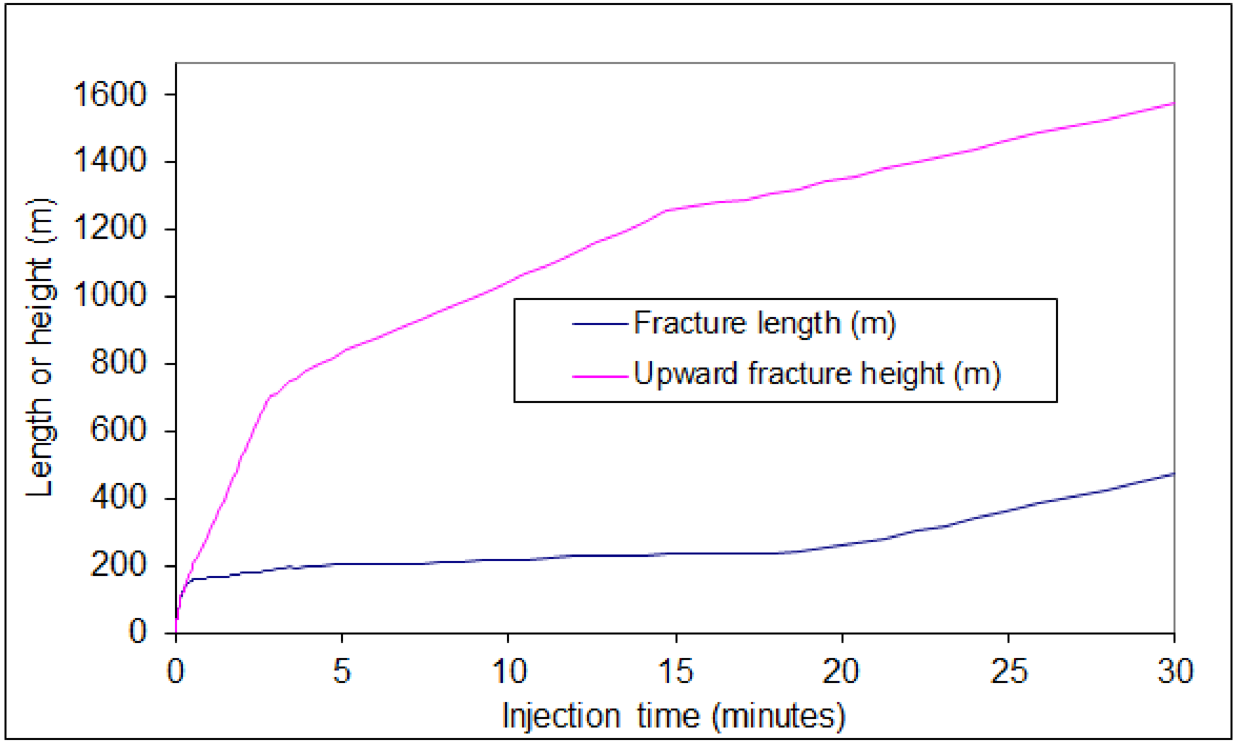
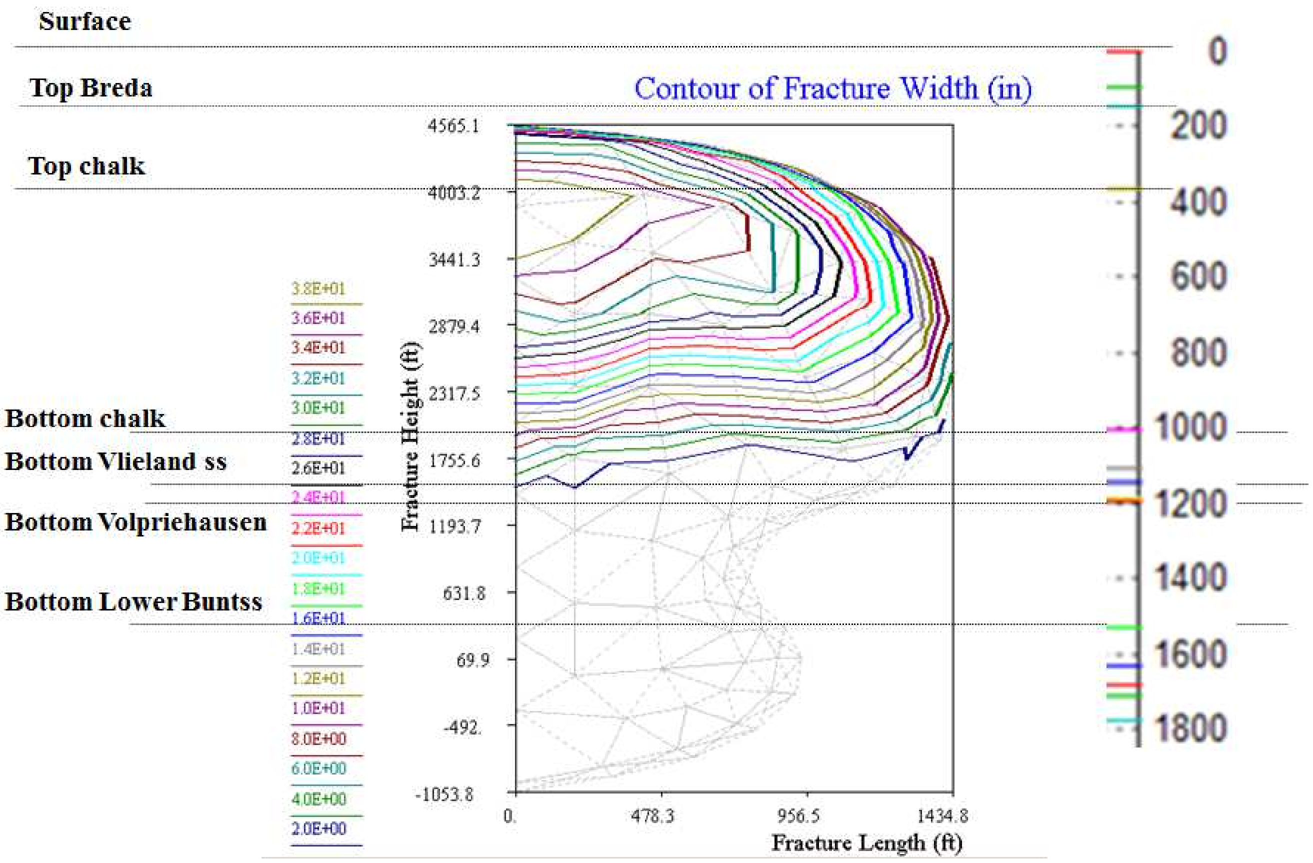


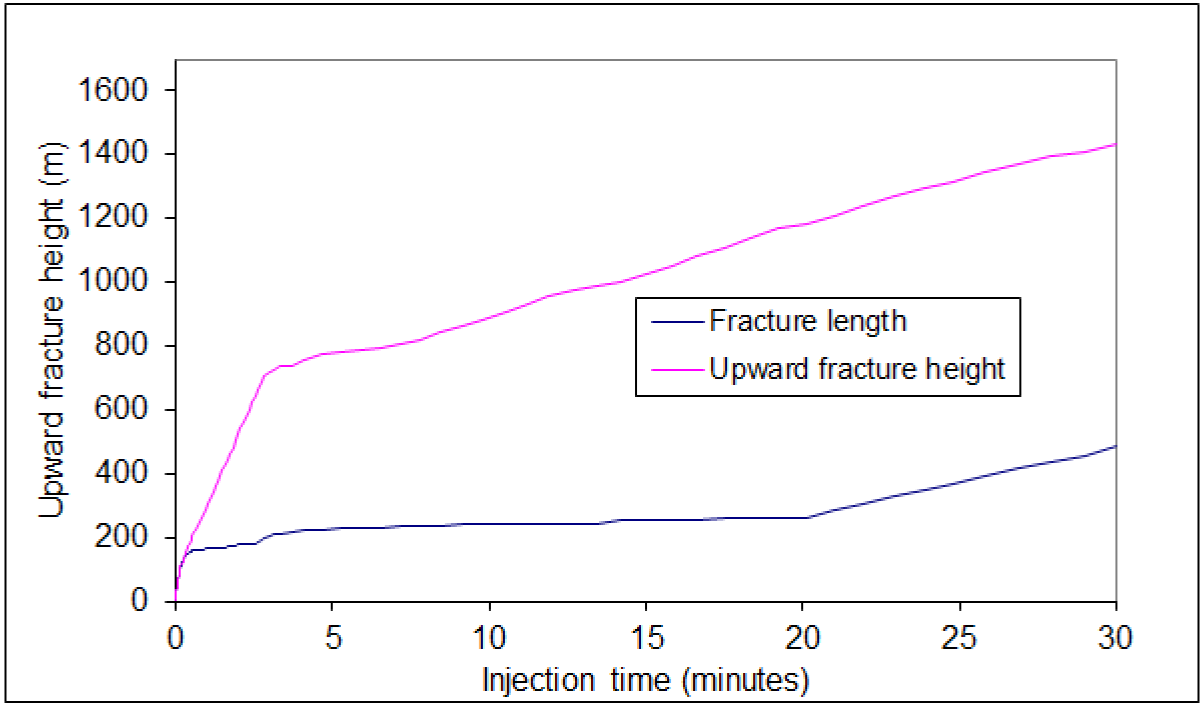
Sensitivity 1c: low stress contrasts (2x lower than bc) Vlieland sand/clay(BEM)

- First injection cycle (50000 m3/h during 30 minutes) **with low** stress contrasts between Vlieland sandstone and Vlieland clay
- Fracture does not reach surface after 30 minutes of injection though it does get close to the shallow high-permeability sands



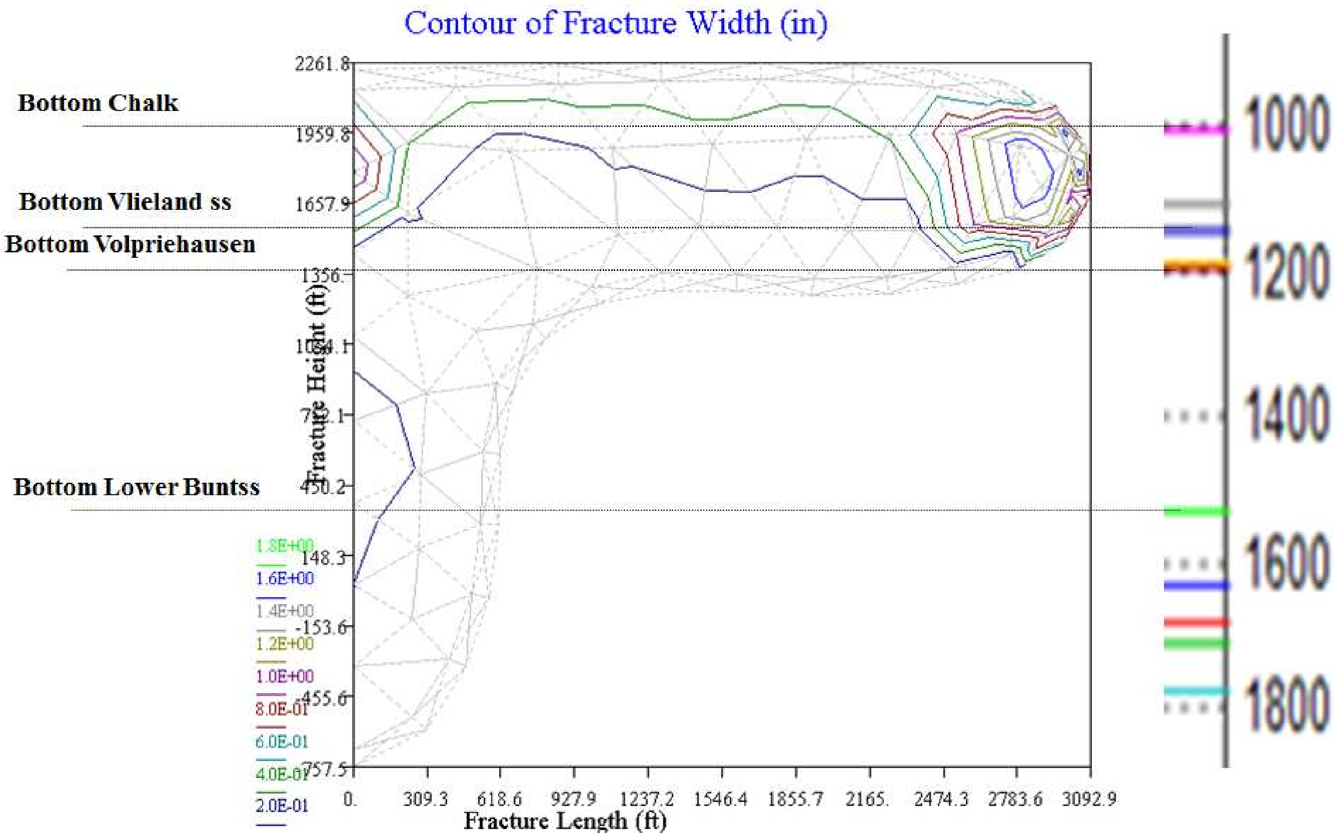
Sensitivity 1c: low stress contrasts (2x lower then bc) Vlieland sand/clay(BEM)

- First injection cycle (50000 m3/h during 30 minutes) **with low** stress contrasts between Vlieland sandstone and Vlieland clay
- Fracture does not reach surface after 30 minutes of injection though it does get close to the shallow high-permeability sands



Sensitivity 1d: high stress contrasts (2x higher then bc) Vlieland sand/clay(BEM)

- First injection cycle (50000 m3/h during 30 minutes) **with high** stress contrasts between Vlieland sandstone and Vlieland clay
- Results are very similar to the base case



Sensitivity 1d: high stress contrasts (2x higher then bc) Vlieland sand/clay(BEM)

- First injection cycle (50000 m3/h during 30 minutes) **with high** stress contrasts between Vlieland sandstone and Vlieland clay
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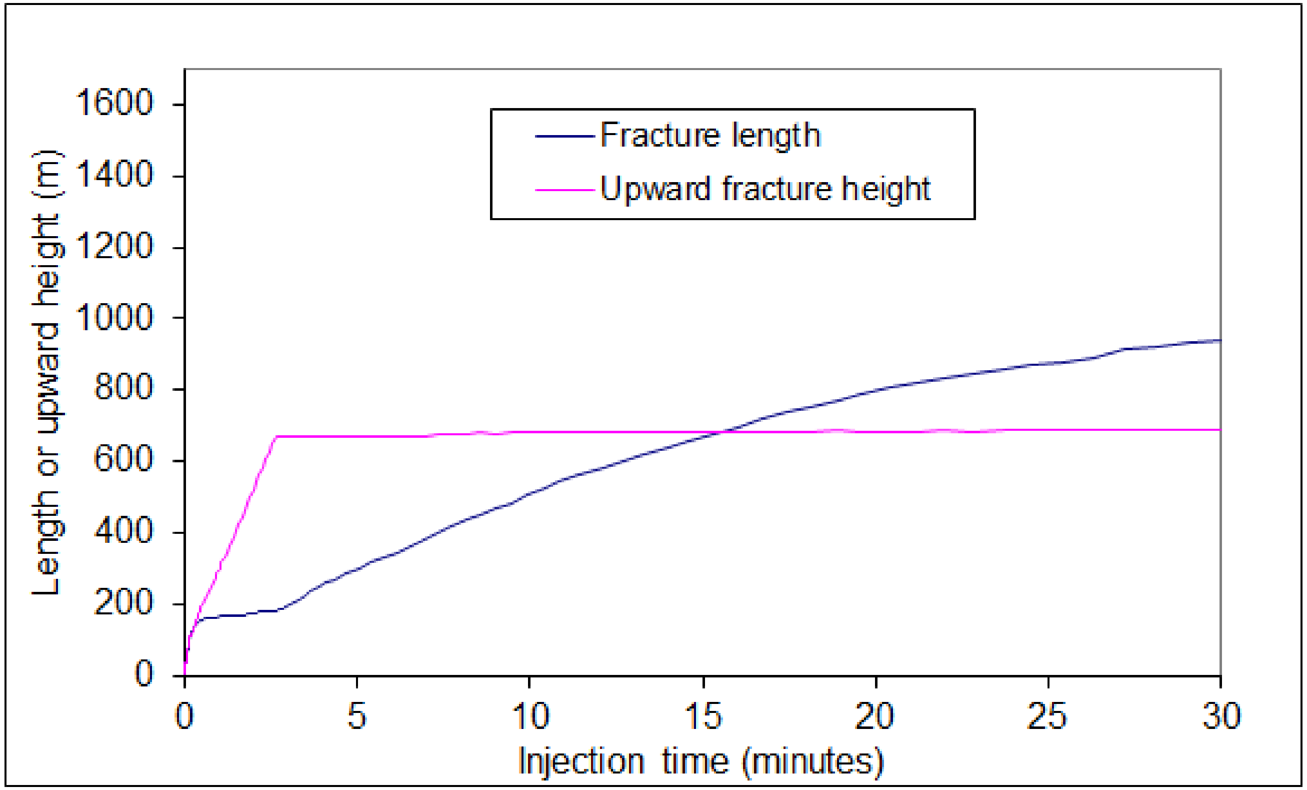
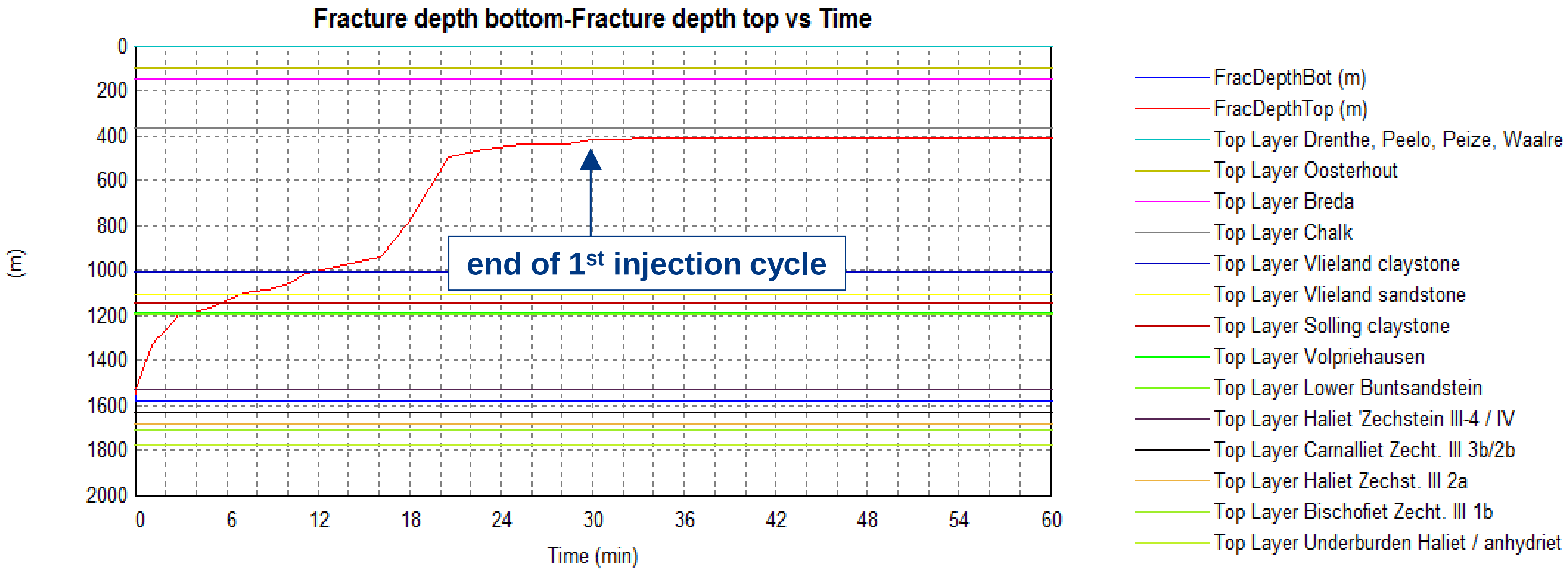
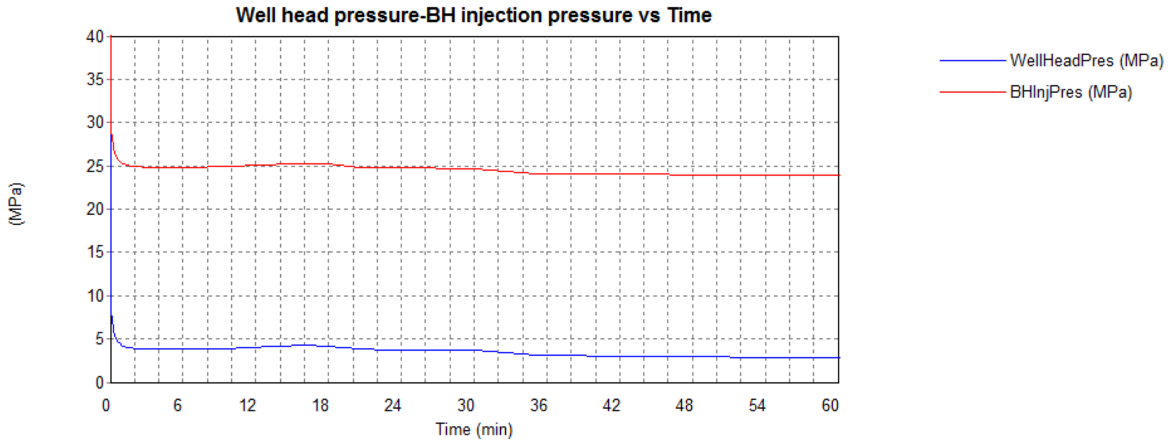


Sensitivity 2: injection point in top halite

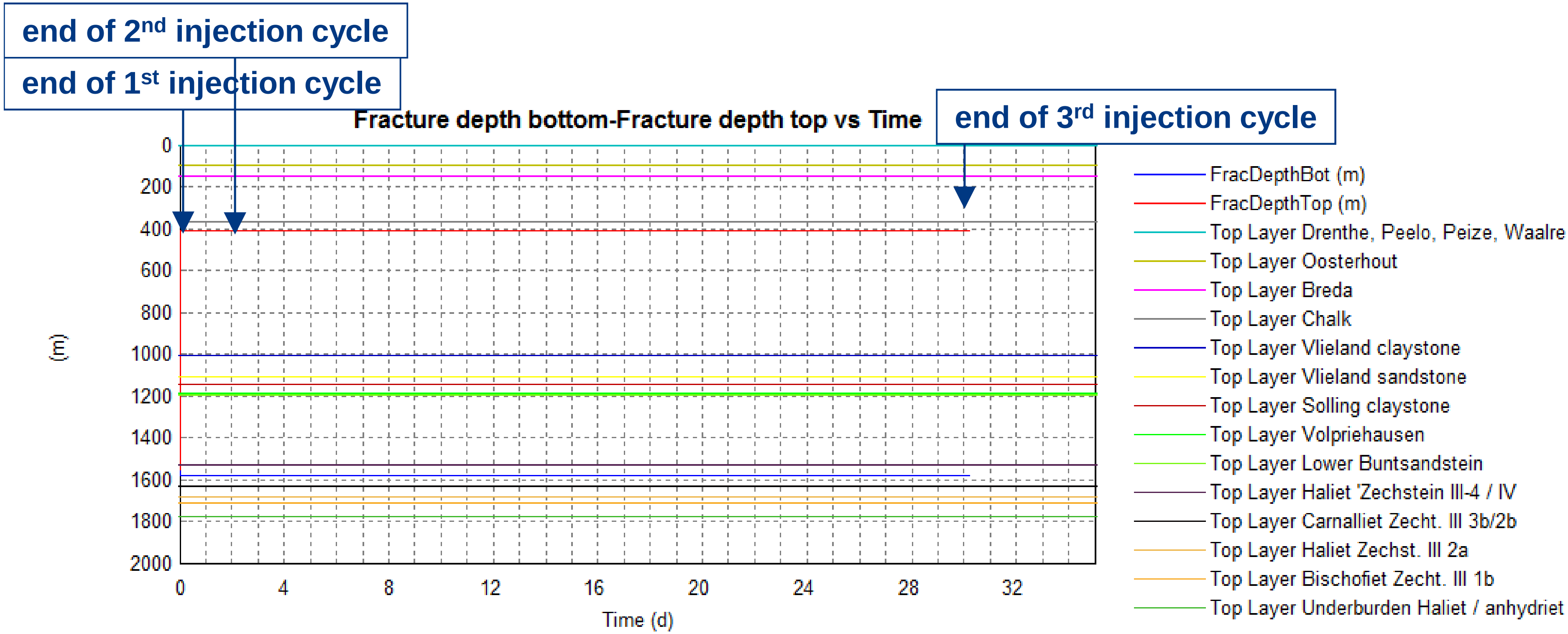
Results after 1 hour of injection

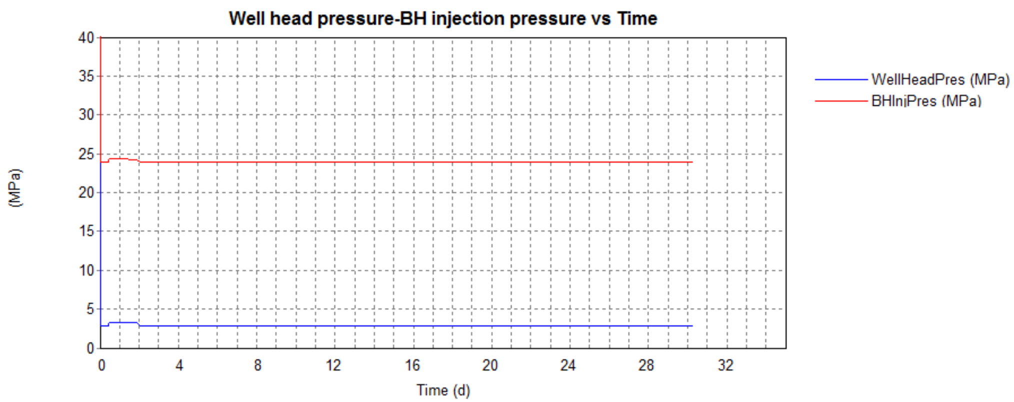




Sensitivity 2: injection point in top halite

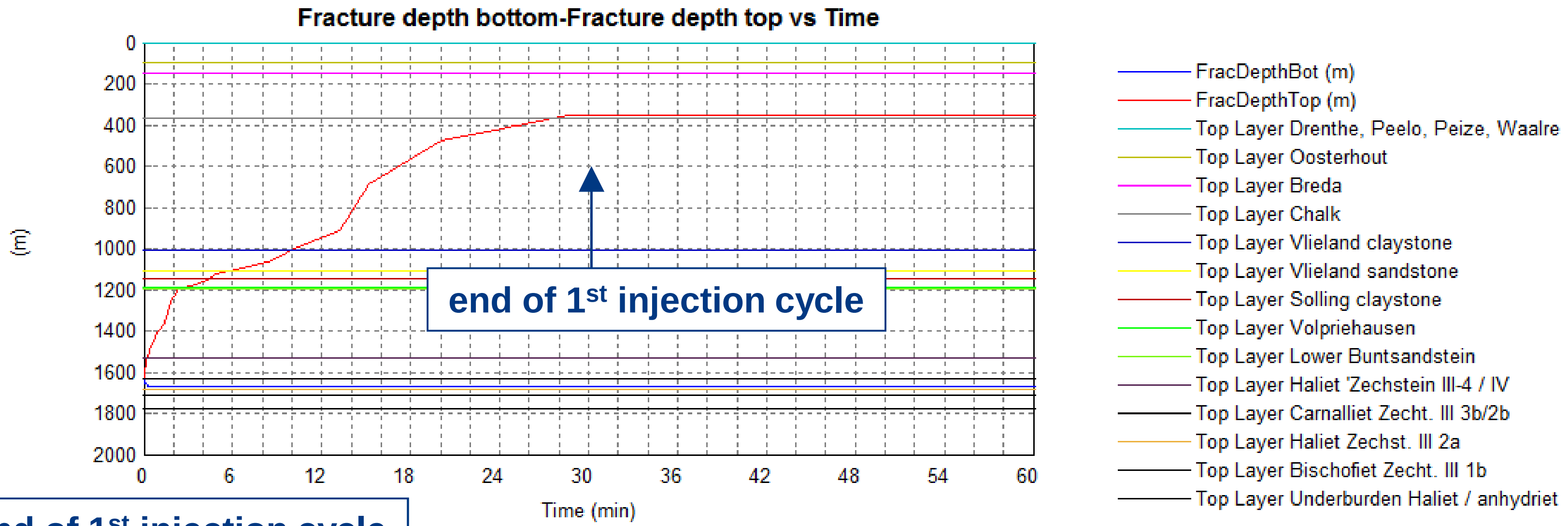
Results after 30 days of injection

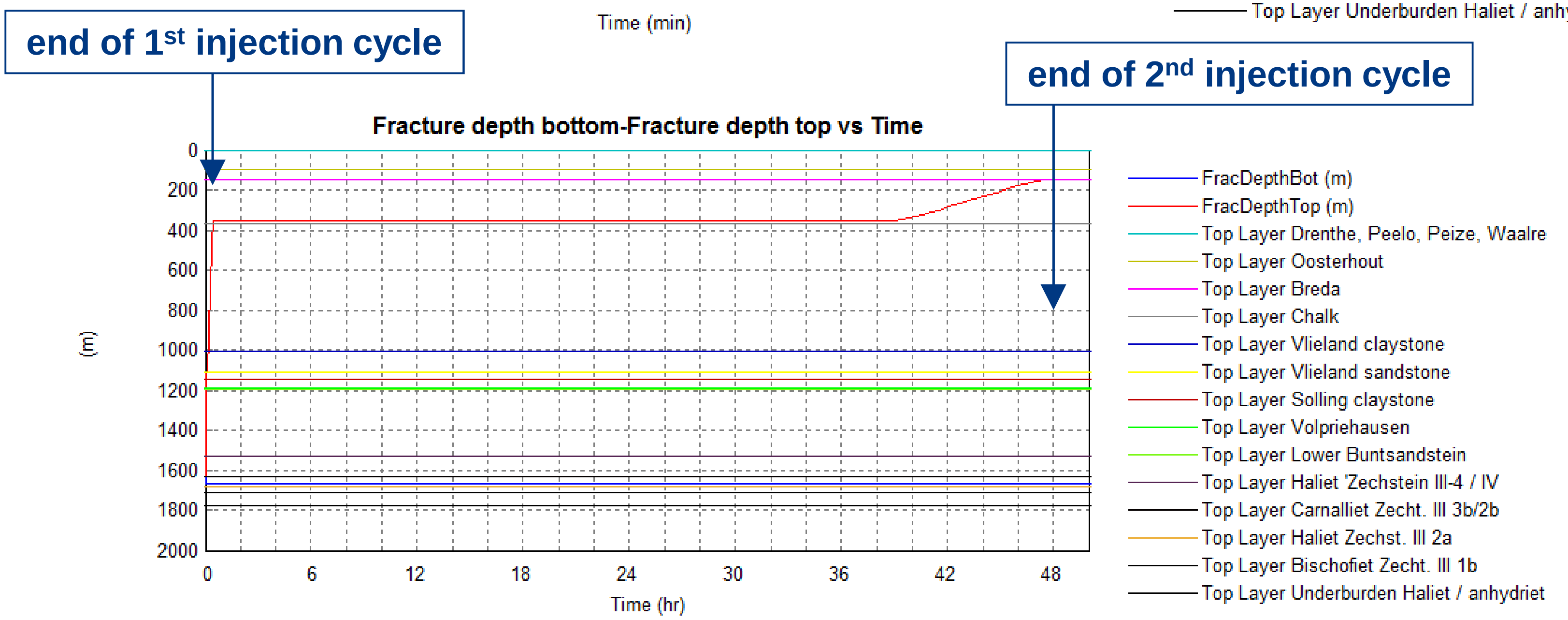




Sensitivity 3: low $k_{Vlieland}$ (30 mD)

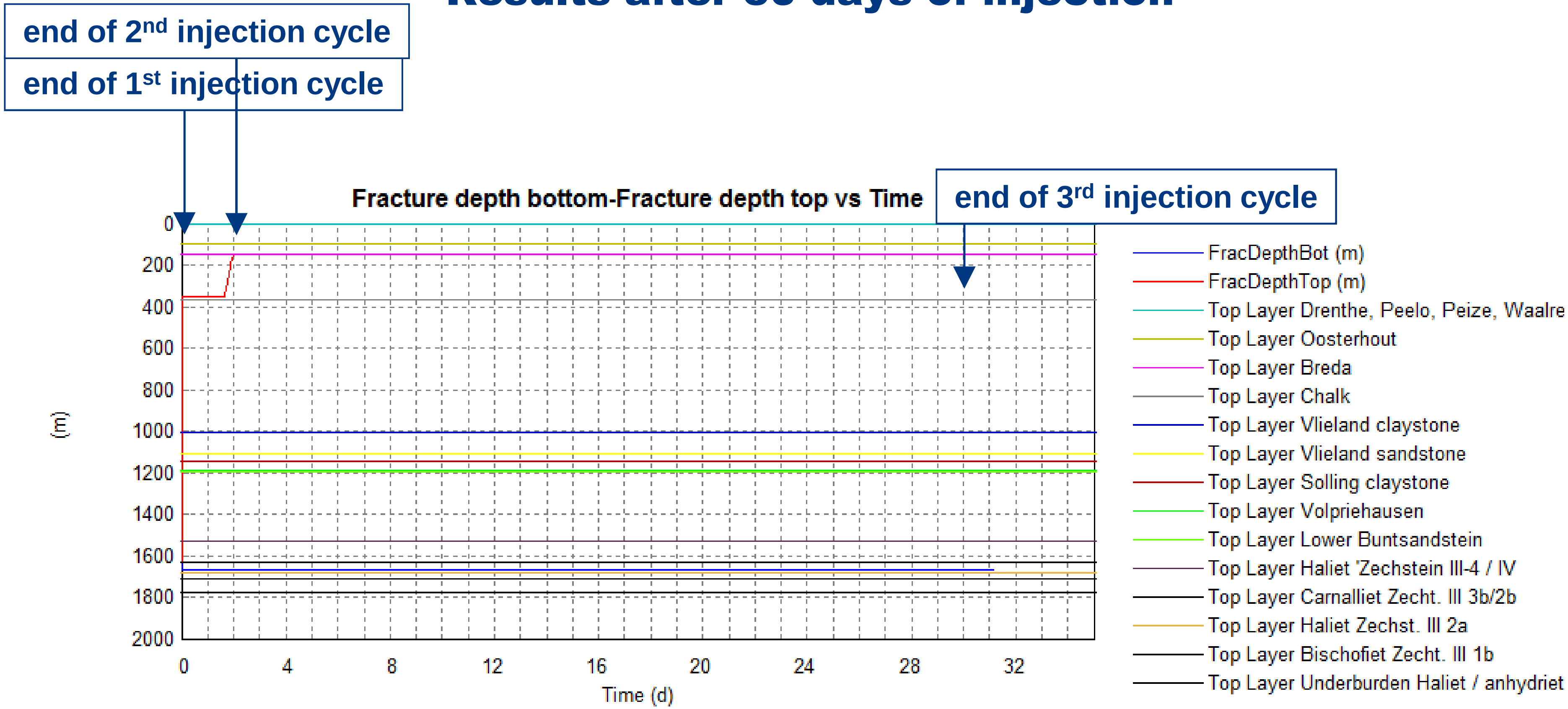
Results after 1 hour & 50 hours of injection

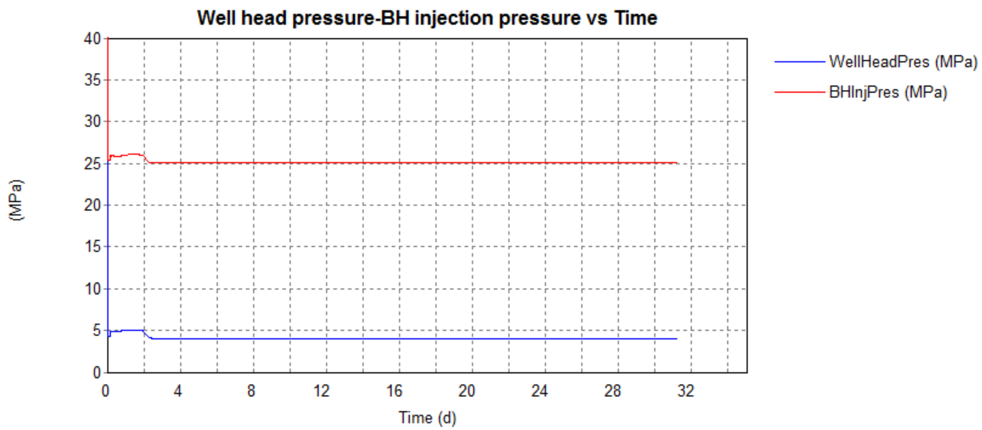




Sensitivity 3: low $k_{Vlieland}$ ($k_{Vlieland}$=30 mD)

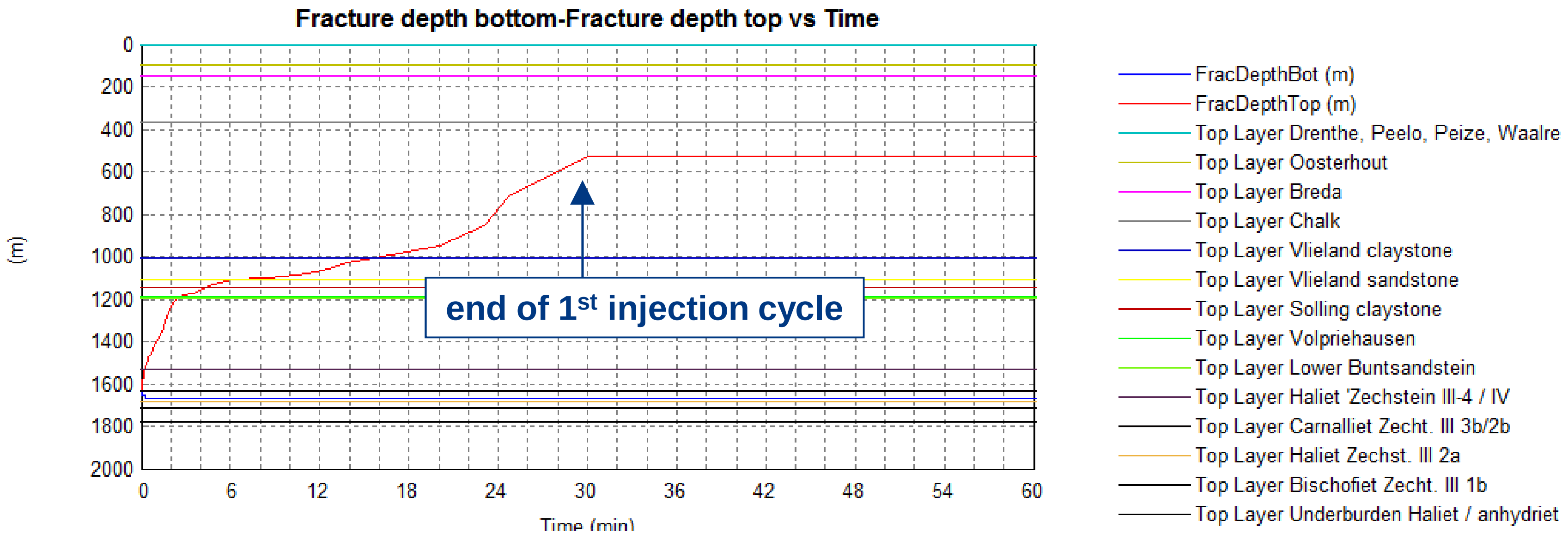
Results after 30 days of injection

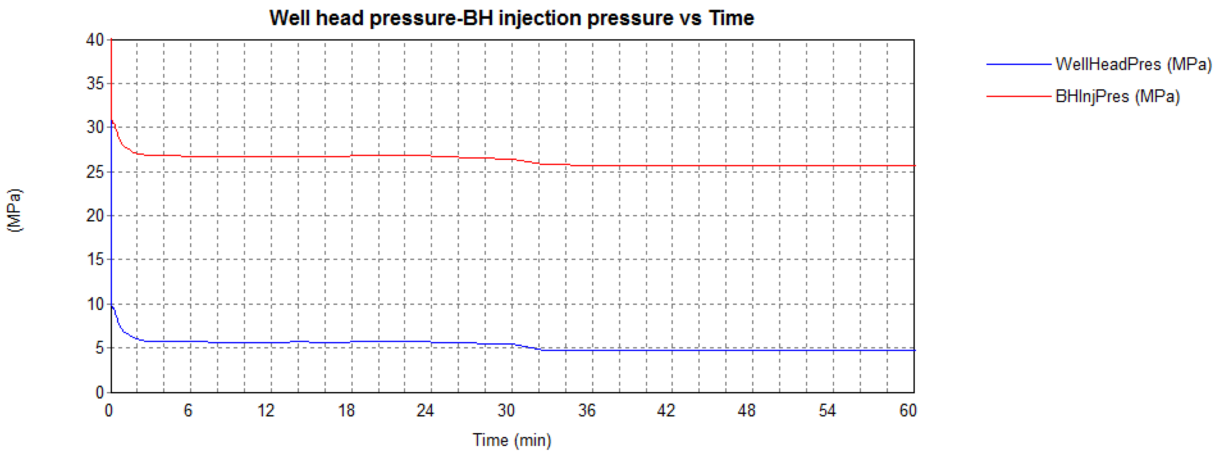




Sensitivity 4: high $k_{Vlieland}$ ($k_{Vlieland}$= 3000 mD)

Results after 1 hour of injection



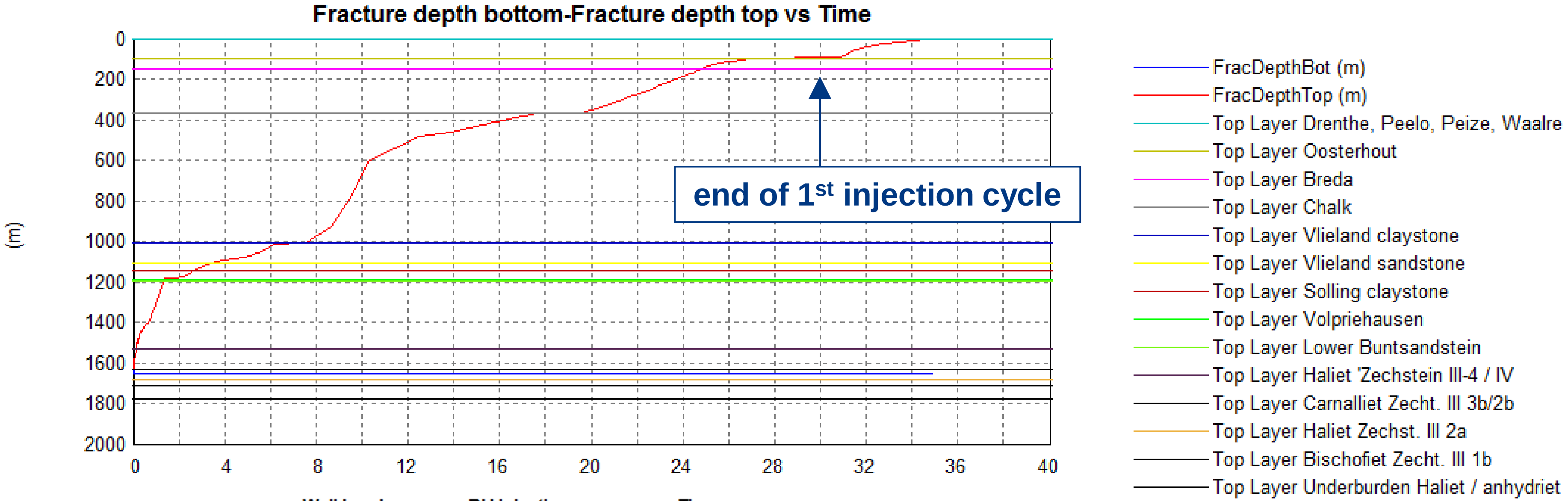


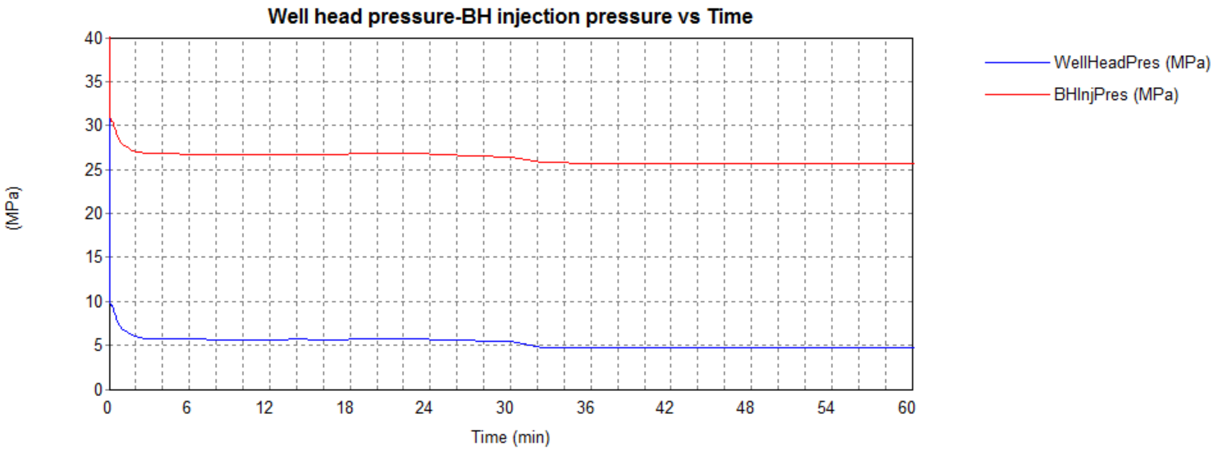
- No further upward growth after cycle 1 (as in base case)

Sensitivity 5: high injection rates

(75000 m3/h – 1575 m3/h – 150 m3/h)

Results after 40 minutes of injection

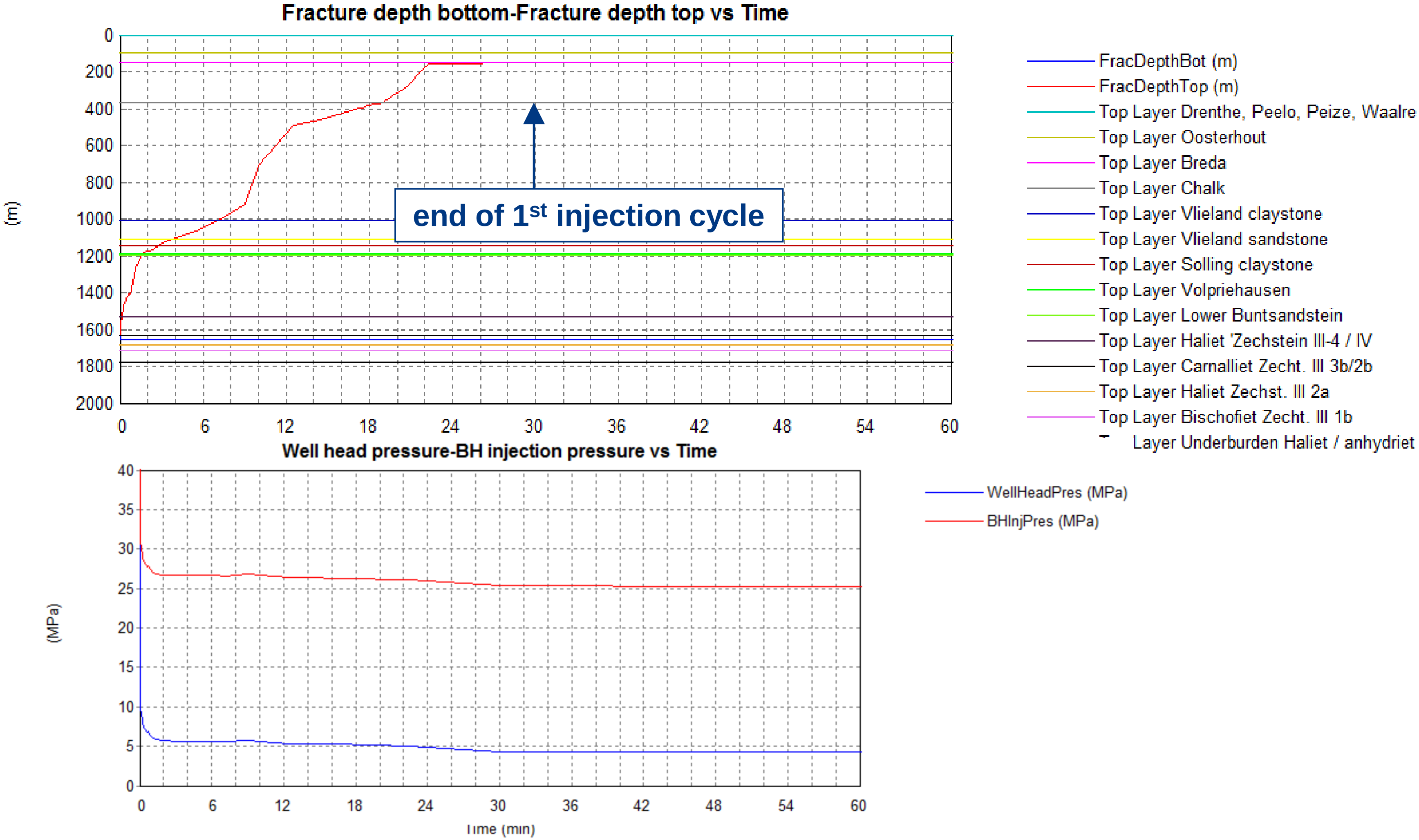




- Fracture grows to surface

Sensitivity 5a: high injection rates & low E (0.1 GPa) in top sands

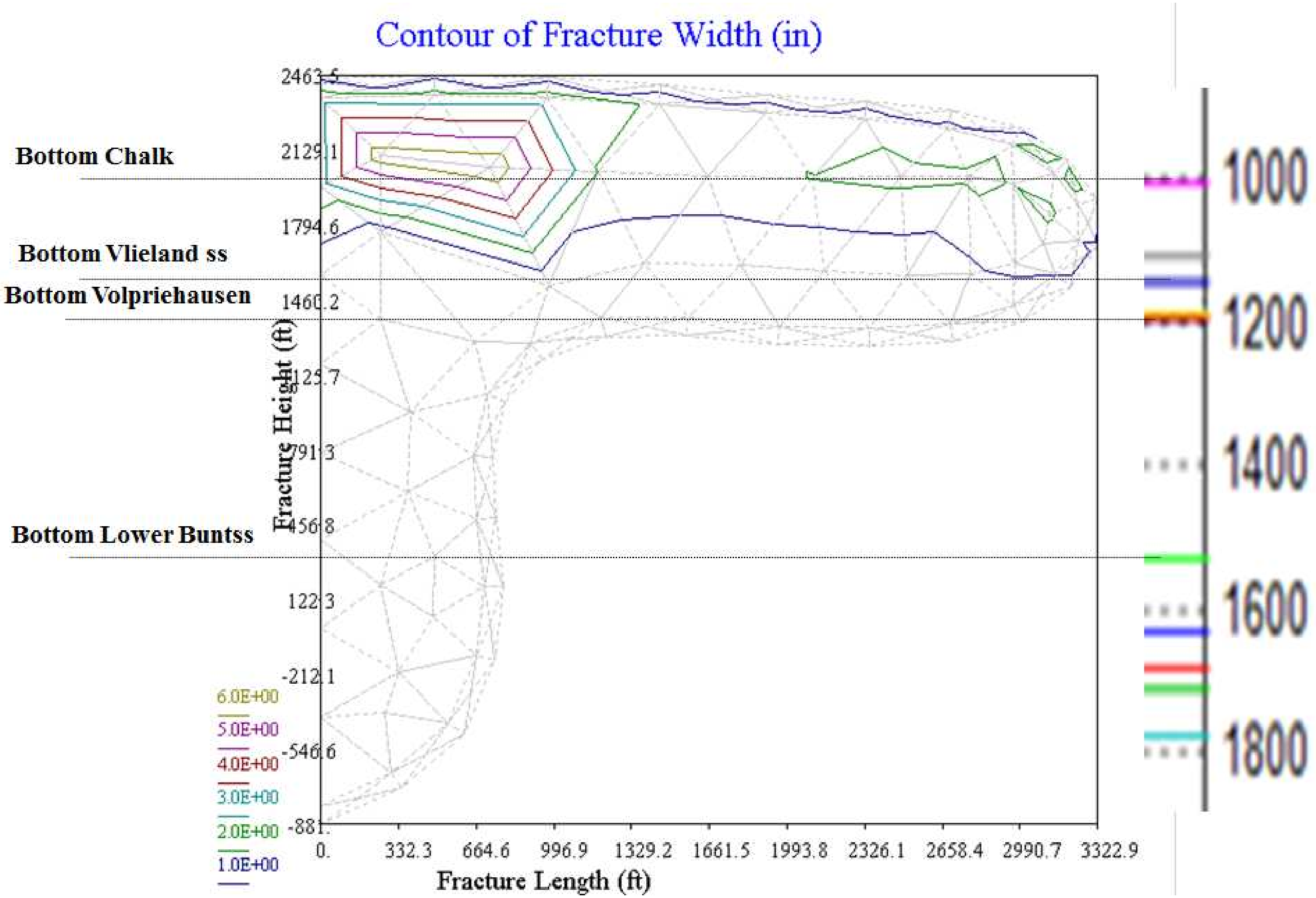
Results after 60 minutes of injection



- No further upward growth after cycle 1 (as in base case)

Sensitivity 5b: high injection rate 1st cycle

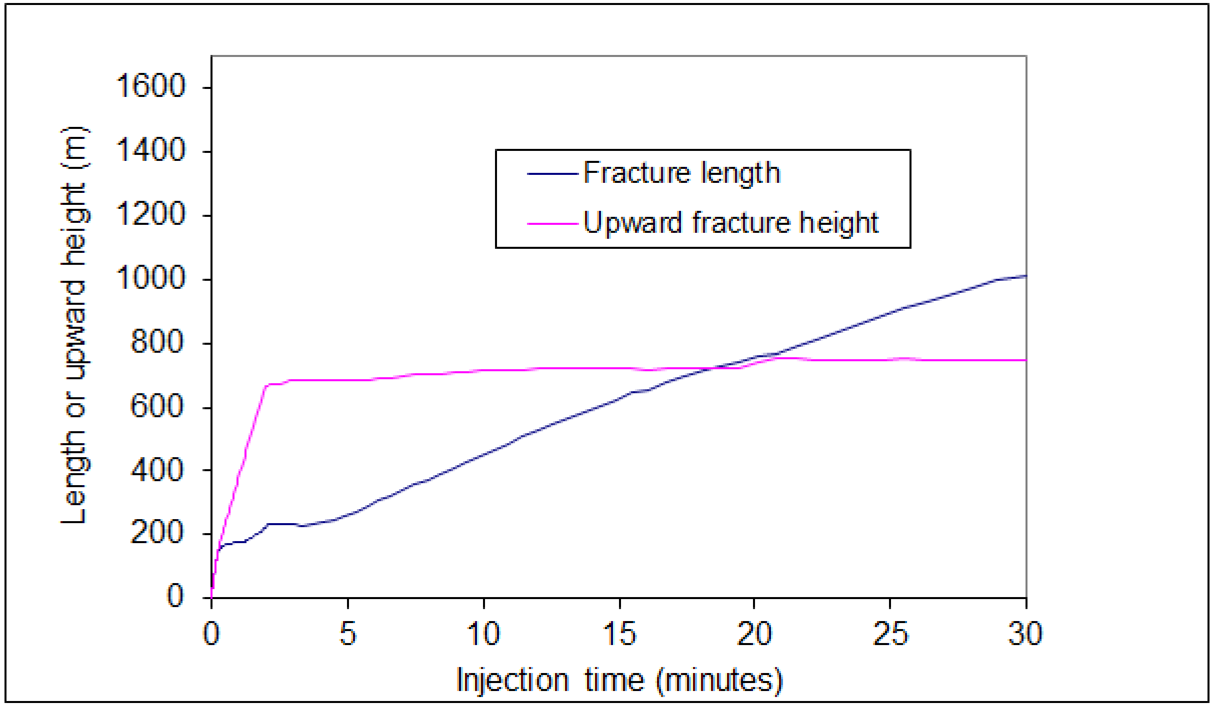
BEM model Results after 30 minutes of injection



- Results very similar to base case

Sensitivity 5b: high injection rate 1st cycle

BEM model Results after 30 minutes of injection

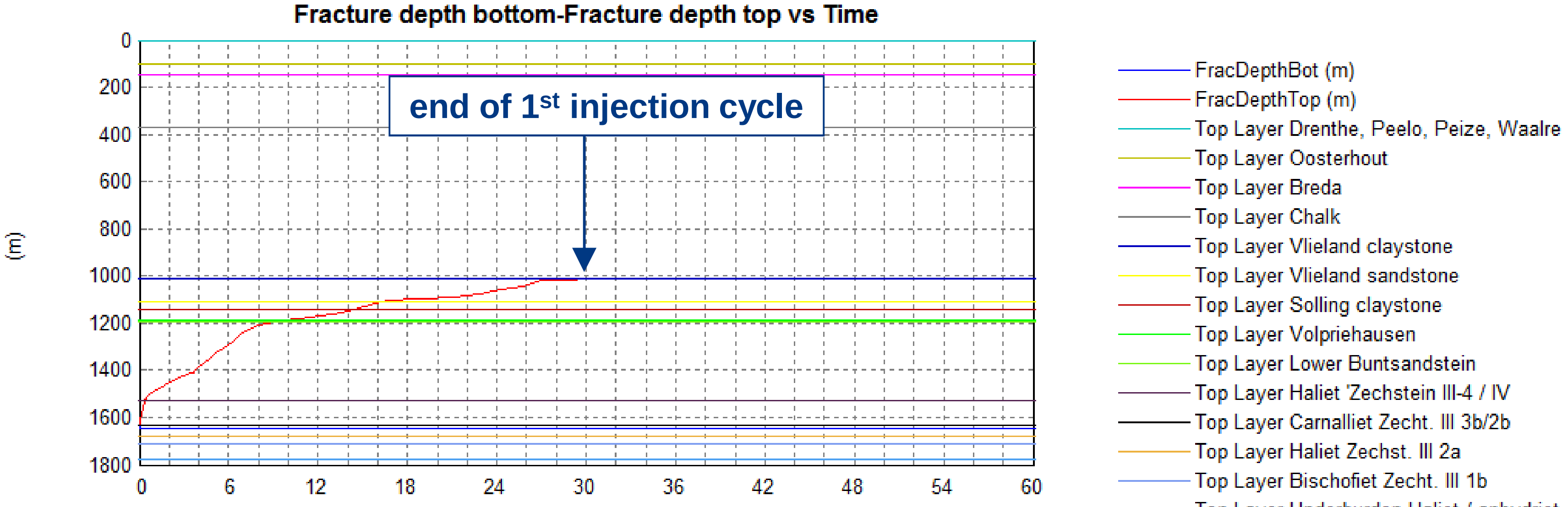


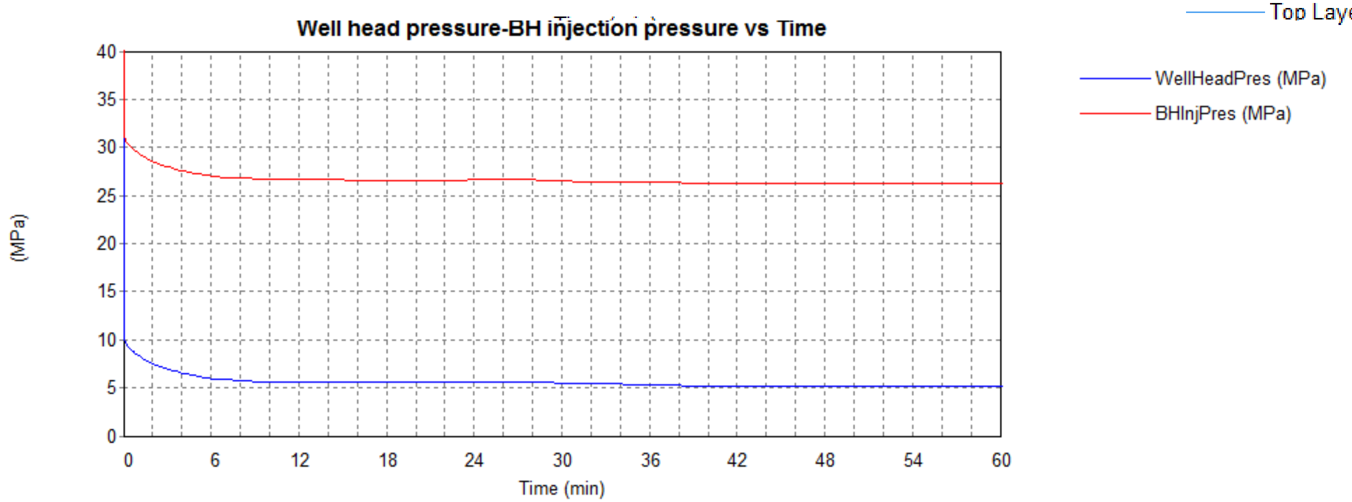
- Results very similar to base case

Sensitivity 6: low injection rates

(25000 m3/h – 525 m3/h – 50 m3/h)

Results after 60 minutes of injection

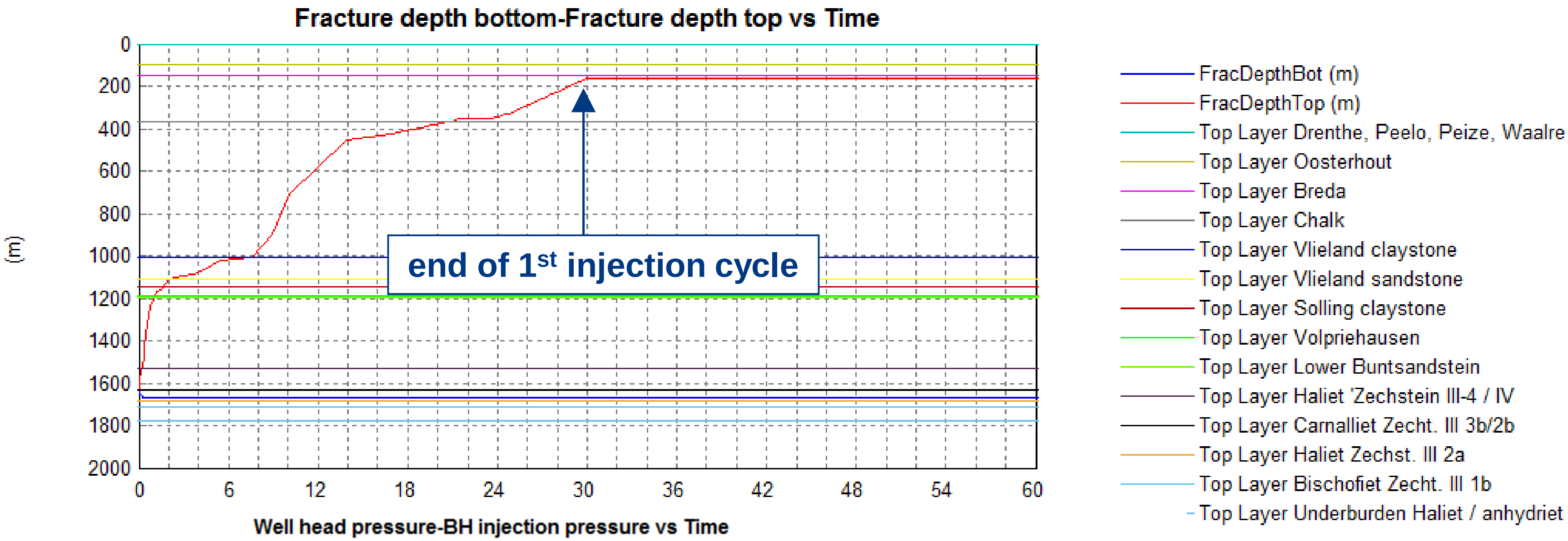


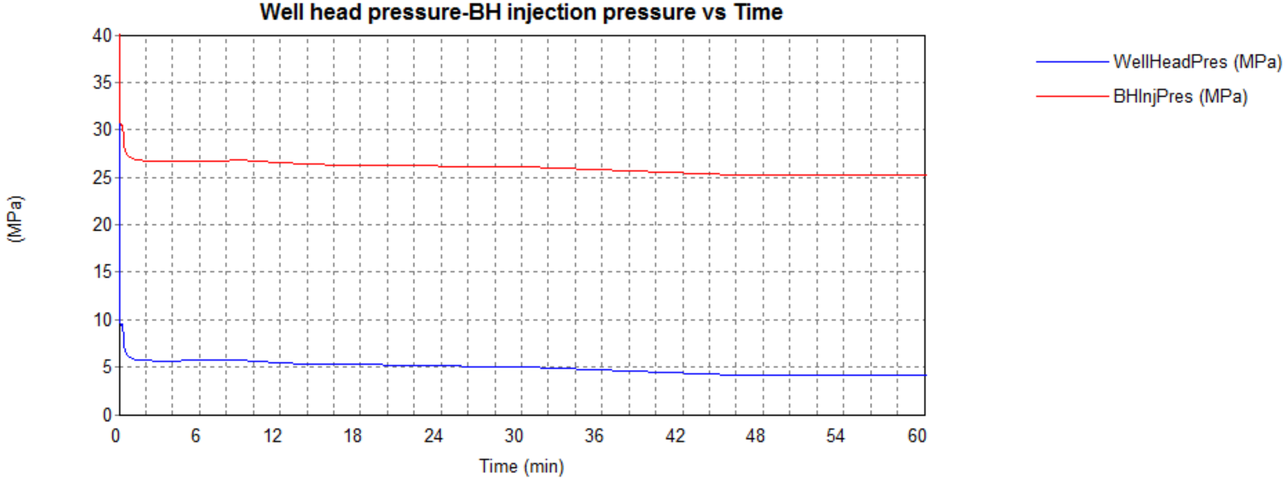


- No further upward growth after cycle 1 (as in base case)

Sensitivity 7: low k_{Bunter} (k_{Bunter} = 0.1 mD)

Results after 60 minutes of injection

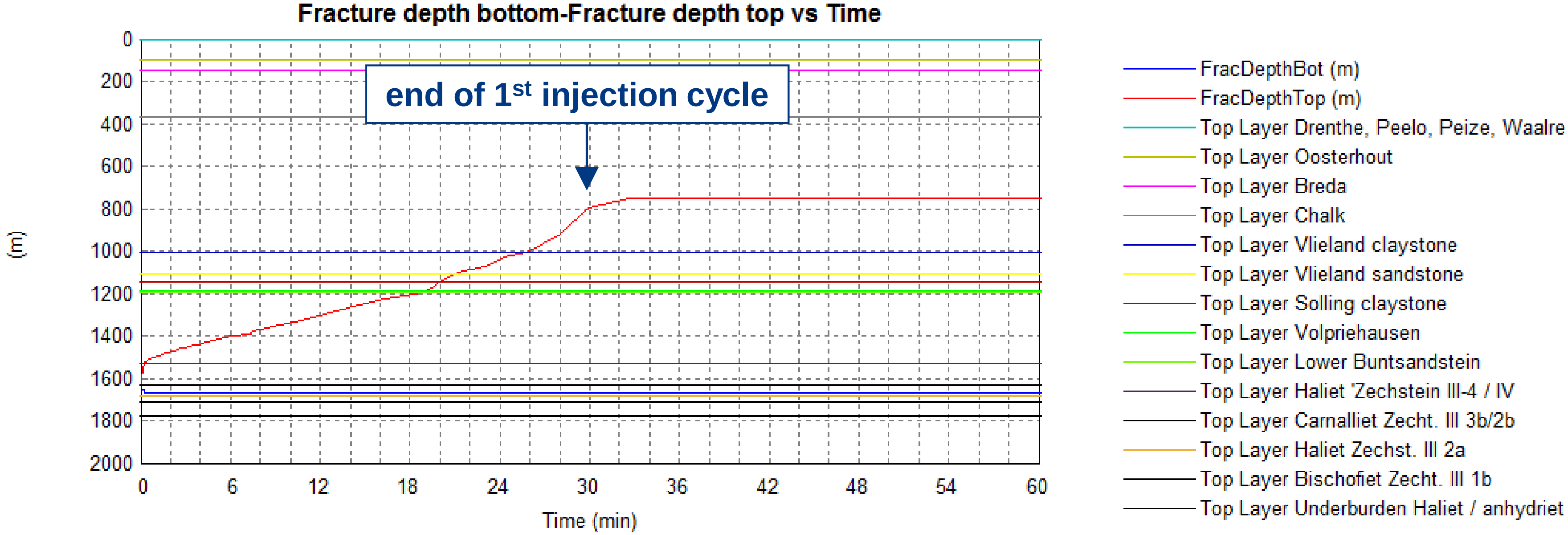


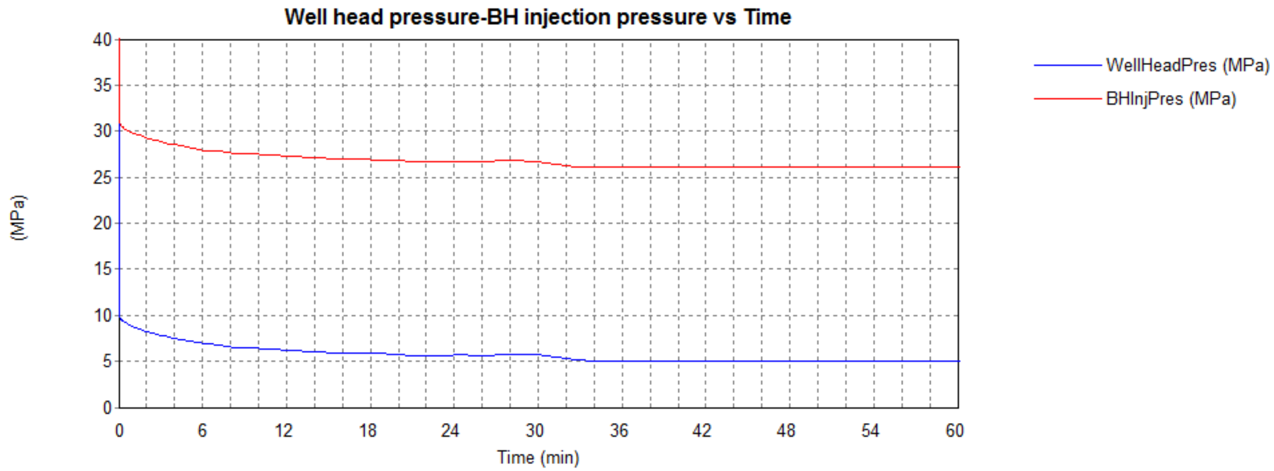


- No further upward growth after cycle 1 (as in base case)

Sensitivity 8: high k_{Bunter} (k_{Bunter} = 10 mD)

Results after 60 minutes of injection

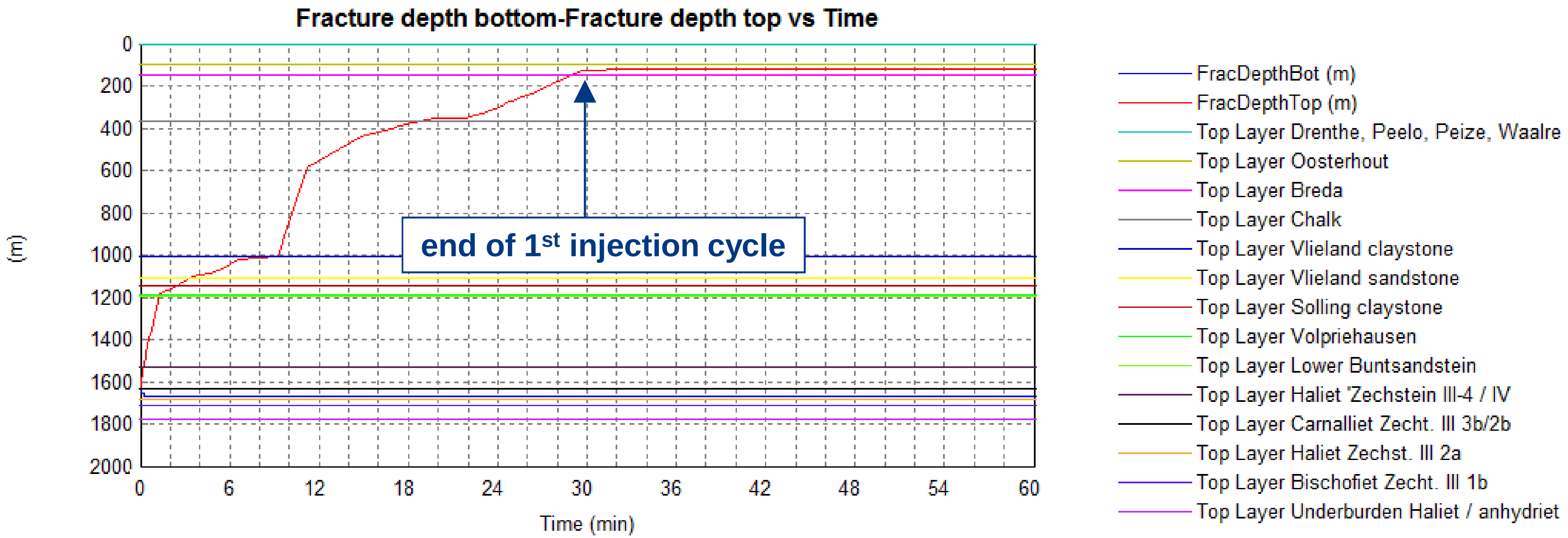


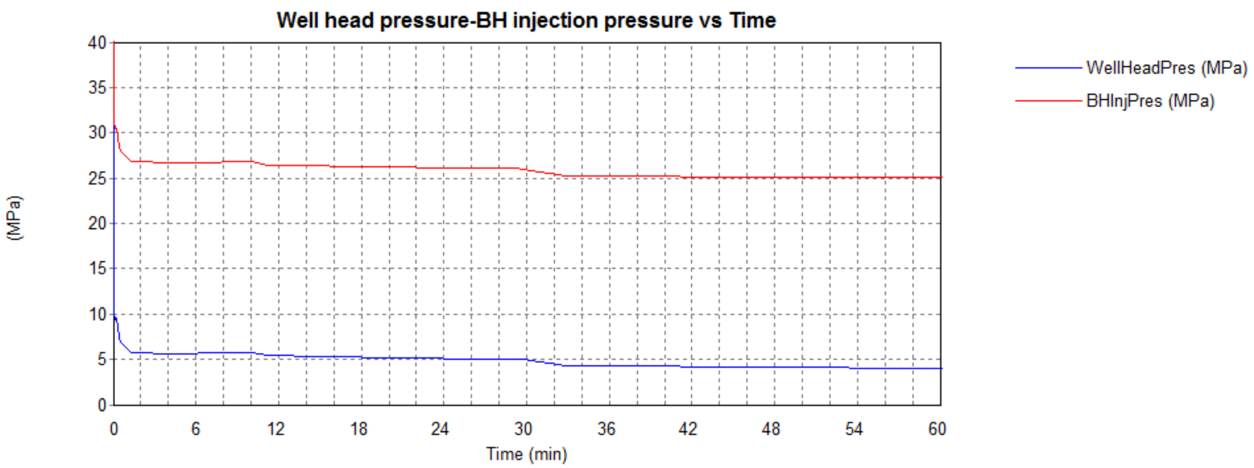


- No further upward growth after 32-33 minutes (beginning of cycle 2)

Sensitivity 9: all formation k's divided by 3

Results after 60 minutes of injection

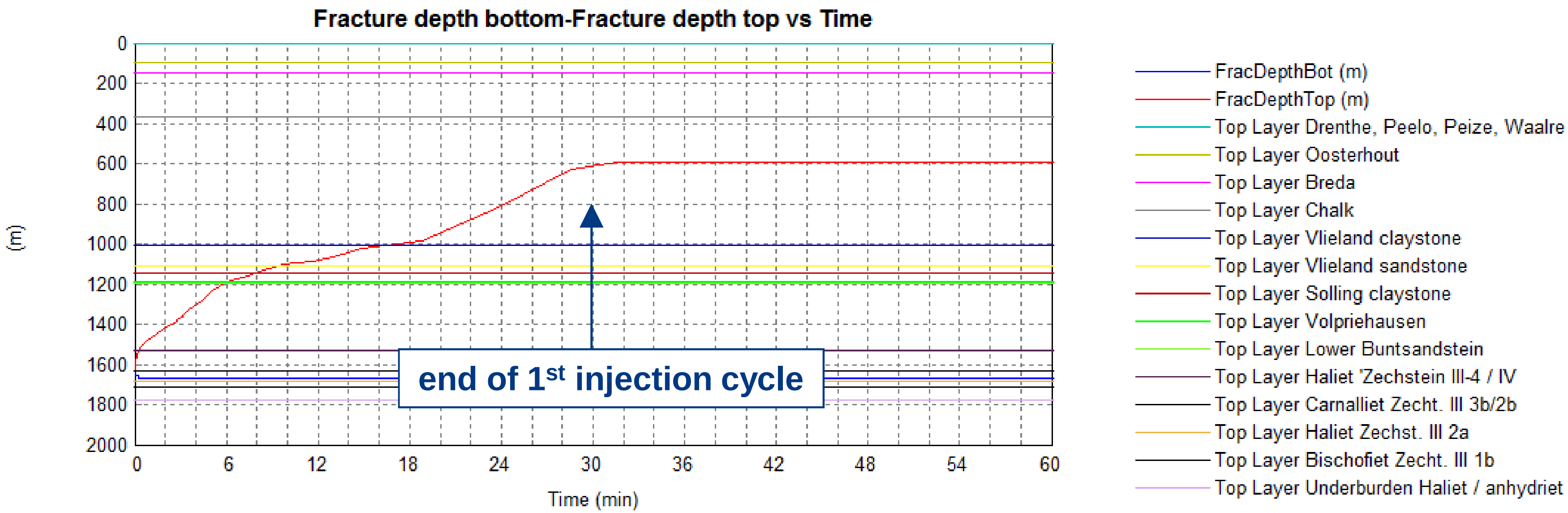


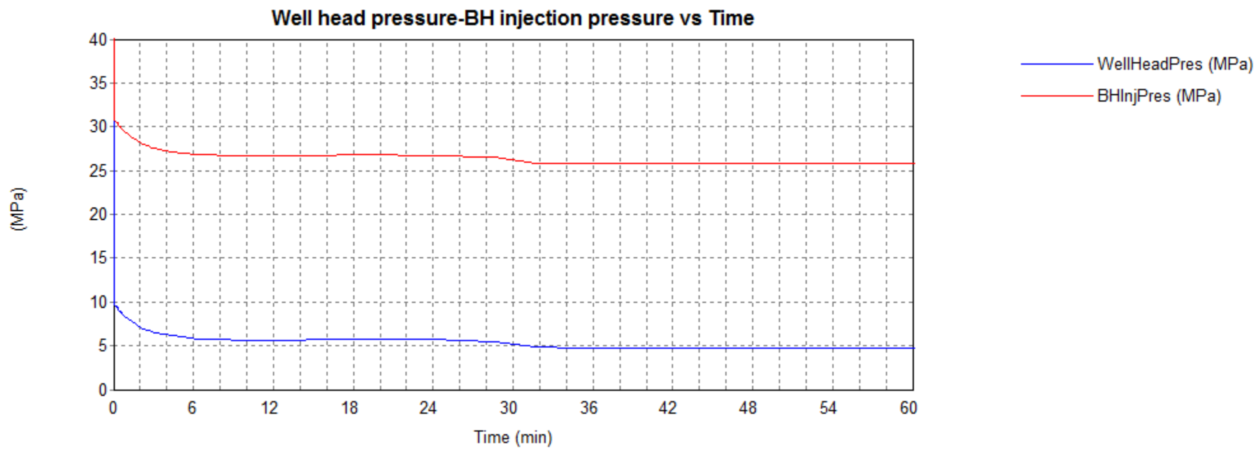


- No further upward growth after 32-33 minutes (beginning of cycle 2)

Sensitivity 10: <u>all</u> formation k's multiplied by 3

Results after 60 minutes of injection

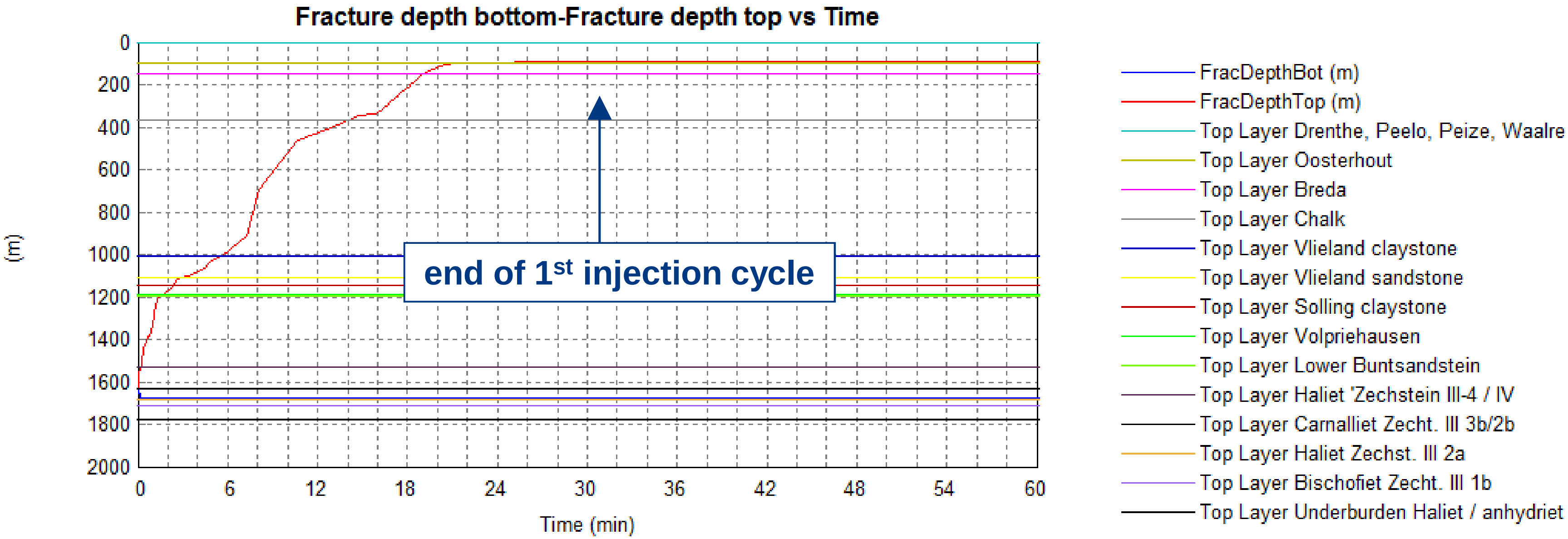




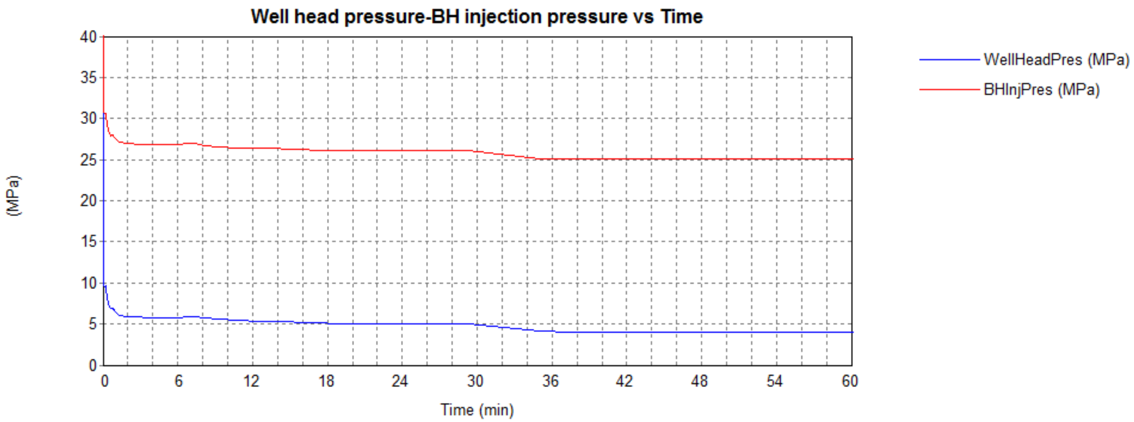
- No further upward growth after 32-33 minutes (beginning of cycle 2)

Sensitivity 11: fracture length at start: 100 m

Results after 60 minutes of injection



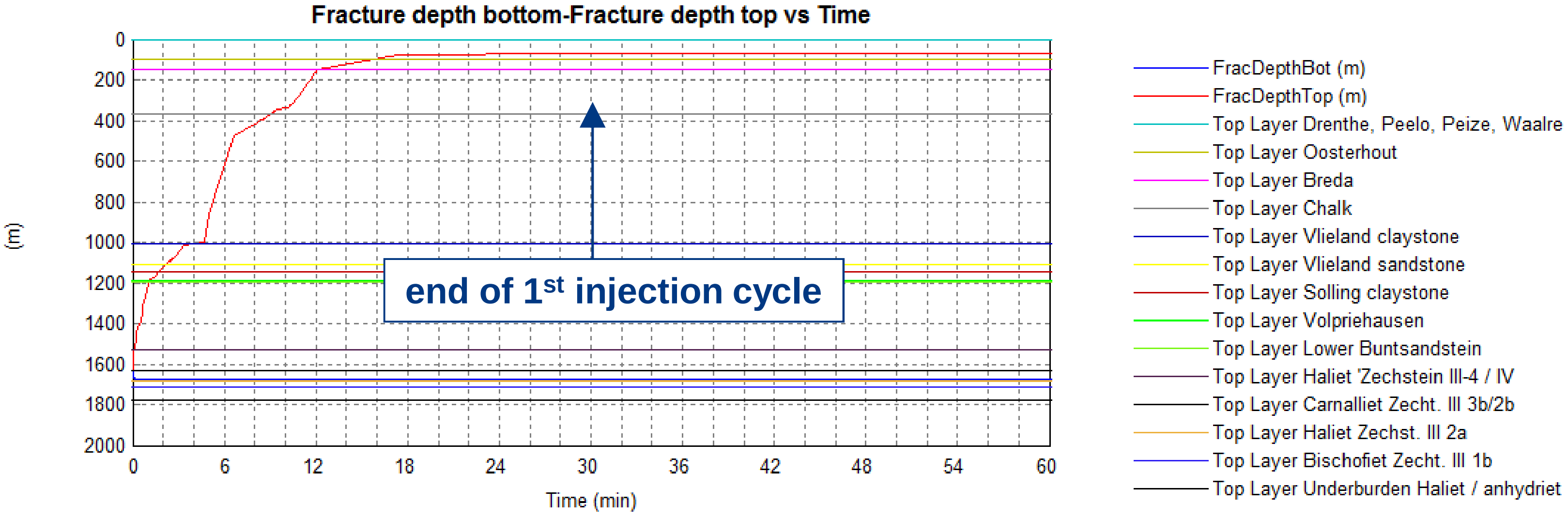
- Final fracture length: 100 m



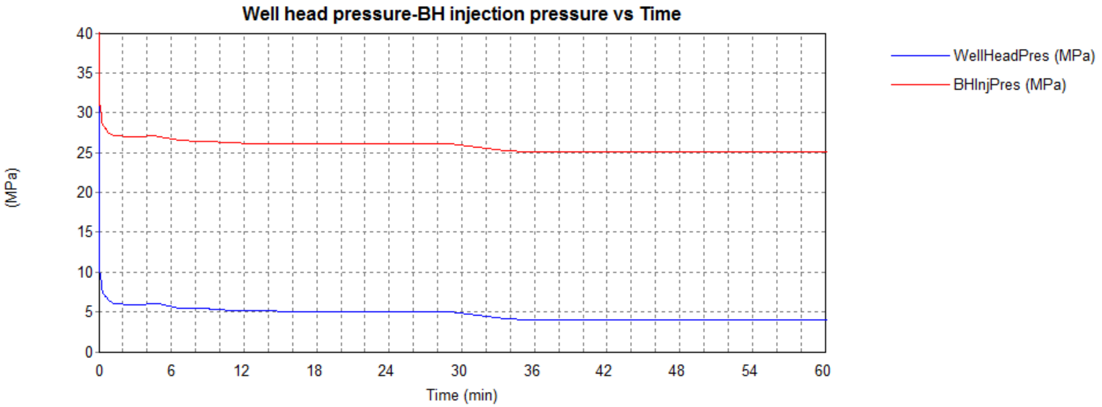
- No further upward growth after cycle 1 (as in base case)

Sensitivity 12: fracture length at start: 50 m

Results after 60 minutes of injection



- Final fracture length: 76 m



- No further upward growth after cycle 1 (as in base case)

Discussion of sensitivities (1)

- **Stress contrasts (sens. no 1):** The two models used yield different results. The final result using the fractured water injection model (‘model 1’) is hardly sensitive to the presence of absence of stress contrasts between sands and clays. By contrast, results using the BEM model (‘model 2’) strongly depend on the presence on stress contrasts, primarily between Vlieland sandstone and Vlieland clay. For fracture containment to the deeper layers, an appreciable stress contrast (ca. 20 bar) is required. For lower stress contrasts, the BEM model also predicts fracture growth towards the shallow layers or surface.
- **Injection rate (sens. no 5):** Higher injection rates yield larger fractures, in line with expectations. They grow either more upward (model 1) or in length (model 2 with sufficiently high stress contrasts). Conversely, lower injection rates yield smaller fractures.
- **Young’s modulus of shallow sands (sens. no’s 1a, 5a):** A lower Young’s modulus (0,1 GPa) for the shallow high permeability sands helps to retard upward fracture growth because larger deformations are allowed before the formation starts to crack.
- **Permeabilities of Vlieland (sens. 3,4) OR Bunter (sens. 7,8) sandstones:** Significant permeability changes (factor 10) are required in order to have an impact on fracture growth. This is because if only one of these layers ‘has its permeability changed’, the impact on fracture growth is partly compensated for by leakage into another layer. Impact of permeability changes on fracture growth is qualitatively as expected.
- **Permeabilities of <u>all</u> permeable layers (sens. 9,10):** Changing permeabilities of <u>all</u> layers simultaneously, even by a ‘modest’ amount (factor 3) has a clear impact on fracture growth.

Discussion of sensitivities (2)

- **Injection point (sens. no 2):** Injection from the top Halite instead of the top Carnalite does not impact the final results.
- **Length of initial fracture (sens. no 11,12):** In model 1, the fracture length exhibits a limited increase beyond its initial value. This is a consequence of the assumed fracture shape (two half-ellipses, see slide 3). Therefore, for the initial fracture lengths of 100 m and 50 m, which are both lower than the base case, the final fracture upward height is larger. This is because the total leakage area has to remain approximately the same. Please note: although most brine leaks away in the Vlieland sandstone, the leakage volumes in the low-*k*h* formations (Chalk, Volpriehausen, Bunter) are certainly non-negligible, as is also clear from the permeability sensitivities (3,4,7-10).

Conclusions (1)

- Fracture propagation study in order to improve understanding of what happened during leakage event on 20 April 2018
- In this study two different hydraulic fracture simulators are used that complement each other
- The Leakage incident is modeled by three **subsequent** injection cycles:
  1. *Very high rate (50000 m^3/h) during 30 minutes*
  2. *High rate (1050 m^3/h) during 47,5 hours*
  3. *'Medium' rate (100 m^3/h) during 30 days*
- Observed trends in injection pressure can be reasonably well reproduced by the simulations
- The simulation study shows that during the first cycle with very high injection rate, a large fracture was created. This fracture propagated up toward the Vlieland sand/clay and Chalk, and possibly further upward towards the shallow high-permeability sands (Drente, Peelo, Peize, Oosterhout), depending on the magnitude of the (unknown) stress contrasts between Vlieland sands and clays.
- The simulations also show that further upward fracture propagation during subsequent cycles of lower injection rate is unlikely.

Conclusions (2)

- It is estimated that during the leakage incident on 20 April 2018 and the following month, about 150000 m3 of brine leaked away into the subsurface
- About 90% of this volume is estimated to have leaked away into the Vlieland sandstone, whilst the other 10% has leaked away into the Chalk, Volpriehausen and lower Bunter.
- Formation pressure transient calculations show that pressure penetration fronts after about 1 year do not reach beyond 10 km into the Vlieland sandstone and not beyond 1 km in the other formations into which brine is leaking away.
- The Vlieland sandstone in the Veendam area is laterally continuous and very extensive with the same thickness over large distances. There are some fault networks, but these are not continuous. Therefore, no no-flow boundaries can be identified in this formation. Consequently, the leakage is not expected to result in laterally extensive areas of very high pore pressure which would be a requirement for possible earthquakes.