Maasdijk GT: Fracture Containment

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Contents

1 Nederlandse samenvatting

Op basis van de SodM gradiënt (SodM, 2013) blijkt dat bij een injectie temperatuur van 35°C er geen thermisch geïnduceerde scheuren ontstaan wanneer met een debiet van 275 m^3/uur in de Lower Alblasserdam en 230 m^3/uur in de Delft geïnjecteerd wordt. HVC is voornemens om te produceren met een hoger debiet van 325 m^3/uur en hiervoor zijn in deze studie verschillende scheurvormingssimulaties uitgevoerd om meer inzicht te krijgen in de te verwachten breuk lengte en injectie druk. Hieruit komt naar voren dat de integriteit van de belangrijkste afsluitende laag, de Rodenrijs Claystone, gewaarborgd blijft.

De kans op scheurvorming hangt onder andere samen met de permeabiliteit van het reservoir gesteente, omdat bij lagere permeabiliteiten makkelijker scheurvorming ontstaat. De simulaties zijn uitgevoerd voor de zandpakketten in de Nieuwerkerk Formatie, de Delft en Lower Alblasserdam. Bij injectie in de Lower Albasserdam kan scheurvorming beperkt optreden in de onderste meters van het Upper Alblasserdam pakket, maar de hoofd afsluitende laag (Rodenrijs Claystone) van de Nieuwerkerk Formatie zal altijd intact blijven (Table 5-2). Hetzelfde geldt voor injectie in de Delft waarbij scheurvorming beperkt kan optreden in de onderste meters van het Rodenrijs Claystone pakket (Rodenrijs Claystone ''waste zone''), maar de belangrijkste afsluitende laag zal altijd intact blijven (Table 5-2). Om scheurvorming te voorkomen in deze dieper gelegen lagen direct boven de zandpakketten wordt geadviseerd om voor injectie in de Delft en Lower Alblasserdam zanden een druk gradiënt aan te houden die lager is dan 0.156 bar/m (Table 5-1 en Table 5-2). Maar, zoals hierboven beschreven, wordt niet verwacht dat breuken die ontstaan bij injectie een reservoir integriteitsrisico vormen, omdat integriteit van de belangrijkste afsluitende laag in de Nieuwerkerk Formatie, de Rodenrijs Claystone, gewaarborgd blijft.

2 Introduction

HVC requested PanTerra to investigate whether in Maasdijk (MSD) it would be possible to inject under induced (thermal) fracturing conditions into the Lower Alblasserdam and / or Delft formations without loss of containment by fracturing into the overlying cap rocks and / or underlying base rocks. This request was triggered by the fact that the current maximum allowable injection pressure for geothermal operations *without thermal fracturing* is 0.135 bar/m for cooling up to 40°C which has to be lowered by 1 bar per degree beyond 40 °C (SodM, 2013). Strict adherence to this guideline may limit injection capacity of the MSD wells.

For the Maasdijk (MSD) injection well, the reservoir temperature is 96°C at a true vertical depth (TVD) of 2630 m. Using the SodM criteria as mentioned above, the maximum allowable injection rate and tubing head pressure (THP) *without allowing thermal fracturing* have been computed as a function of injection temperature. The results are given in Figure 2-1 for Lower Alblasserdam, and in Figure 2-2 for Delft.

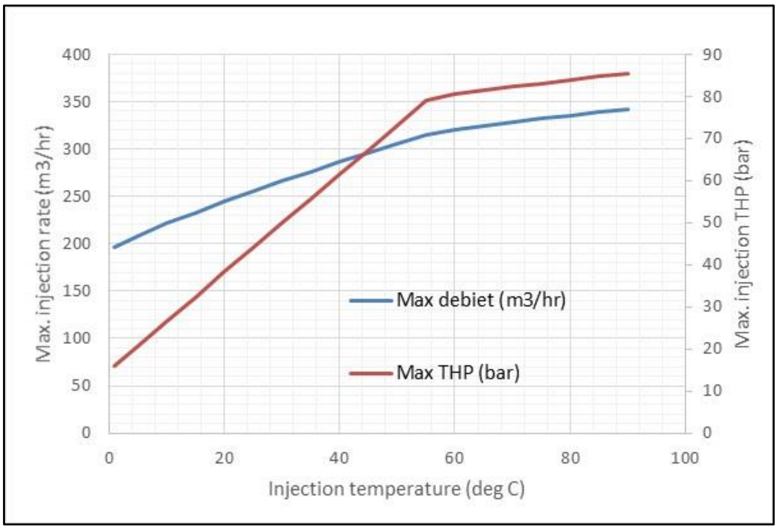

Figure 2-1: Maximum allowable injection rate and THP *without allowing thermal fracturing* for MSD Lower Alblasserdam, as a function of THT.

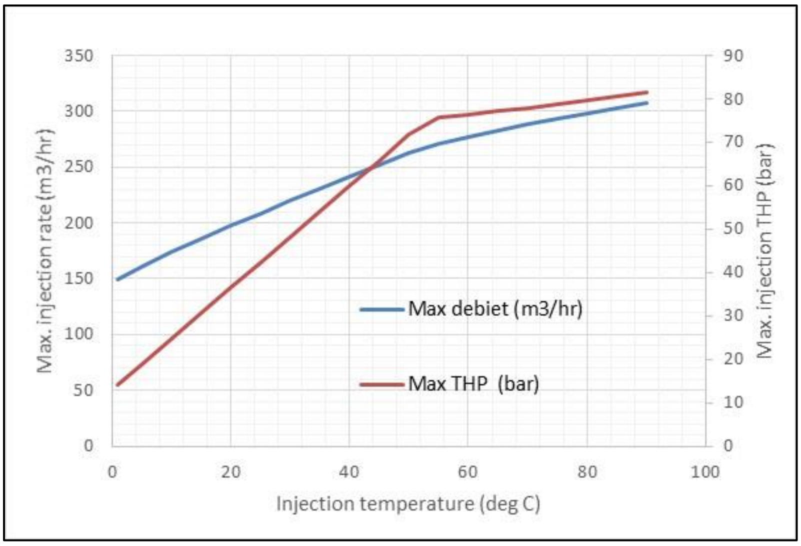

Figure 2-2: Maximum allowable injection rate and THP *without allowing thermal fracturing* for MSD Delft, as a function of THT.

As can be seen from these figures, for an injection temperature of 35°C (61°C cooling), the maximum allowable injection rate for the Lower Alblasserdam is around 275 m^3/hr, whilst for the Delft it is 230 m^3/hr. Therefore, for both formations, the maximum allowable injection rate is significantly below the planned (nominal) injection rate of 325 m^3/hr.

Within the SodM protocol for maximum injection pressures (SodM, 2013), the intention of limiting the pressure is to safeguard the environment of the injection well. The principle of 'containment' and 'confinement' describes the limits of the sphere of influence of the doublet. In the licensed volume (the container) it is acceptable that on a limited scale (by temperature effects) fractures are induced to layers other than the formation in which injected. However, it must be demonstrated that the integrity of the overlying layers that have been defined as seals (confinement) is not affected. Also the induced fractures, and thus the flow of injected cold water, have to remain within the areal limits of the permit.

More recently a "toezichtsignaal Integriteit van het geothermisch reservoir en de afsluitende lagen" (SodM, 2020) was published by SodM in which it was explicitly stated that induced fractures shall not at all penetrate from the reservoir into adjacent cap- or baserock. However, it is noted that deviations from the methodology can be allowed if operations can be performed safely.

The current work is aimed at investigating whether in the presence of induced (thermal) fractures, the injected water in MSD is still contained as mentioned in the SodM protocol (2013) and the "toezichtsignaal". This applies both to injection into the Lower Alblasserdam formation and to injection into the Delft formation.

This study consists of fracture simulations to compute the size (length, height) of induced fractures and corresponding injection pressures for a number of realistic scenarios for the geothermal operation in MSD. In particular, the risk of (non-) containment of an induced thermal fracture to cap rock and / or base rock is addressed. The study uses the same minimum in-situ stress profile that was derived in an earlier study for the nearby Maasland (MLD) geothermal field. The in-situ stress profile will be presented in this report for completeness.

Fracture simulations were performed using the methodology of Gheissary (1998) and van den Hoek (1999, 2000). This is an extension of the Koning method (Koning, 1988) that is also used by TNO (Veldkamp et al., 2016), including more complicated geologies with multiple layers of reservoir and cap rock.

3 Description of seal

3.1 Subsurface description

The Maasdijk doublets will be situated in the West Netherlands Basin (Figure 3-1), which is an inverted rift basin (De Jager et al, 1996). Rifting was accompanied by compressional movements and resulted in convergent oblique-slip faulting, general uplift, erosion and basin inversion, reactivating pre-existing normal faults.

The new Maasdijk geothermal wells are in the same fault block as wells MLD-GT-01 and -02 in the nearby Maasland geothermal project (Figure 3-2). A series of NW-SE trending normal and thrust faults are present in the study area. The target locations of the planned doublets are situated in the centre of the fault block and the pairs are oriented parallel to the local major fault trend, minimizing the risk of the presence of faults in between the injector and producer.

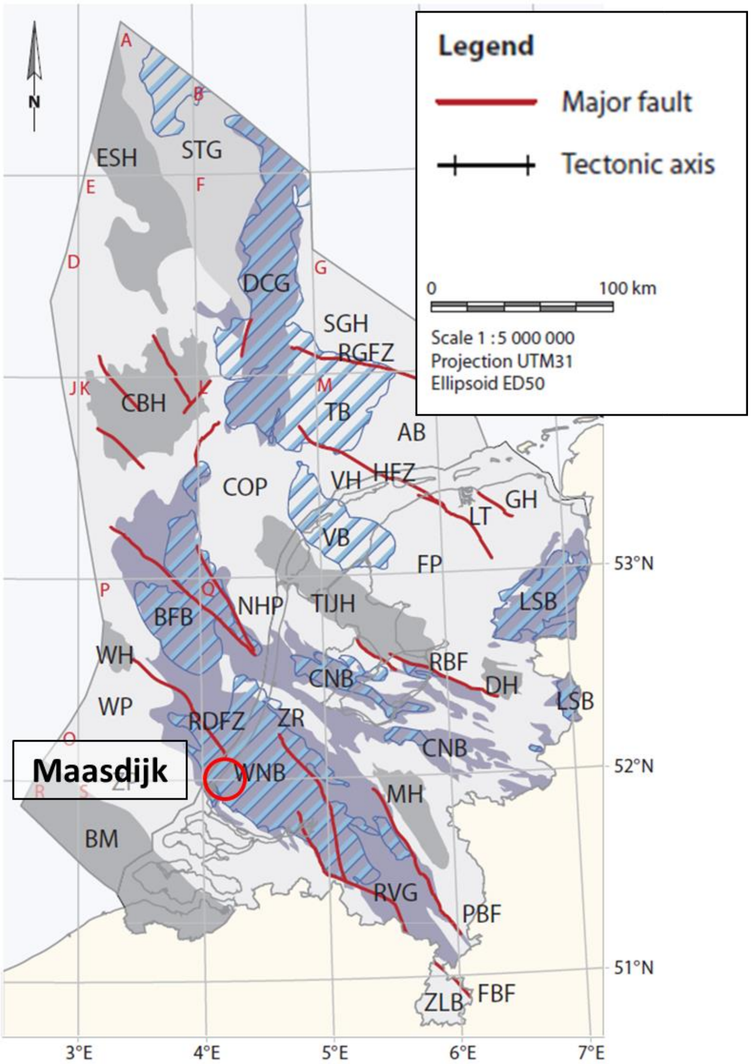

Figure 3-1: Structural elements and major fault zones as present during the Late Jurassic-Early Cretaceous (Duin et al., 2016)

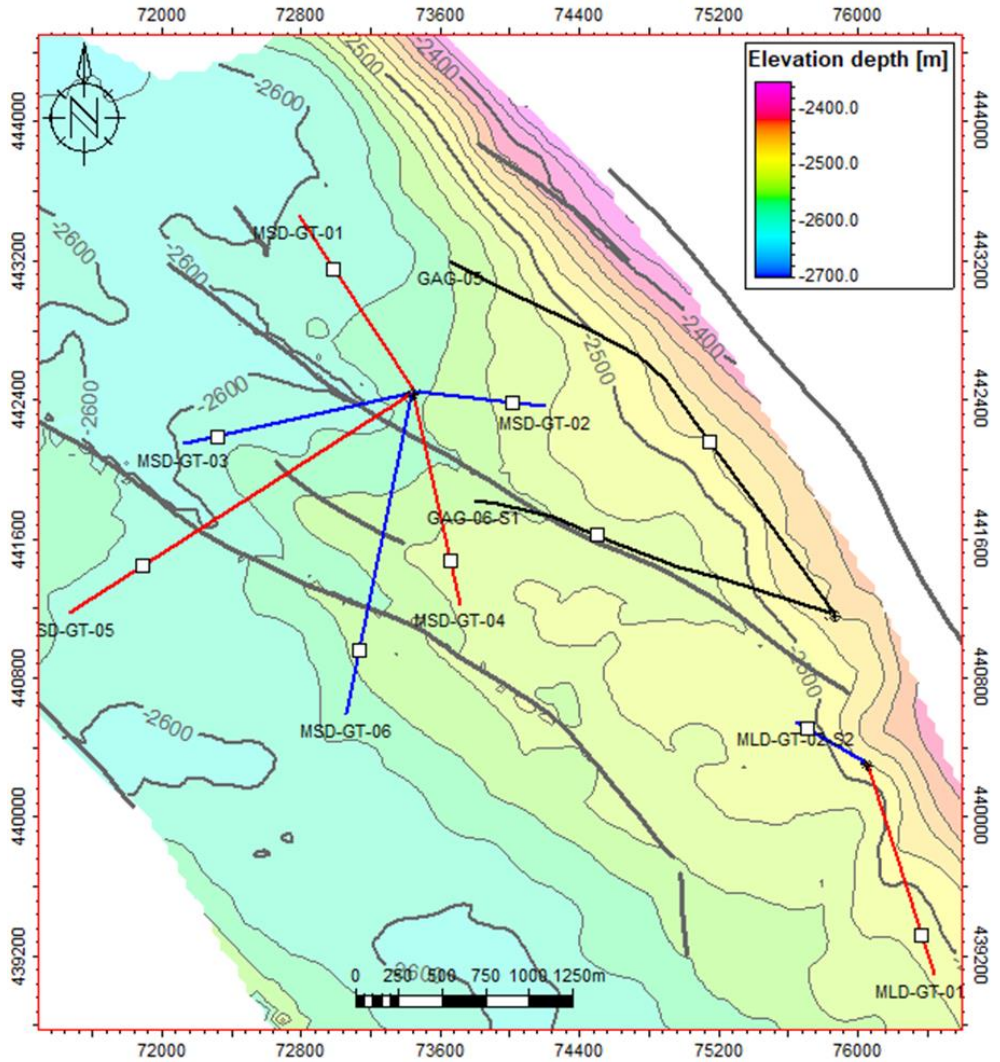

Figure 3-2: Location of the three Maasdijk doublets planned from a common surface location. Top Delft depth map, and the square indicates the top of the Delft reservoir. Production wells in red, injection wells in blue.

3.1.1 Stratigraphy

The target reservoirs are the Jurassic to Cretaceous fluvial sands of the Delft Sandstone Member and the underlying Alblasserdam Member, both part of the Nieuwerkerk Formation. A schematic overview of the sequence stratigraphy of these fluviomarine deposits is depicted in Figure 3-3.

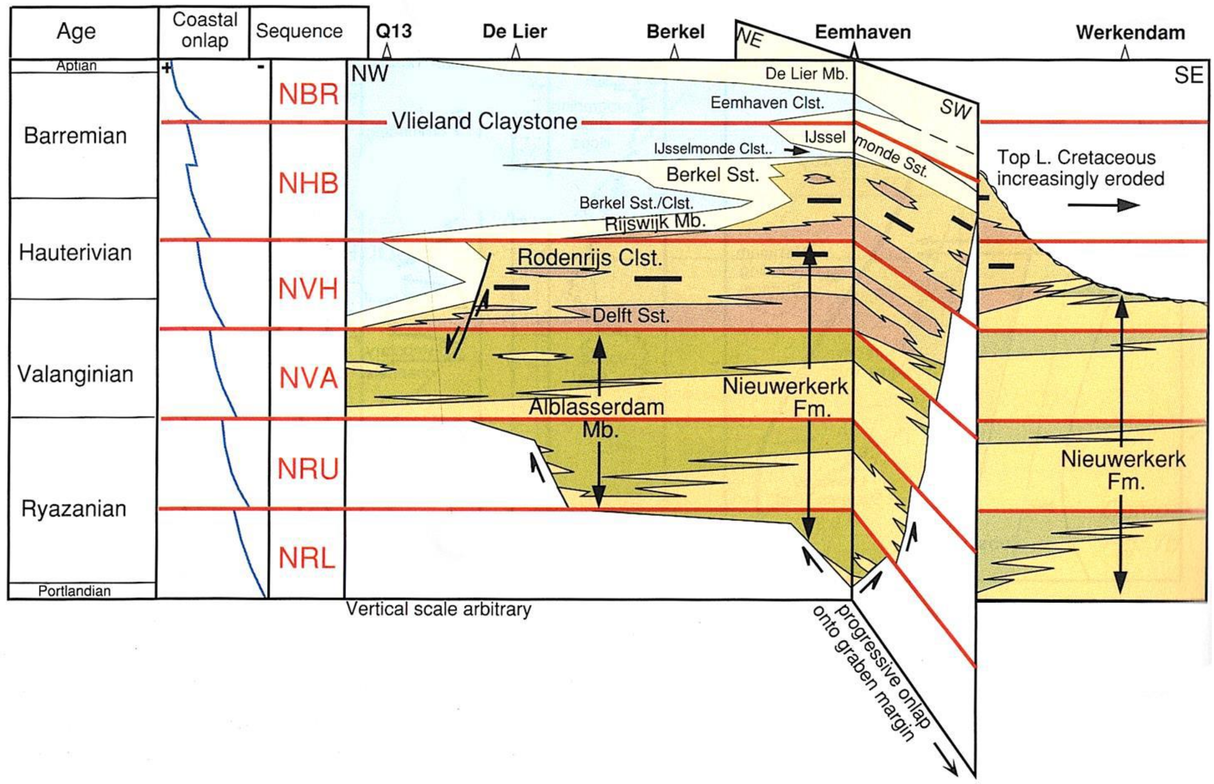

Figure 3-3: Sequence stratigraphic scheme for the Lower Cretaceous of the West Netherlands Basin based on seismic and biostratigraphic data (Den Hartog Jager, 1996). The target reservoirs of the Maasdijk doubles are the Jurassic to Cretaceous fluvial sands of the Delft Sandstone Member and the underlying Alblasserdam Member.

Figure 3-4 shows the gamma ray (GR) log of representative wells that are in close proximity to the planned Maasdijk doublets. The GR reveals the sandy intervals in the wells. The Alblasserdam is subdivided into four parts; a sandy part at the base, followed by central shaly part, a smaller sandy interval near the top followed by a shaly fining upwards top part. The sandier trend that follows is associated with the Delft Sandstone Member. In the seismic cube, an angular unconformity is observed near the depth of the base of the Delft (Panterra, March 2019). The Delft Sandstone Member is overlain by shales of the Rodenrijs Claystone Member. The Alblasserdam Member, Delft Sandstone Member and Rodenrijs Claystone Member together form the Nieuwerkerk Formation.

GR logs from previously drilled wells at GAG, NLW-GT and MLD-GT sites confirm all the target and sealing intervals are laterally continuous (Figure 3-3). The character of the members, however, is varying in terms of thickness and sand/shale distribution. Because of this, the Delft and Alblasserdam could potentially be regarded as one unit since the shaly Upper Alblasserdam is intercalated with sands that could be connected (as further described in section 3.1.1.1) and the Delft erodes into this underlying Alblasserdam interval (Panterra, March 2019). Within the heterogeneous Nieuwerkerk Formation, the Delft Sandstone Member is considered to have the best reservoir properties (see section 4.4 for description of the rock parameters).

Thickness maps in the area of interest show a general thickening trend of the reservoir towards the Southwest within the target fault block (Panterra, March 2019). It is therefore concluded that the thickness of the reservoirs is very likely to increase towards Maasdijk as compared to the thickness encountered in the wells mentioned above.

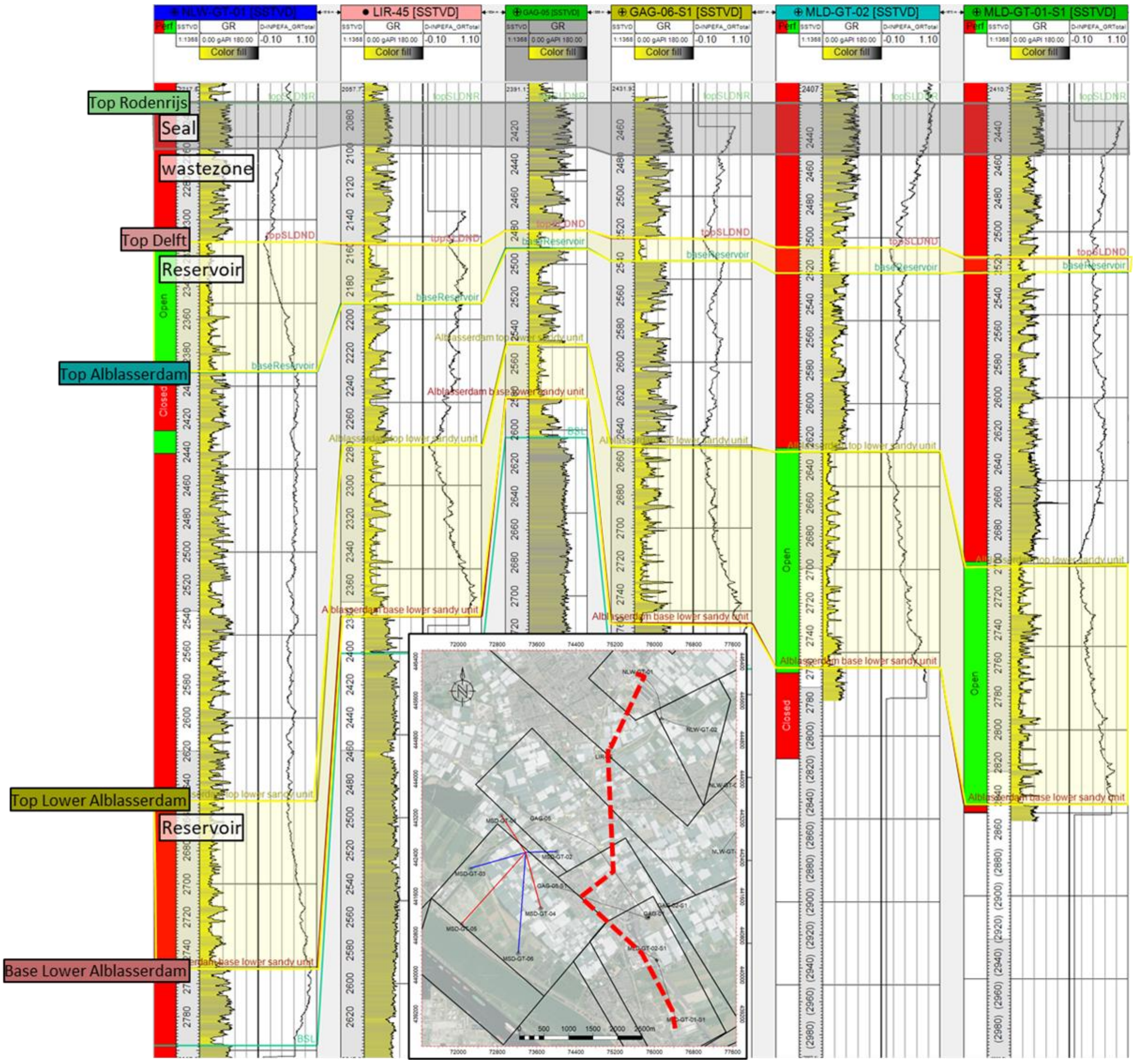

Figure 3-4: Regional correlation panel showing the gamma ray logs (non-normalised) flattened with respect to the top Rodenrijs Member. Also shown is the INPEFA log (black curve). The inlay map shows the location of the wells used, connected by the red, dashed line.

3.1.1.1 Seal

MSD-GT wells target the sands in the Alblasserdam Member (Lower Alblasserdam sands) and Delft Sandstone Member, separated by a *likely* sealing shale unit in the upper part of the Alblasserdam. The Delft Sandstone Member is overlain by shales of the Rodenrijs Claystone Member that act as the main sealing interval for the entire Nieuwerkerk Formation.

<u>Rodenrijs seal</u>

Drilling of offset wells reveals that especially the upper part of the Rodenrijs Claystone Member consists of a good quality shaly package that is laterally continuous (Figure 3-4). This upper part is regarded as the seal and on average 30 m thick. The lower part of the Rodenrijs (~55 m TVT) is less shaly and will act as a ‘’wastezone’’ as it is neither a good seal or reservoir. Within the wastezone some very thin sands could be encountered as seen in Figure 3-4 and illustrated in Figure 3-3.

Alblasserdam seal

The deeper lying shales of the Upper Alblasserdam are a *likely* sealing unit. Figure 3-4 demonstrates that this shaly unit is intercalated with thin sand layers that could potentially break-up the lateral continuity of the shaly intervals as the thickness of the shaly- and sandy intervals is highly variable across the area of interest. Additionally, the Delft is erosionally deposited on top and these sands could be in communication. The Delft and entire Alblasserdam package could therefore potentially be regarded as one unit. Drilling of offset wells reveals that the Upper Alblasserdam package is on average ~145m thick (Figure 3-4).

4 Description of input for fracture model

4.1 Investigated scenarios

The following scenarios were investigated:

- Injection into the Lower Alblasserdam sands with the Upper Alblasserdam shales as seal (Base case; see Section 4.2 and 5.1.1). Figure 5-1 and Figure 5-2, show the computed results when injection is in the top of the Lower Alblasserdam.
- Injection into the Lower Alblasserdam sands with the Rodenrijs shales as seal. This scenario actually falls within the Base case as injection-induced fractures in this formation will *never* grow further upwards than the shale below Top Alblasserdam.
- Injection into the Delft sands with Rodenrijs shales as the seal (Back-up scenario; see Section 5.1.3). Figure 5-21 and Figure 5-22 show the computed results when injection is in the top of the Delft.

4.1.1 **Alblasserdam injection**

The set-up of the base case is described in section 4.2. In addition, several sensitivities with different permeabilities, perforation depths, in-situ stresses and start-up speeds are included for injection into the Lower Alblasserdam (Table 5-1). The permeability in the base case is set to 120 mD for the Lower Alblasserdam and lowered in the sensitivity to 90 mD. The perforations in the base case were set at 2613 m TVD (i.e., top-reservoir at 2 m below Top Lower Alblasserdam). Sensitivities are simulated based on the occurrence of the first thick sand observed in offset well GAG-06-S1, which is 22 m (TV) below Top Lower Alblasserdam. This results in a first perforation at 2633 m TVD. Consecutive sensitivities are run with perforations at 2680 m TVD (i.e., mid-reservoir at 69 m below Top Lower Alblasserdam) and 2735 m (i.e., bottom-reservoir at 10 m above Base Lower Alblasserdam). The base-case for in-situ stress was run with 0.158 bar/m, and sensitivity runs for the Lower Alblasserdam are based on alternative stress gradients in the West Netherlands Basin area as illustrated in Figure 4-2.

4.1.2 **Delft injection**

For the Delft reservoir simulations were performed for fracture initiation at 2536 m TVD (i.e., top-reservoir at 2 m below Top Delft) and 2542 m TVD (i.e., mid-reservoir at 8 m below Top Delft).

4.2 Simplified stratigraphy/Base case

The simplified stratigraphy as used in the fracture simulations is depicted in Figure 4-1. Since the expected geological and operational parameters of the three planned doublets will be alike, one doublet (i.e., doublet I) is subjected to study. Stratigraphic depths are taken from the planned injector MSD-GT-02 whilst taking into account the expected reservoir thicknesses of the Delft and Lower Alblasserdam sands.

Other main features of the base case are:

- Geological 'layer-cake' model.
- Minimum horizontal in-situ stress based on general correlation for the West-Netherlands Basin (0.158 bar/m, see also below; Verwey et al. 2012).
- No in-situ stress differences between sand layers and shale layers. This can be considered as a 'conservative' approach in the sense that normally, sandstone formations have a lower horizontal in-situ stress than shale layers. As a result of the higher in-situ stress in the shale,

(thermal) fractures that are induced in sandstones will often be (partially) contained by the bounding shales.

- Hydraulic formation pressure gradiënt.
- Elastic parameters of the rock (Young's modulus, Poisson's ratio) based on general geomechanical estimates from literature (soft rock E ~ 1GPa, mid-strength rock E~ 5-10 GPa, tight rock E > 15 GPa).
- Permeabilities for the Lower Alblasserdam and for the Delft sandstone are k = 120 mD with N/G = 0.72 and k = 500 mD with N/G = 0.90, respectively. Permeabilities of all other layers are from ThermoGIS (by analog from an earlier study on the nearby Maasland area and summarized in Table 4-1).
- All geological layers continuous with a constant pressure boundary at the drainage radius (= ½ × distance between wells of the doublet).
- Injection depth of water into the Lower Alblasserdam and Delft formations is varied throughout this work in order to estimate its impact on fracture containment.
- Injection rate 325 m^3/hr during 30 years.

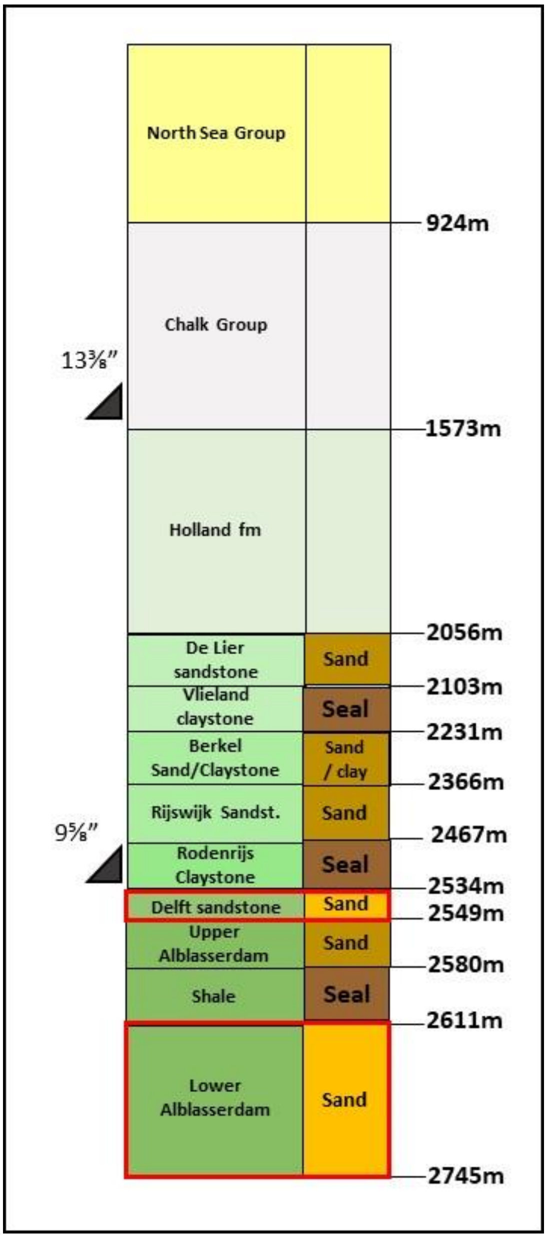

Figure 4-1: Stratigraphic scheme.

4.3 In-situ stress estimate

In-situ stress trends are mostly based on measured leak-off pressures as reported by Verweij et al. (2012). These authors distinguished a number of different geological areas within the Netherlands. For each of these areas, an in-situ stress trend map was generated. The geological area that is relevant for the current discussion is the so-called West Netherlands Basin for which the data are given in Figure 4-2. This figure displays measured leak-off pressure tests (LOT) as a function of depth in the West Netherlands platform area. The Verweij et al. data has been complemented by four Formation Integrity Test (FIT) measurements in the nearby Maasland (MLD) field.

As can be seen from Figure 4-2, the data can be trended very well (R^2 = 0.96). Until a depth of around 1500 m, the trend closely follows the well-known minimum in-situ stress gradient of 0.158 bar/m (0.7 psi/ft) for an extensional stress regime (which is used in the base case model), whilst at greater depths it starts to bend somewhat towards higher stresses (0.189 bar/m). It can be seen from the figure that the

FIT results in MLD are somewhat below the overall trend. All MLD formation integrity tests where limit tests, with the goal to prove a minimum shoe integrity for drilling purposes. This means that no leak-off point was observed at the end of the test and resulting values can be considered as lower bounds to the local minimum in-situ stress. In the MLD-study, both the FIT-value at 9-5/8" shoe was considered most representative for the reservoir because it is closest in depth. Based on the lowest FIT-value, a minimum in-situ stress trend of 0.144 bar/m was used as ultra-low stress state sensitivity input.

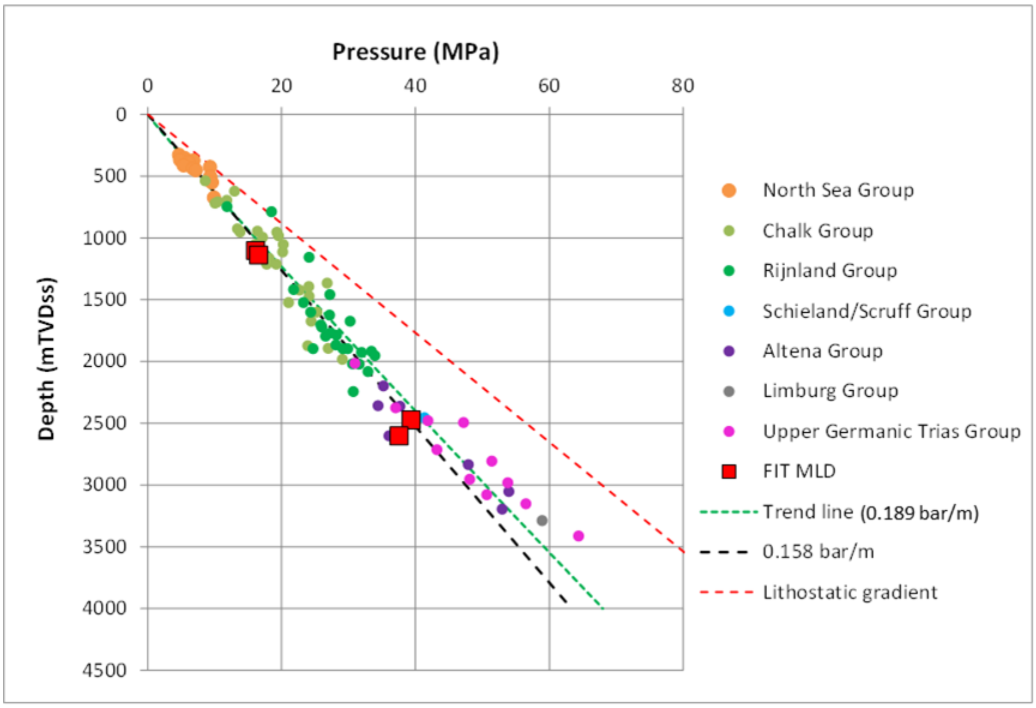

Figure 4-2: Minimum in-situ stress versus depth trend in the West Netherlands platform area based on leak-off pressures (Verweij et al, 2012) and Formation Integrity Tests (FIT) in geothermal wells of MLD. See text for more details.

4.4 Physical rock parameters

Physical characteristics of all layers used in the model are listed in Table 4-1.

In response to temperature changes, the reservoir rock will tend to expand (heating) or shrink (cooling). Because in the subsurface there is no 'room' in the horizontal direction to expand or shrink ('plane strain'), this results in a change of total horizontal stress that is given by

$$\Delta\sigma_{\mathrm{h}} = A_{\mathrm{T}}.\Delta T$$

where ΔT is the temperature change (negative for cooling) and A_T is the "thermo-elastic constant". The thermo-elastic constant is a material property of the rock. Koning [6] and Perkins and Gonzalez [13] use values for A_T in the range 0.9-1.0 bar/°C for 'medium-strength' reservoir sandstones with Young's moduli in the range 10-15 GPa. The Berkel and Delft sandstones are in general poorly consolidated sandstones and Young's moduli are not expected to be higher than 10 GPa. We therefore use a value for A_T of 1.0 ± 0.25 bar/°C, where the error bounds serve to capture the uncertainty in the Young's modulus.

Table 4-1: Overview of layers used in the model plus their physical parameters. Note that the permeabilities in the Delft and Lower Ablasserdam are N/G corrected (also see section 4.2 for input parameters).

Layer name	Depth at top (m)	Depth at bottom (m)	Permeability (mD)	Porosity (fraction)	Young's modulus (MPa)	Poisson's ratio
North Sea	0	924	500	0.3	1000	0.25
Chalk	924	1573	1	0.05	1000	0.25
Holland	1573	2056	11	0.15	5000	0.35
De Lier sandstone	2056	2103	2	0.15	5000	0.25
Vlieland claystone	2103	2231	0.1	0.15	5000	0.35
Berkel sandstone	2231	2240.5	220	0.2	5000	0.25
Berkel sand-claystone	2240.5	2366	50	0.15	5000	0.25
Rijswijk sandstone	2366	2467	28	0.2	5000	0.25
Rodenrijs claystone	2467	2534	0.1	0.15	5000	0.35
Delft sandstone	2534	2549	450	0.171	5000	0.25
(Upper) Alblasserdam	2549	2580	0.1	0.15	5000	0.25
Shale	2580	2611	0.1	0.15	5000	0.35
(Lower) Alblasserdam	2611	2745	86.4	0.16	5000	0.25
Altena	2745	2806	0.1	0.15	5000	0.35
Triassic	2806	3500	10	0.01	15000	0.25
Underburden Zechstein	3500	10000	0.1	0.01	25000	0.5

5 Results

5.1 Computations of induced fracture dimensions

5.1.1 Injection into Lower Alblasserdam: Base case

Results for the base case are shown in Figure 5-1 and Figure 5-2. In this case, the induced fracture initiates from the top at 2613 m (i.e., 2 m below the Top Lower Alblasserdam as described in section 4) and grows quickly up towards the overlying shale at 2611 m. Subsequently, it slightly grows into this overlying shale of the Upper Alblasserdam (~3m). The Rodenrijs Claystone Member however, which is overlying the Alblasserdam package, can be regarded as the ultimate seal (Figure 3-4). The resulting fracture after 30 years of injection is about 12 m long. The fact that the fracture almost entirely grows into the Lower Alblasserdam (and not into the overlying shale) can be explained by:

- No in-situ stress contrasts between the shale and the Lower Alblasserdam, <u>but</u>:
- Lower Alblasserdam cools considerably $\rightarrow$ due to the thermo-elastic effect (shrinking rock as a result of cooling), the in-situ stress decreases, so that the crack remains contained in this formation
- Slow start-up to pre-cool the formation

The computed injection THP is around 75 bar, which is a stable value after fracture initiation. Note that in general, this value very much depends on in-situ horizontal stress estimate and cooling. The corresponding injection pressure gradient (BHIP) is 0.160 bar/m.

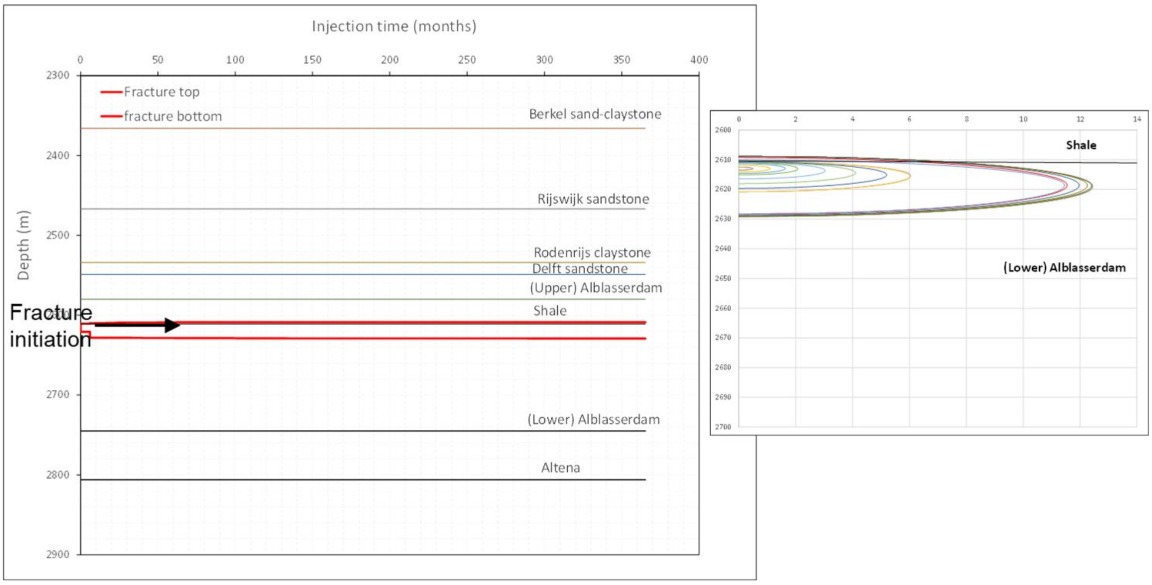

Figure 5-1: Fracture top and bottom as a function of time for base case; fracture contours for base case. Fracture is 'contained' by the top shale, though it slightly grows into this Upper Alblasserdam shale. BHIP = 0.160 bar/m. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

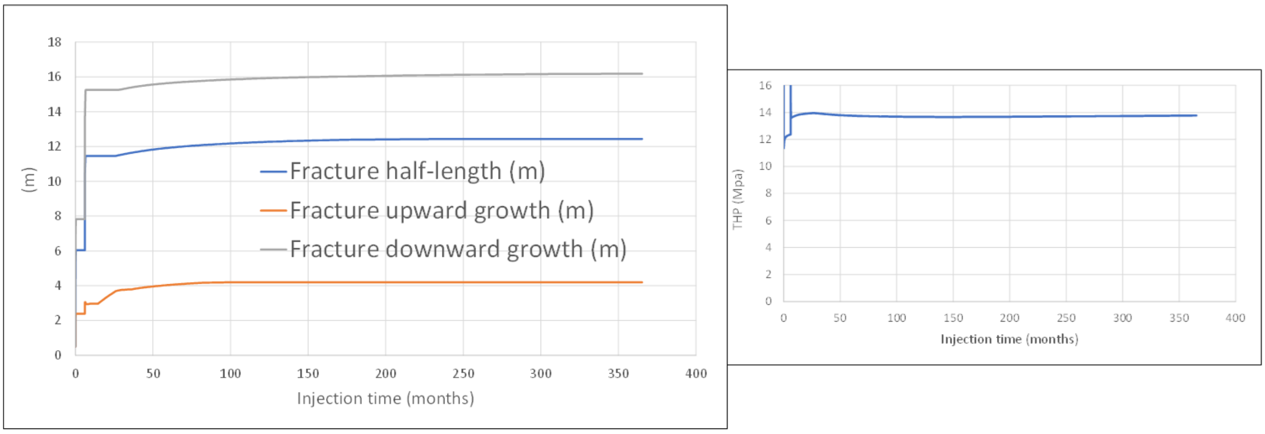

Figure 5-2: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for base case.

5.1.2 Injection into Lower Alblasserdam: Sensitivities

Because of the recent guideline by the SodM "toezichtsignaal" (SodM, 2020), sensitivity runs were performed with respect to depth of injection point in order to optimise this such that no fracture penetration takes place into either cap- or baserock.

In addition, a low-permeability sensitivity and a low permeability with slow start-up was addressed to simulate pre-cooling of the Lower Alblasserdam in order to minimise loss of containment. Sensitivities on in-situ stress were also performed to understand the impact of potentially different stress regimes in the area (Figure 4-2).

An overview of the addressed sensitivities (also see section 4 for mor information) plus a summary of the results for each sensitivity is given in the table below (Table 5-1). Figure 5-3 to Figure 5-24 show more detailed results.

Table 5-1: Injection into Lower Alblasserdam: Sensitivities+Results.

No	Description of sensitivity	Results after 30 years injection
1	Fracture initiation point at 2633 m (i.e., 22m below top-reservoir L. Alblasserdam).	Fracture remains small, it does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.
2	Fracture initiation point at 2680 m (i.e., mid-reservoir L. Alblasserdam).	Fracture remains small, it does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.
3	Fracture initiation point at 2735 m (i.e., bottom-reservoir L. Alblasserdam).	Fracture remains small. It does not reach the Upper Alblasserdam shale and is contained at the bottom by the Altena. BHIP = 0.159 bar/m.
4	Low $k_{Lower\ Alblasserdam}$ (90 mD with N/G = 0.54) Fracture initiation point at 2613 m (i.e., top-reservoir L. Alblasserdam). Slow start-up.	Fracture is ‘contained’ by the top shale, though it sightly grows into this Upper Alblasserdam shale. BHIP = 0.162 bar/m. Note the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.
5	Low $k_{Lower\ Alblasserdam}$ (90 mD with N/G = 0.54) Fracture initiation point at 2633 m (i.e., mid-reservoir L. Alblasserdam).	Fracture is ‘contained’ by the top shale, though it grows slightly into this Upper Alblasserdam shale. BHIP = 0.157 bar/m. Note the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.
6	Low $k_{Lower\ Alblasserdam}$ (90 mD with N/G = 0.54) Fracture initiation point at 2680 m (i.e., bottom-reservoir L. Alblasserdam).	Fracture does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.
7	Low $k_{Lower\ Alblasserdam}$ (90 mD with N/G = 0.54) Fracture initiation point at 2735 m (i.e., bottom-reservoir L. Alblasserdam).	Fracture contained at the bottom by the Altena, it does not reach the Upper Alblasserdam shale. BHIP = 0.159 bar/m.
8	In-situ stress of 0.144 bar/m. Slow start-up to pre-cool formation.	Fracture is ‘contained’ by the top shale, though it slightly grows into this Upper Alblasserdam shale. BHIP = 0.138 bar/m (lower because of lower shmin). Note the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.
9	In-situ stress of 0.189 bar/m. Slow start-up to pre-cool formation.	Fracture remains very small and is ‘contained’ by the top shale, though it slightly grows into this Uper Alblasserdam shale. BHIP = 0.209 bar/m because of higher shmin. Note the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

From the table and the results as presented in Figure 5-1 to Figure 5-24, the following conclusions can be drawn:

- In view of SodM’s “toezichtsignaal” (SodM, 2020), it appears safest to initiate a fracture in the centre of the Lower Alblasserdam (ca. 2680 m) or slightly below, as in this case the likelihood of “touching” either the overlying shale or underlying Altena is lowest. However, it must be noted that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package and that this main seal remains unaffected.
- However, if the permeability of the Lower Alblasserdam is low enough, induced fractures may still “touch” either overlying shale or underlying Altena or both, although it is highly unlikely that it will penetrate more into (either of) those by more than 1-2 m.

- One way to optimize the chance of fracture containment is to inject with a low rate (i.e., pressures below the SodM protocol) at start-up. By doing this the reservoir around the injector will cool and subsequently a pressure difference will built-up between the reservoir and the caprock. This pressure differential will be beneficial for optimizing fracture containment at a later stage, e.g., when the flow rate will be increased after a few months.

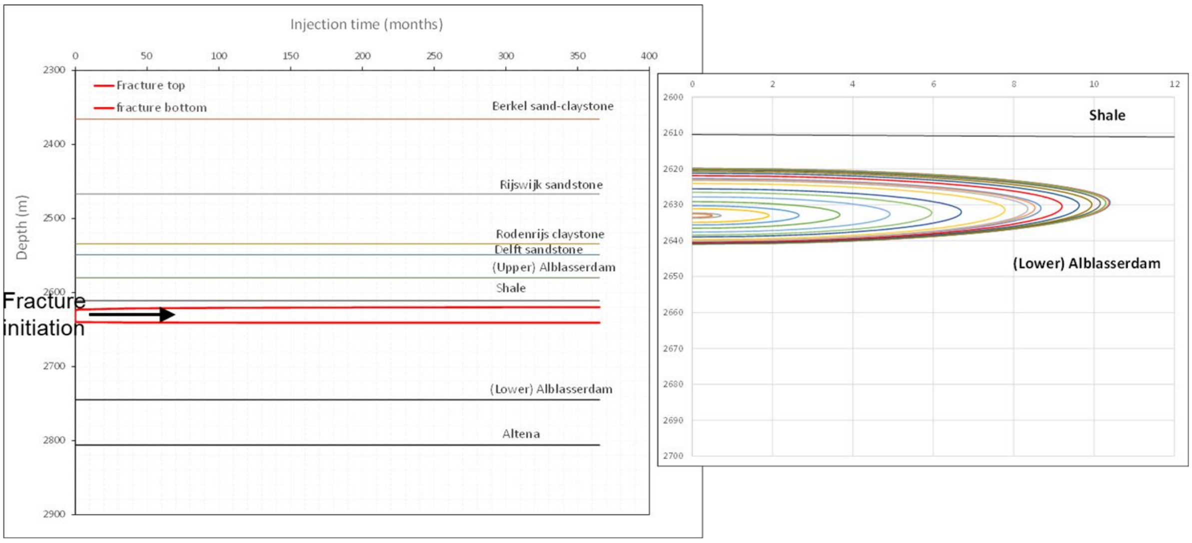

Figure 5-3: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 1. Fracture remains small, it does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.

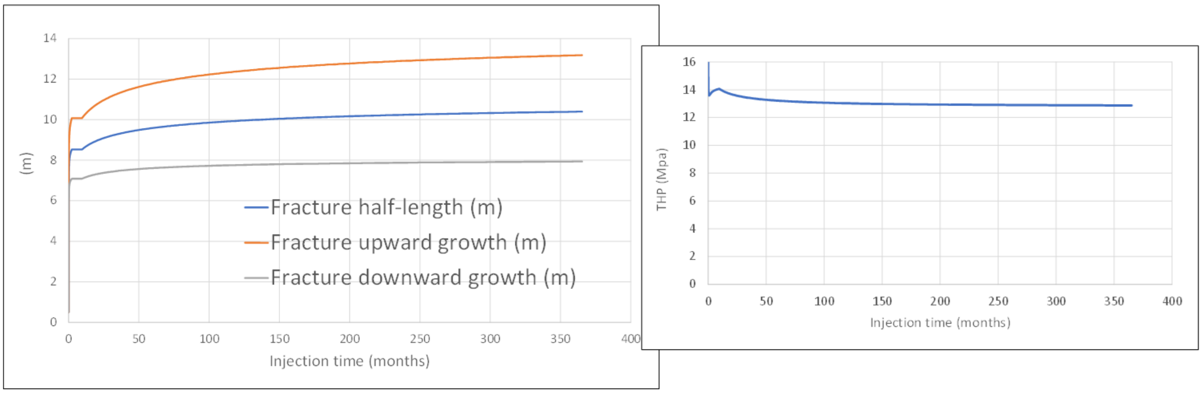

Figure 5-4 Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 1. Fracture remains small, it does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.

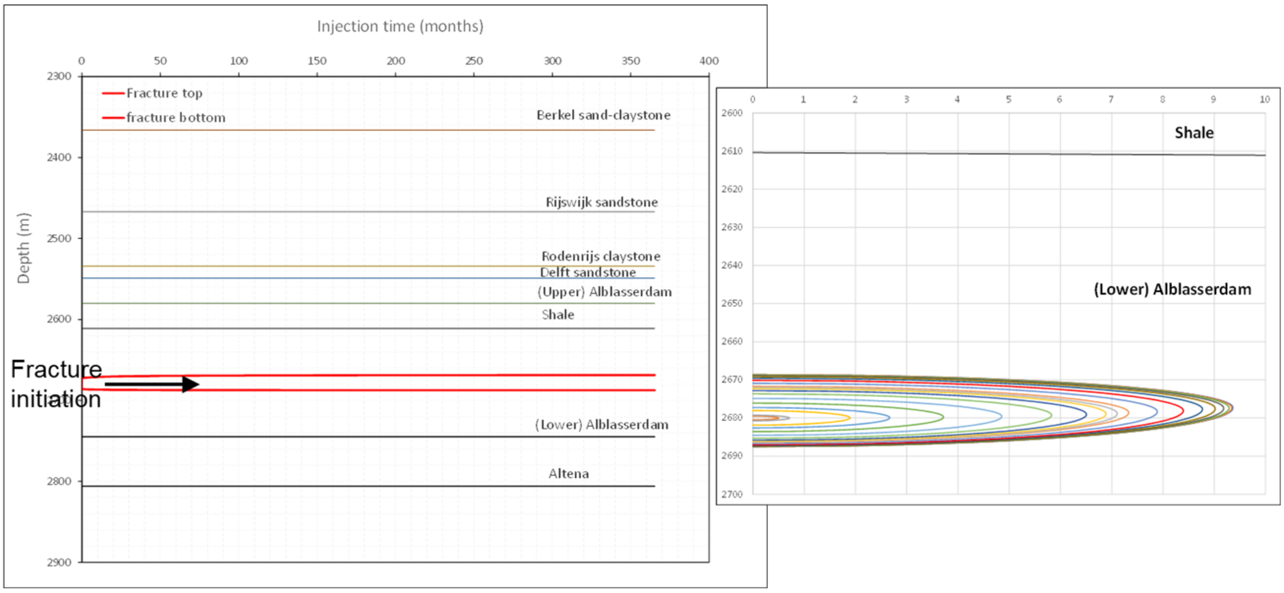

Figure 5-5: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 2. Fracture remains small, it does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.

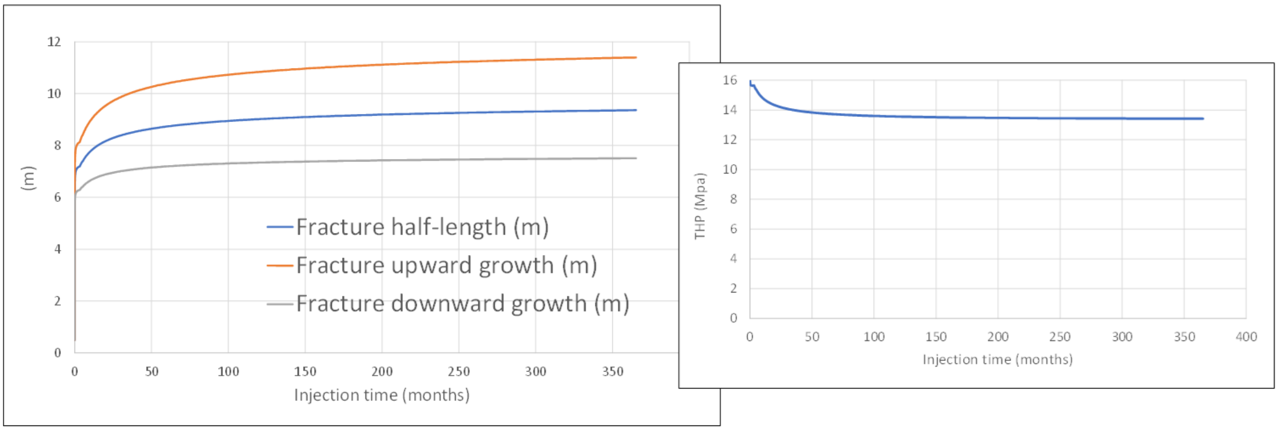

Figure 5-6: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 2. Fracture remains small, it does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.

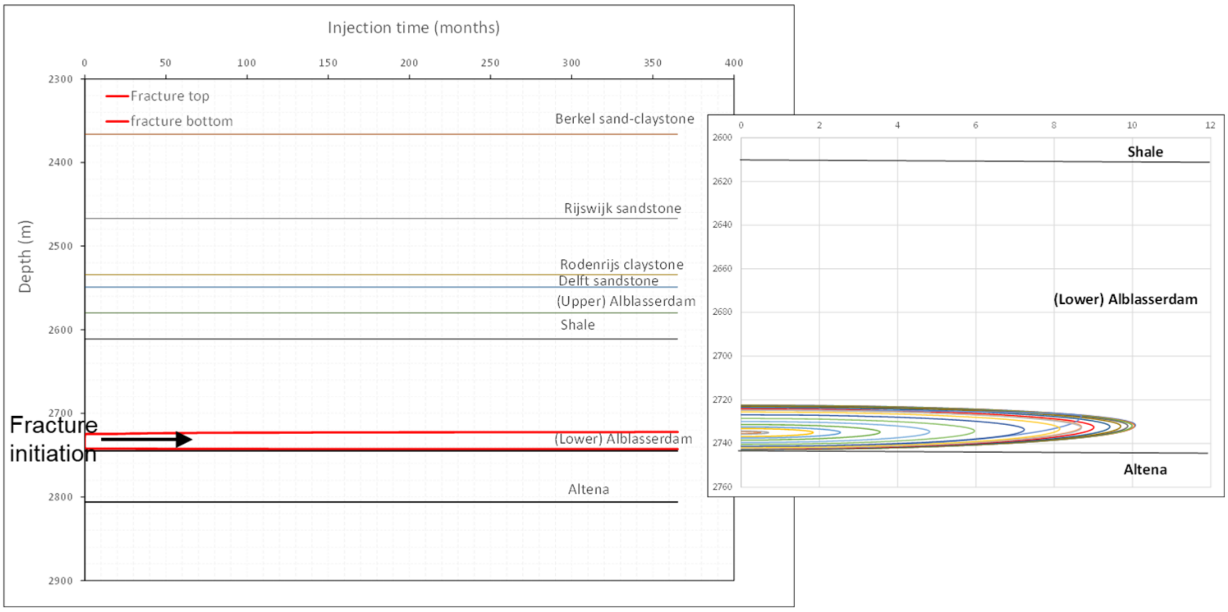

Figure 5-7: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 3. Fracture remains small. It does not reach the Upper Alblasserdam shale and is contained at the bottom by the Altena. BHIP = 0.159 bar/m.

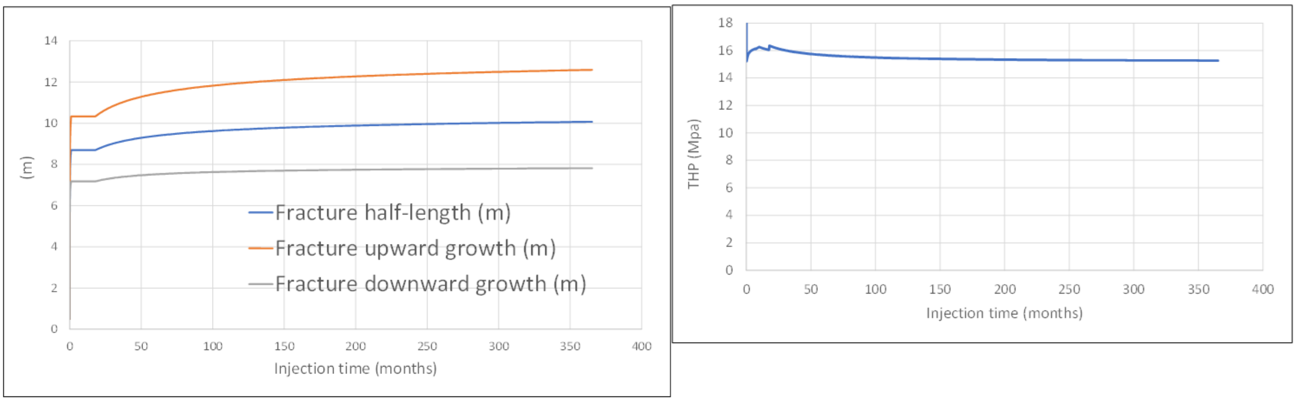

Figure 5-8: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 3. Fracture remains small. It does not reach the Upper Alblasserdam shale and is contained at the bottom by the Altena. BHIP = 0.159 bar/m.

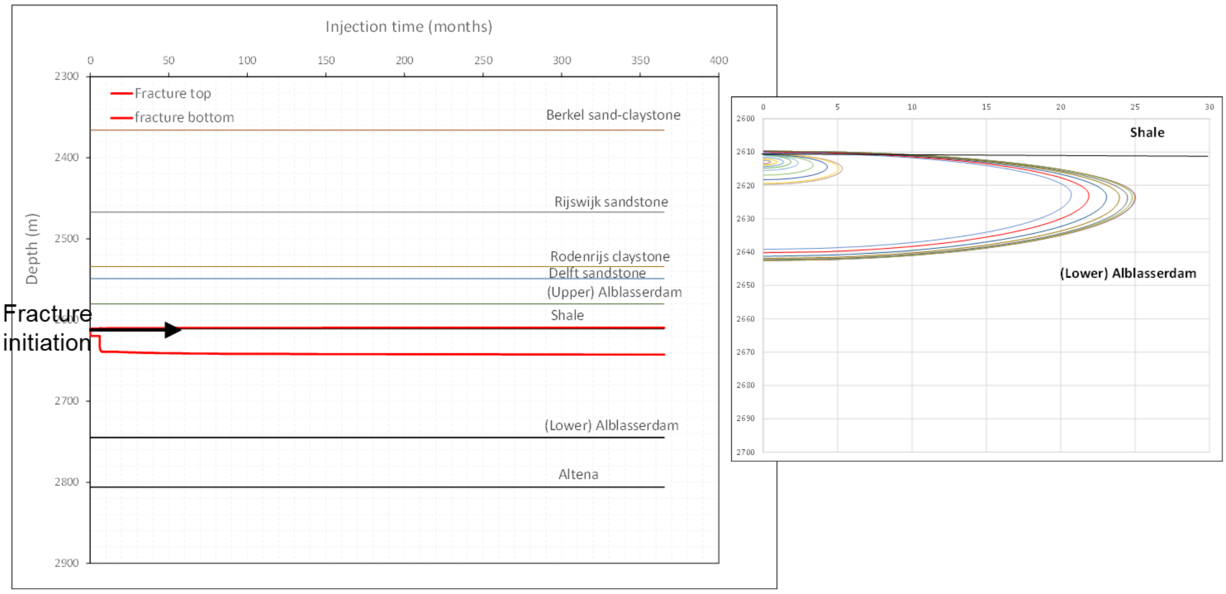

Figure 5-9: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 4. Fracture is 'contained' by the top shale, though it somewhat sightly grows into this Upper Alblasserdam shale. BHIP = 0.162 bar/m. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

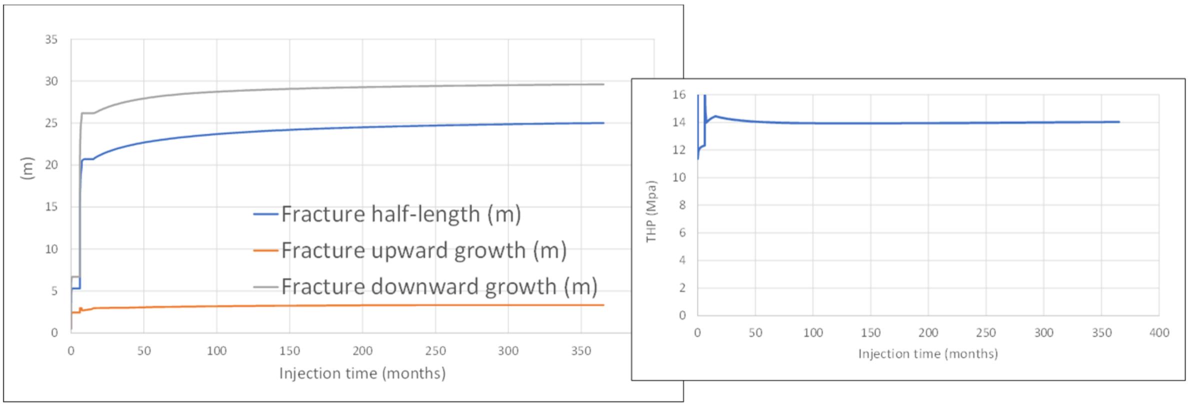

Figure 5-10: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 4. Fracture is 'contained' by the top shale, though it somewhat sightly grows into this Upper Alblasserdam shale. BHIP = 0.162 bar/m. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

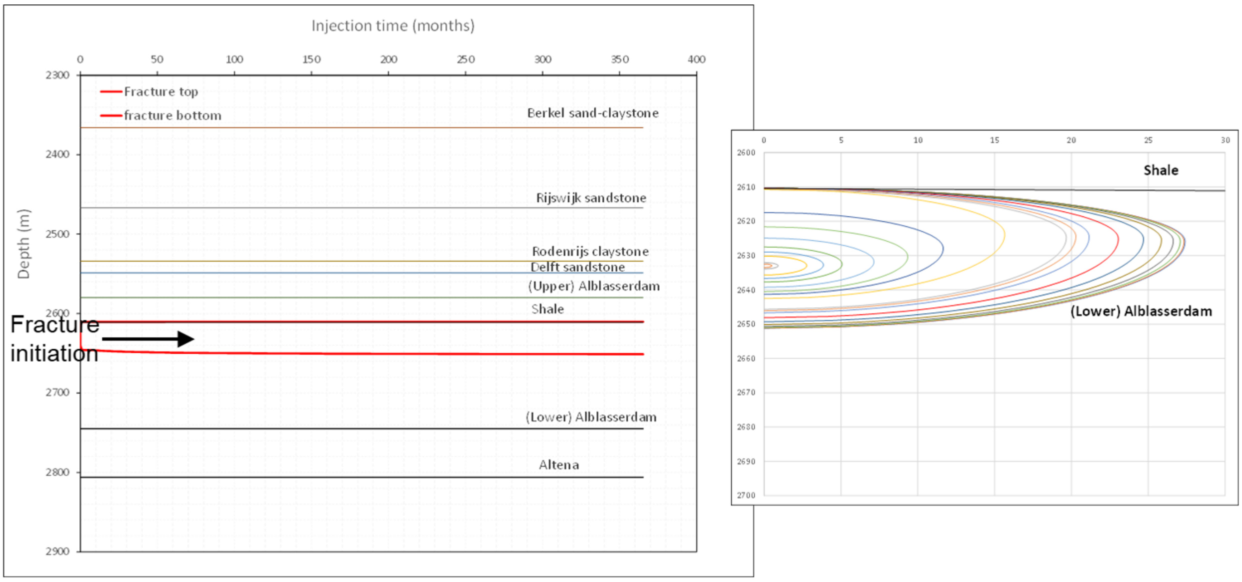

Figure 5-11: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 5. Fracture is 'contained' by the top shale, though it somewhat sightly grows into this Upper Alblasserdam shale. BHIP = 0.157 bar/m. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

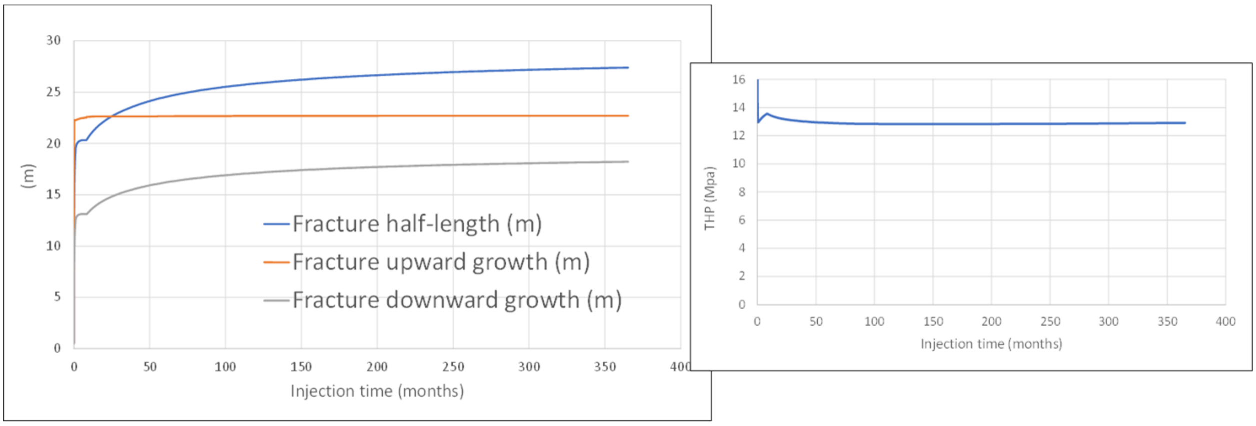

Figure 5-12: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 5. Fracture is 'contained' by the top shale, though it somewhat sightly grows into this Upper Alblasserdam shale. BHIP = 0.157 bar/m. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

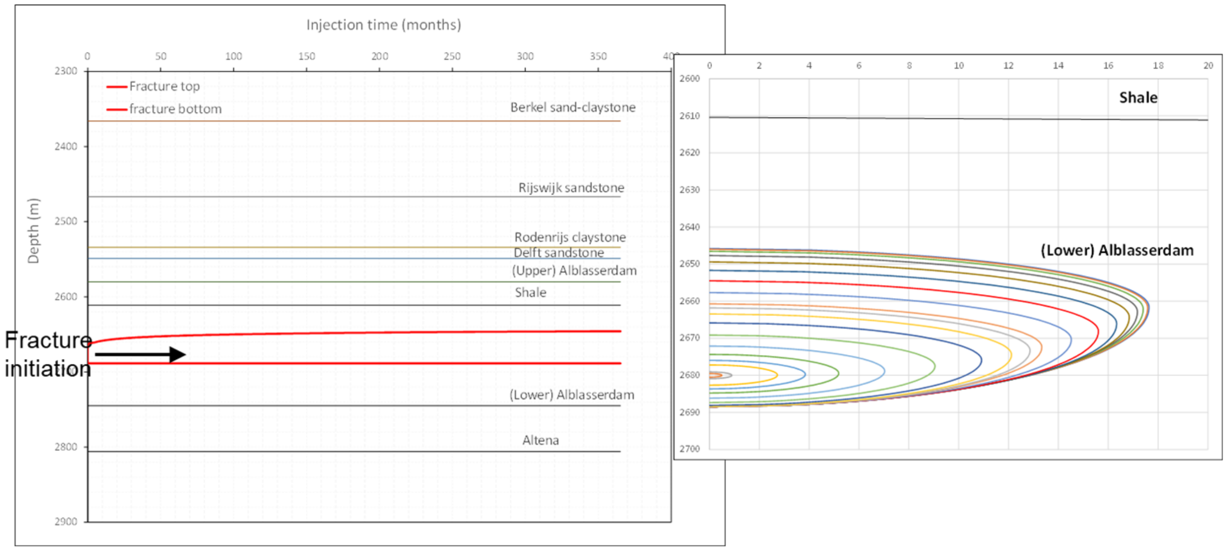

Figure 5-13: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 6. Fracture does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.

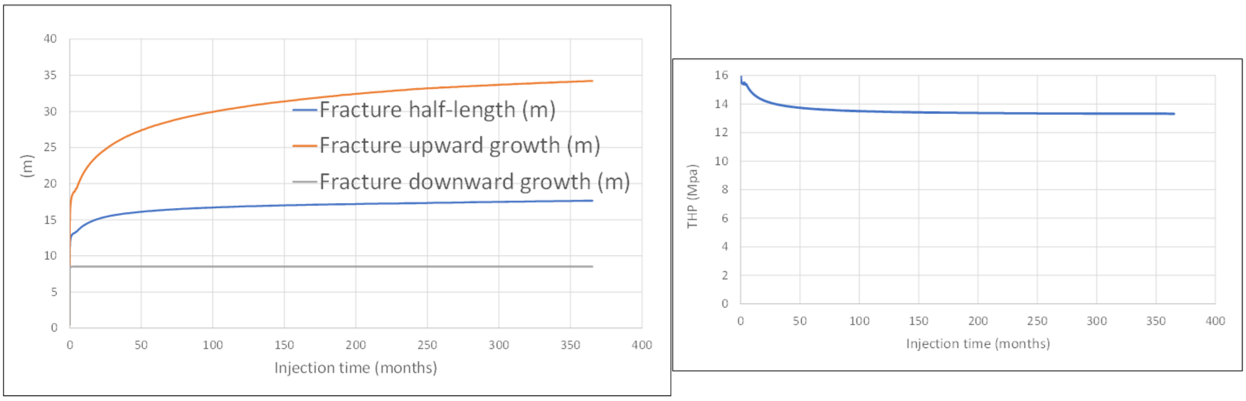

Figure 5-14: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 6. Fracture does not reach the Upper Alblasserdam shale. BHIP = 0.156 bar/m.

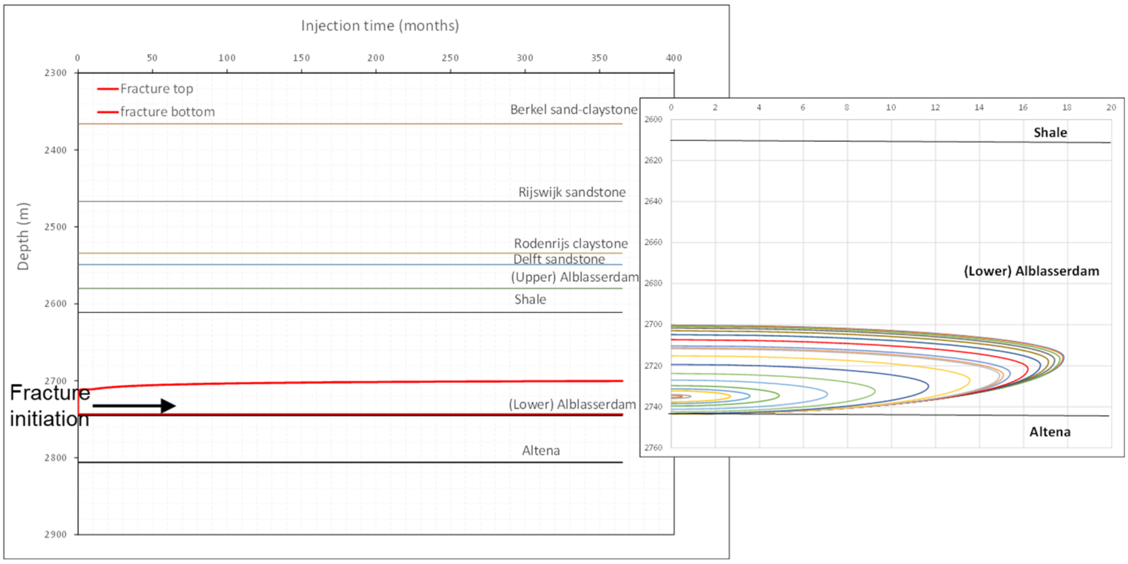

Figure 5-15: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 7. Fracture contained at the bottom by the Altena, it does not reach the Upper Alblasserdam shale. BHIP = 0.159 bar/m.

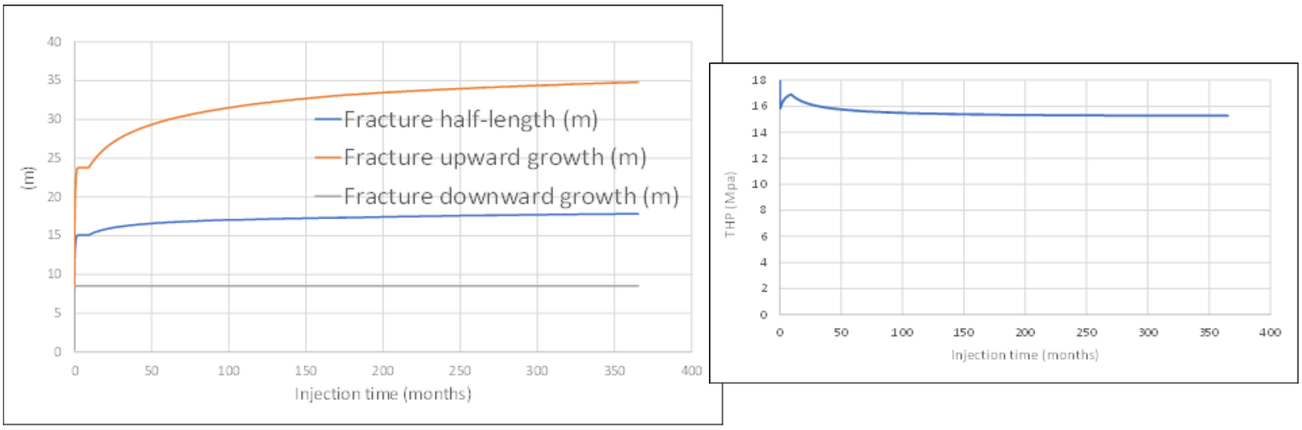

Figure 5-16: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 7. Fracture contained at the bottom by the Altena, it does not reach the Upper Alblasserdam shale. BHIP = 0.159 bar/m.

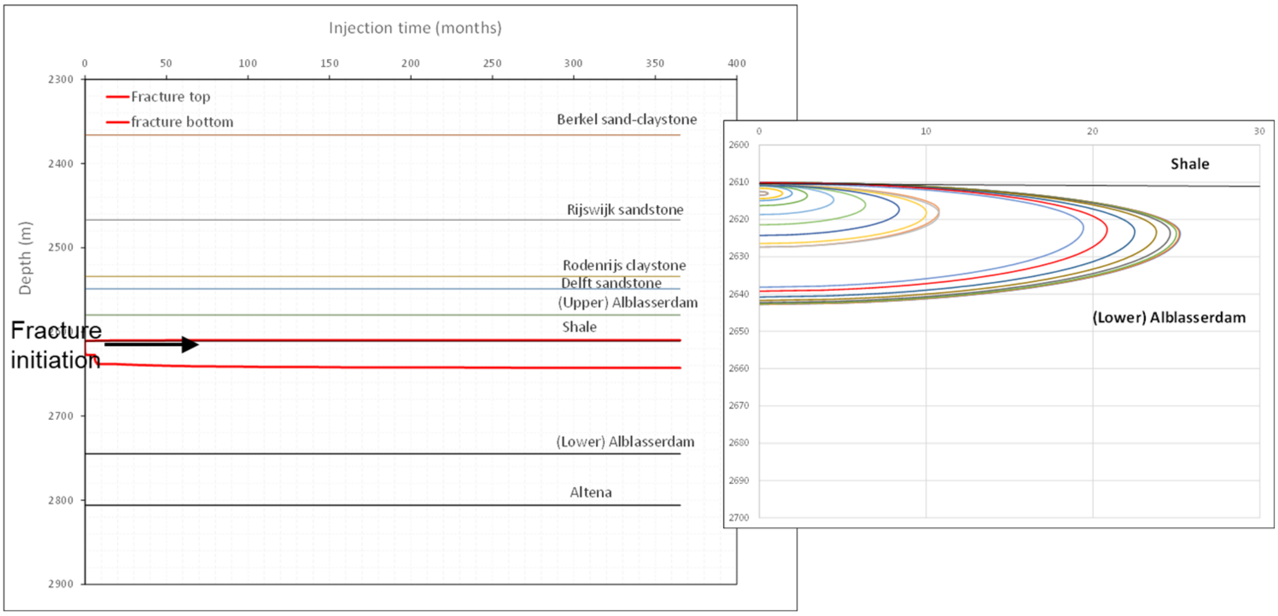

Figure 5-17: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 8. Fracture is 'contained' by the top shale, though it slightly grows into this Upper Alblasserdam shale. BHIP = 0.138 bar/m (lower because of lower shmin). However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

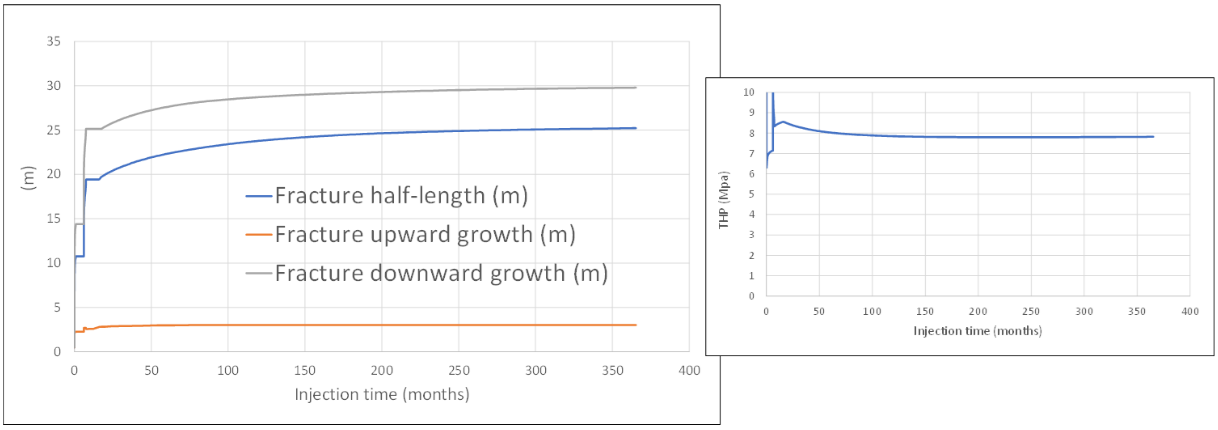

Figure 5-18: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 8. Fracture is 'contained' by the top shale, though it slightly grows into this Upper Alblasserdam shale. BHIP = 0.138 bar/m (lower because of lower shmin). Fracture is significantly smaller than in base case. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

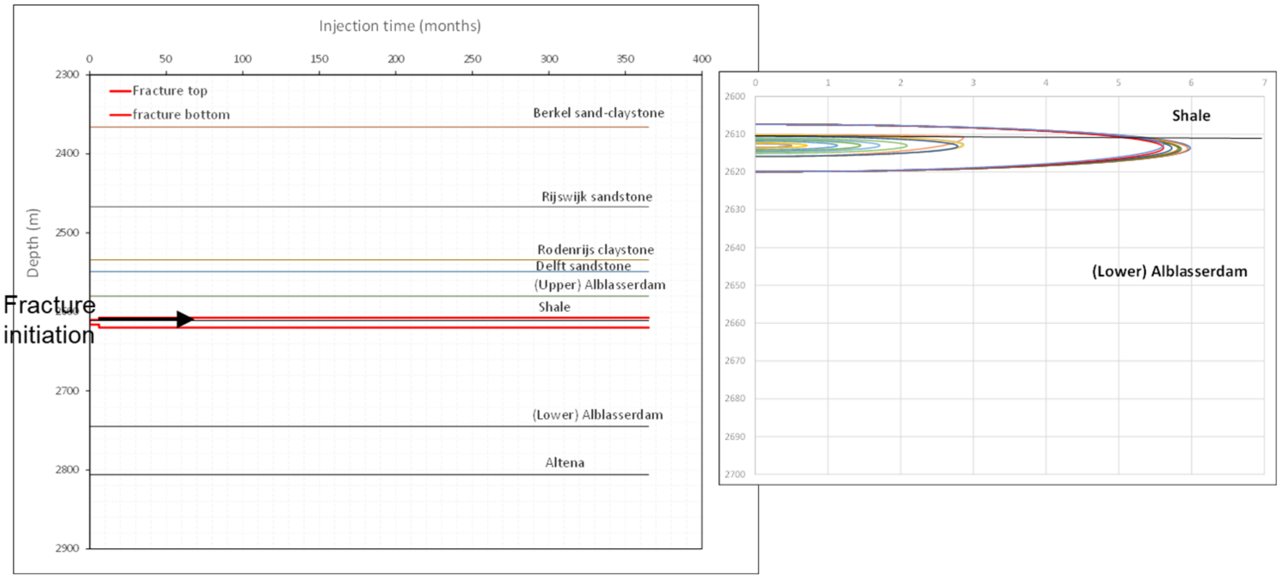

Figure 5-19: Fracture top and bottom as a function of time for base case; fracture contours for sensitivity 9. Fracture remains very small and is 'contained' by the top shale, though it slightly grows into this Uper Alblasserdam shale. BHIP = 0.209 bar/m because of higher shmin. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

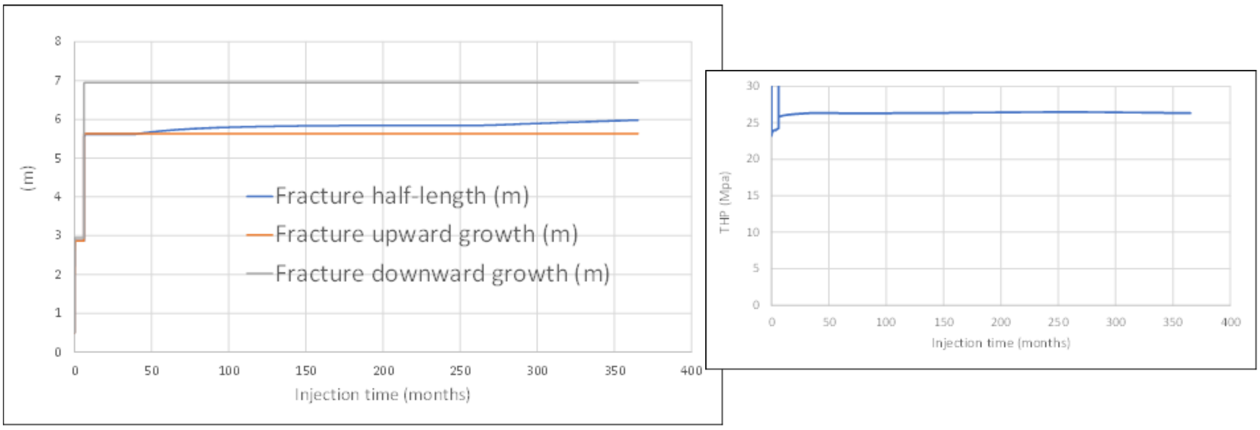

Figure 5-20: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) for sensitivity 9. Fracture remains very small and is 'contained' by the top shale, though it slightly grows into this Uper Alblasserdam shale. BHIP = 0.209 bar/m because of higher shmin. Fracture is significantly smaller than in base case. However, please note that the Rodenrijs shale is another sealing unit overlying the Alblasserdam package.

5.1.3 Injection into Delft

The product k.h in the Delft formation is slightly more than half of that of the (entire) Lower Alblasserdam formation. Therefore, injection of water into the Delft for the same parameters as in the Lower Alblasserdam (325 m^3/h @ 35°C) is expected to result in induced fractures as well. This is indeed what is seen (Figure 5-21, Figure 5-22, Figure 5-23 and Figure 5-24).

Simulations were performed for fracture initiation at 2536 m TVD (i.e., top-reservoir at 2 m below Top Delft) and 2542 m TVD (i.e., mid-reservoir), both with a slow start-up. Results are shown in Figure 5-21 and Figure 5-22 (fracture initiation @ 2536 m) and Figure 5-23 and Figure 5-24 (fracture initiation @ 2542 m). As can be seen, for both cases a relatively small fracture forms. For initiation at the top of the

Delft sandstone, the fracture penetrates a few meters into the overlying Rodenrijs claystone, while for initiation at the mid of the Delft sandstone it stays entirely in the Delft Sandstone Member, in line with expectations. However, for the first scenario this growth into the Rodenrijs Claystone is within the wastezone below the good sealing upper part of the Rodenrijs (see section 3.1.1.1) and the fracture will therefore still be contained. The corresponding injection pressure gradients (BHIP) are 0.159 and 0.162 bar/m, respectively.

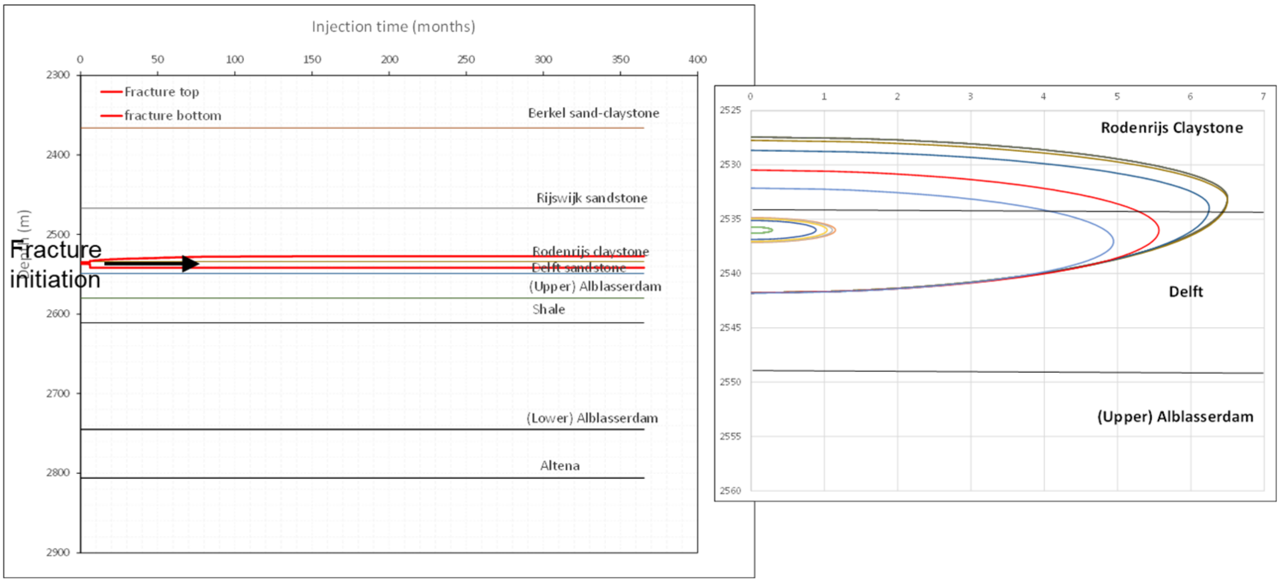

Figure 5-21: Fracture top and bottom as a function of time for fracture initiation at 2536 m (top Delft). Fracture penetrates a few meters into the overlying Rodenrijs claystone. Note that this ~7m growth into the Rodenrijs Claystone is within the wastezone below the good sealing upper part of the Rodenrijs (see section 3.1.1.1). BHIP = 0.159 bar/m.

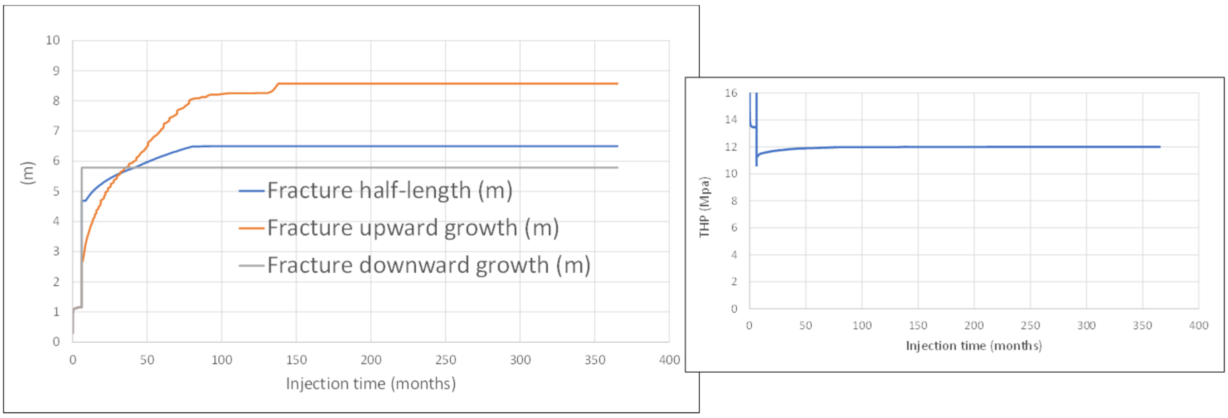

Figure 5-22: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) as a function of time for fracture initiation at 2536 m (top Delft). Fracture penetrates a few meters into the overlying Rodenrijs claystone. Note that this ~7m growth into the Rodenrijs Claystone is within the wastezone below the good sealing upper part of the Rodenrijs (see section 3.1.1.1). BHIP = 0.159 bar/m.

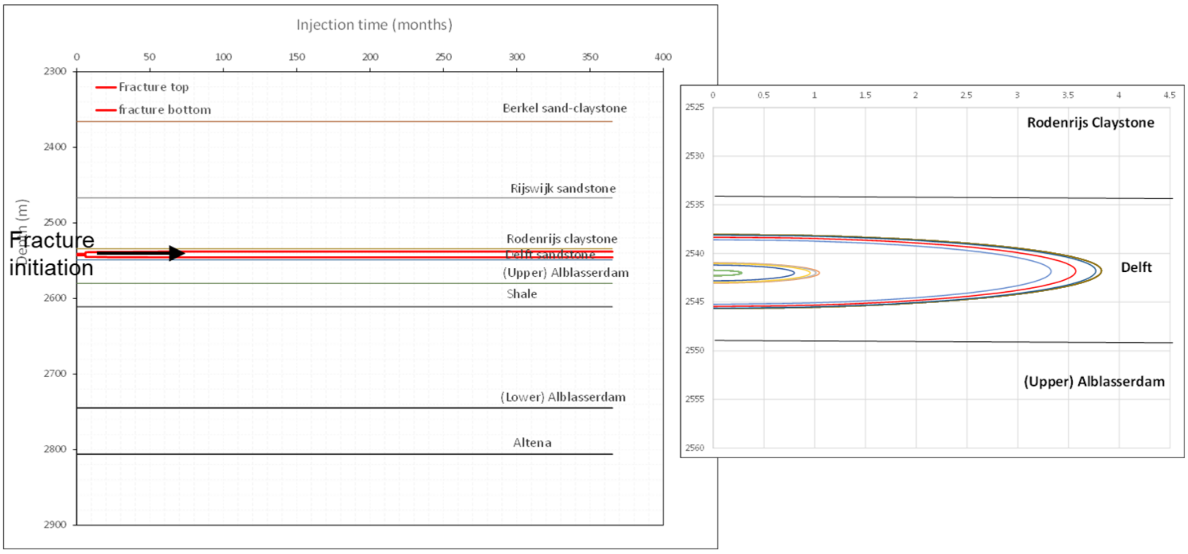

Figure 5-23: Fracture top and bottom as a function of time for fracture initiation at 2542 m (mid Delft). Small fracture that entirely remains in the Delft formation. BHIP = 0.162 bar/m.

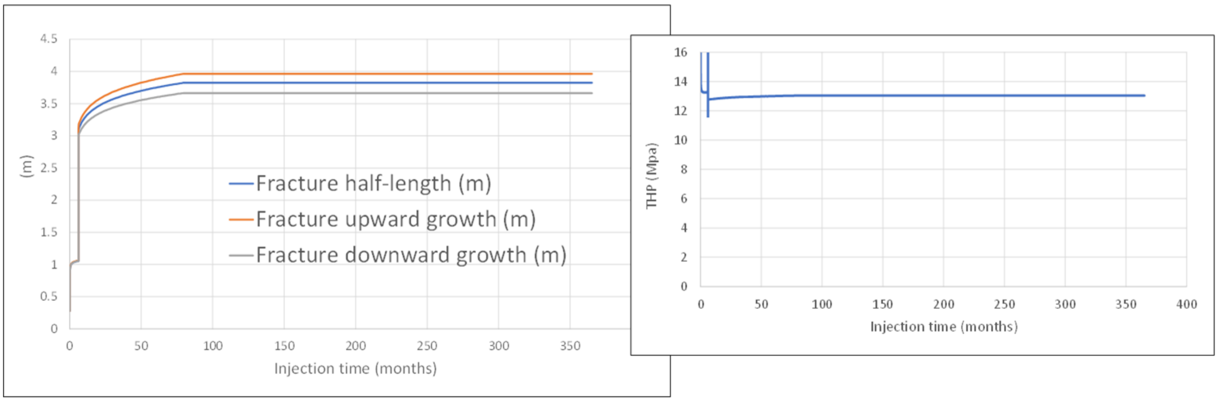

Figure 5-24: Fracture length, upward height, downward height, and injection Tubing Head Pressure (THP) as a function of time for fracture initiation at 2542 m (mid Delft). Small fracture that entirely remains in the Delft formation. BHIP = 0.162 bar/m.

5.1.4 Overview of Alblasserdam and Delft injection

Table 5-2 gives an overview of the expected fracture dimensions, tubing head pressures and bottom hole injection pressures for injection into the Lower Alblasserdam and Delft sands.

The results show that in some cases the injection-induced (‘thermal’) fractures might partly penetrate the overlying seal, as described in more detail in the previous sections (i.e., sections 5.1.1 to 5.1.3). When using the well-known minimum in-situ stress gradient of 0.158 bar/m, fracture growth into the layers that directly lie on top of the reservoir sands occurs at bottom hole pressures of 0.156-0.162 bar/m for injection into the Delft and Lower Alblasserdam sands (i.e., excluding sensitivities 8 and 9 with alternative stress states; Table 5-2). Nonetheless, the upper part of the Rodenrijs Claystone Member is regarded as the ultimate seal for the Nieuwerkerk Formation, and not the underlying Rodenrijs ‘’waste zone’’ nor the Upper Alblasserdam shales (see section 3.1.1.1). The upper part of the Rodenrijs Claystone Member is therefore regarded to be able to contain any injection-induced fractures.

Table 5-2: Fracture dimensions, stabilized tubing head pressures (THP) and bottom hole injection pressures (BHIP) for injection into the Lower Alblasserdam and Delft reservoirs. *Upper Alblasserdam shale as seal, ** Rodenrijs Claystone as seal.

	Fracture dimension after 30 yrs (m)			THP (Mpa)	BHIP (bar/m)	Notes
	Total length (m)	Height in overlying seal (m)	Height in underlying seat (m)	Stabilized (30 yrs)		
Lower Alblasserdam injection						
Base case	12	~2*	no	14	0.160	Fracture is 'contained' as the Rodenrijs Claystone is another sealing unit that is overlying the Upper Alblasserdam seal.
Sensitivity 1	10	no	no	13	0.156	No issues.
Sensitivity 2	9	no	no	14	0.156	No issues.
Sensitivity 3	10	no	no	15	0.156	No issues.
Sensitivity 4	25	~1*	no	14	0.162	Fracture is 'contained' as the Rodenrijs Claystone is another sealing unit that is overlying the Upper Alblasserdam seal.
Sensitivity 5	28	~1*	no	13	0.157	Fracture is 'contained' as the Rodenrijs Claystone is another sealing unit that is overlying the Upper Alblasserdam seal.
Sensitivity 6	18	no	no	13	0.156	No issues.
Sensitivity 7	18	no	no	15	0.159	No issues.
Sensitivity 8	25	~1*	no	8	0.138	No issues.
Sensitivity 9	6	~3.5*	no	27	0.209	No issues.
Delft injection						
Scenario 1	6.5	~6.5**	no	12	0.159	Fracture is 'contained' as this 3m is within the wastezone below the good sealing upper part of the Rodenrijs Claystone.
Scenario 2	3.8	no	no	13	0.162	No issues.

6 Conclusions

- Injection of 35°C water at 325 m^3/h into either the Lower Alblasserdam or the Delft sands cannot be achieved by adhering to SodM's injection protocol (SodM, 2013). Injection into either the Lower Alblasserdam (Figure 5-1 to Figure 5-20) or the Delft (Figure 5-21 to Figure 5-24) is expected to result into injection-induced ('thermal') fractures.
    - *Injection of 35°C water at 325 m^3/h into the Delft sands* can result in (very limited) fracture growth into the overlying Rodenrijs Claystone.
        - However, this growth into the Rodenrijs Claystone is within the wastezone below the good sealing upper part of the Rodenrijs (see section 3.1.1.1) and injection-induced fractures will therefore still be "contained".
        - In order to inject safely in the Delft it is advised not to exceed a bottom hole pressure gradient of 0.159 bar/m (Table 5-2).
    - *Injection of 35°C water at 325 m^3/h into the Lower Alblasserdam sands* can result in (very limited) fracture growth into the overlying Upper Alblasserdam shale. Injection could be designed such that the likelihood of induced fracture penetration into the overlying shale (i.e., Upper Alblasserdam shale) can be reduced to a minimum. This could for example be achieved by a perforation policy such that fracture initiation takes place (slightly below) the centre of the Lower Alblasserdam (Figure 5-4 and Figure 5-5).
        - However, irrespective of perforation policy in the Lower Alblasserdam, injection-induced fractures in this formation will *never* grow further upwards than the shale below Top Alblasserdam. This means that the main Rodenrijs seal will never be effected and can "contain" any Alblasserdam injection-induced fractures.
        - In order to inject safely in the Lower Alblasserdam it is advised not to exceed a bottom hole pressure gradient of 0.156 bar/m (Table 5-2, i.e., excluding sensitivities 8 and 9 with alternative stress states).
- In theory, it would also be possible to achieve 325 m^3/h within the limits of SodM's injection protocol by means of commingled injection into both reservoirs.

7 References

De Jager, M. A. ,Doyle, M.A., Graham, P.J. and Mabillard, J.E. Hydrocarbon habitat of the West Netherlands basin, in *Geology of gas and oil under the Netherlands*, H. E. Rondeel, D. A. J. Batjes and W. H. Nieuwenhuijs, Eds., Dordrecht, Kluwer Academic Publishers, 1996, pp. 191-210.

Den Hartog Jager, D.V., 1996. Fluviomarine sequences in the Lower Cretaceous of the West Netherlands basin: correlation and seismic expression. In: Geology of Gas and Oil under the Netherlands. Kluwer (Dordrecht): Rondeel, H.E., Batjes, D.A.J. & Niewenhuis, W.H. (eds). 229-242.

Duin, E. J., Doornenbal, J. C., Rijkers, R. H., Verbeek ,J. W. and Wong, T. E. Subsurface structure of the Netherlands - Results of recent onshore and offshore mapping, *Netherlands Jounral of Geosciences,* vol. 85, no. 4, pp. 245-276, 2016.

Gheissary, G. et al. 1998. Simulation of Fractures Induced by Produced Water Re-Injection in a Multi-Layer Reservoir. SPE 54735, presented at the SPE/ISRM Eurock held in Trondheim, Norway, 8–10 July

Koning, E.J.L., Waterflooding under fracturing conditions, Ph.D. Thesis, Technical University of Delft, 1988.

Martins, J.P. *et al.* Produced-Water Reinjection and Fracturing in Prudhoe Bay. SPE 28936, SPERE, August 1995, 176-182.

Panterra, Analysis of welltest MLD-GT-02-S2, 15 December 2017.

Panterra, “Geological report Maasdijk” Prepared for: Energie Transitie Partners B.V., Poeldijk, March 2019.

Staatstoezicht op de Mijnen. 2013. Protocol bepaling maximale injectiedrukken bij aardwarmtewinning – versie 2. 23 november.

Staatstoezicht op de Mijnen. 2020. Toezichtsignaal Integriteit van het geothermisch reservoir en de afsluitende lagen. 26 november.

Van den Hoek, P.J., et al. 1999. Simulation of Produced Water Injection Under Fracturing Conditions, SPE Prod. & Facilities 14 (3) August, p. 166-176.

Van den Hoek, P.J., Sommerauer, G., L. Nnabuihe, N. and Munro, D. 2000. Large-scale produced water re-injection under fracturing conditions in Oman. SPE 87267 (ADIPEC 0963), presented at Abu Dhabi Petr. Conference.

Veldkamp, J.G. et al. 2016. Thermal fracturing due to low injection temperatures in geothermal doublets. TNO Report 2015 R11739.

Verweij, J.M, Simmelink, H.J., Underschultz, J. and Witmans, J. Pressure and fluid dynamic characterisation of the Dutch subsurface. 2012. Netherlands Journal of Geosciences, 91-4, p. 465-490.