Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Under Stress: Measurements Of In-Situ Stress In Geothermal Projects In The Netherlands

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Keywords: In-situ stress, cooling, seismicity

ABSTRACT

For integrity and induced seismicity hazards associated with both injection and cooling in geothermal projects, the in-situ stress conditions are vitally important. In the Netherlands, the largest hazard in geothermal projects in sedimentary systems is from potential fault reactivation from cooling. The existing measurements of in-situ (horizontal) stress have come mostly from oil and gas projects, which are in a different geological situation, i.e. at geological highs, and do not include the impact of cooling. Therefore, a research program (Geo4All) was launched with an objective to measure in-situ stresses and, in addition, take valuable and scarce direct measurements of in-situ horizontal stresses in cooled geothermal reservoirs. Two operational geothermal projects were used, with the plans considering project-specific characteristics. In one project (Middenmeer Geothermie, the Netherlands), a doublet was being redrilled – allowing downhole open hole stress measurements (micro-frac) in both cooled and initial temperature reservoir locations within a short time interval. Another project (Geothermie Delft, the Netherlands), undertook cased hole (micro-frac) measurements prior to any operation, with a plan to test exactly the same location after cooling for several years. The combination of these tests will give insights both into the initial stress conditions in geothermal plays in the Netherlands and the impact of cooling on the stresses in sedimentary geothermal systems, thus facilitating better seismic risk and acceptable injection pressures calculations. This paper reports the initial findings after the first set of tests at each location.

1 INTRODUCTION

Geothermal projects cause stress changes in the subsurface mainly due to the effects of the injected fluids, which can increase the fluid pressure, reducing effective stresses, and cool the reservoir, which reduces effective stresses due to thermal contraction (e.g. Buijze et al., 2023; Ouf et al., 2025). In sedimentary systems, typically dominated by matrix flow, fluid pressure related effective stress changes are usually only significant close to the injection well and are relatively constant over time, whereas cooling induced stress changes move progressively away from the injection well coupled with the cooled zone and therefore have a larger chance of interacting with faults (Ouf et al., 2025).

When the changes in stress exceed a threshold, different phenomena can occur, i.e. fault slip which can lead to seismicity if the stress change reduces the normal stress on the fault sufficiently (Buijze et al., 2023; Ouf et al., 2025), cap rock cracking/damage which can lead to a loss of fluid containment (Gor et al., 2013) or creation of thermal fractures local to the injection well which can increase the injectivity (Luo et al., 2025) if the tensile strength is overcome. The amount of stress change which can be allowed is therefore tightly linked to the in-situ stresses, e.g., fault friction and therefore shear strength is a direct function of the in-situ stresses.

Given the expanding number of license applications in the Netherlands (and globally), potential induced seismicity is given more attention, with project owners having to ensure they have the financial means to pay for induced seismic damages. In addition, calculations using wide ranges of in-situ stresses which result in a broad range of modelled seismicity including high (or certainly non-negligible) end members which can result in the public having a bad impression of safe projects, or on the contrary an over-positive view of un-safe projects.

The in-situ stress state in the deep subsurface is rarely measured in an accurate way, and even less commonly after operations which are likely to change the stress state, e.g. by cooling. Data is even more sparse in geothermal systems, which often target geologically different locations, e.g. geological lows rather than highs in oil and gas projects and possibly higher porosity systems.

This paper outlines the current state-of-the-art knowledge of in-situ stress in geothermal reservoirs in the Netherlands and two recent measurement campaigns which were intended to directly measure the impact of reservoir cooling.

2 COOLING INDUCED STRESS CHANGES AND FAULT REACTIVATION

In general, cooling of reservoir rock leads to a less stable state of stress on steep (>45°) faults in a normal faulting regime, provided the extent of the cooled reservoir zone is larger than its height. The stress changes are mainly due to a reduction in horizontal stress σ_h, which translates into a reduction in effective normal stress and an increase in shear stress. This is already obvious from analytical formulations of cooling of simplified geometries such as laterally extensive reservoirs (Soltanzadeh & Hawkes, 2009), i.e.:

$$\Delta\sigma_h = E\alpha_T\Delta T/(1-\nu) \quad (1)$$

where E is Young's modulus (GPa), α_T is the linear thermal expansion coefficient (1/K), ΔT is the amount of cooling (K), and ν is Poisson's ratio (-). The destabilizing effect of reservoir cooling has also been shown with semi-analytical or numerical models of thermo-elastic stressing around geothermal injection wells (e.g. van den Hoek & Poessé, 2021, Fokker et al.,2023). These models reveal that cooling and thermo-elastic stressing are non-linear in space and time (e.g. Buijze et al., 2025). An example calculation is shown using the publicly available SRIMA tool (Fokker et al., 2025), which shows a progressive evolution of stresses closer to failure with injection time (Figure 1b). Initially, when the height of the cooled zone was larger than its width, stress changes were less destabilizing (see stress path of the 10 m point). Stress changes were largest and most destabilizing within the cooled zone, and the larger the cooled zone became, the larger the stress changes became. Observation points near the injection well approached the estimated minimum horizontal stress for laterally extensive reservoirs given in Equation 1, i.e. -11 MPa. However, further towards the edges of the cooled reservoir volume the stress changes were less, although stress changes occur beyond the cooled zone (e.g. stress path 300 m point in Figure 1b). For the example calculation, pore pressure increases were small and decayed rapidly with distance from the injection well. Hence, the stress path was dominated by thermal effects. For lower permeability reservoirs, short injection times, and high injection rates, pressure effects are expected to impose a bigger effect on the stress path.

The computed stresses were calculated with a simplified model (e.g. uniform reservoir properties), but these first order model assessments guide seismic hazard and risk estimates and can affect operational limitations such as the allowed amount of cooling. As can be observed in **Fehler! Verweisquelle konnte nicht gefunden werden.**b, both the initial stress state and the change in stress are important to consider when assessing the stability of a fault. However, field validation of the in-situ stress and these stress changes is lacking, leading to large uncertainties on model outcomes.

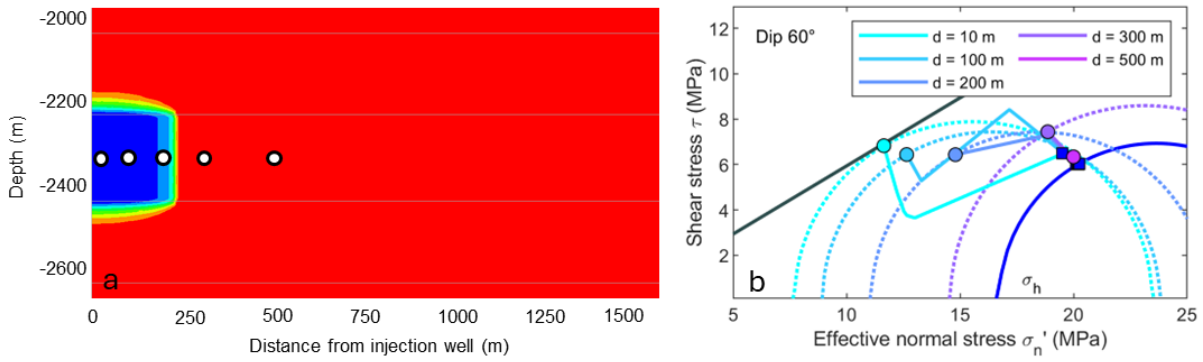


Figure 1. Geothermal cooling and related stress changes. Results were computed using SRIMA (Fokker et al., 2023), for values representative of the Middenmeer Doublet #2 (see Section 4.1) with a 214 m thick reservoir at 2200 m depth, E: 15 GPa, v:0.25, injection rate 135 m^3/hr, initial reservoir temperature 92°C, and an injection temperature 35°C. a) cooling of the geothermal reservoir after 10 years of injection. Dots: observation points. b) stress changes with progressive injection time, at observation points, assuming at each point a virtual fault is present with a dip of 60°.

3 IN-SITU STRESSES IN THE NETHERLANDS – CURRENT OVERVIEW

The prevailing stress regime in the upper crustal sedimentary formations in the Netherlands is predominantly a normal faulting regime, with the vertical stress as the largest stress component (van Balen et al., 2005, Figure 2a-d). The vertical stress gradient was calculated from publicly available density logs (Buijze et al. 2024,

www.nlog.nl). Information on the minimum horizontal stress σ_{hmin} was obtained from publicly available Formation Integrity Tests (FIT), Leak-off Pressures (LOP), and mini-frac (MF) tests (e.g. Bakx et al., 2023, www.nlog.nl, Hettema et al. 2025). FIT and LOT are routinely measured during drilling and have the highest number of measurements; however, they have limited use as an indicator for the σ_{hmin} (Table 1). Also, these are biased towards σ_{hmin} in caprocks and may not be representative of σ_{hmin} in reservoirs (see Figure 2e). Mini-frac tests are often performed before hydraulic fracturing of the reservoir, and give the best estimates for σ_{hmin}, but were taken outside of domains normally considered for geothermal energy.

Table 1 Overview of test types in the stress database Netherlands used as indicators for σ_{hmin}.

	Test type (and number # of tests available)	Where taken?	Which lithology?	Relevance for σ_{hmin} or formation strength
FIT	Formation integrity test (Limit Test) #>1000	Below casing shoe of a completed well section.	Usually strong / caprock lithologies, clay, chalk, salt.	Considered to be a lower bound.
LOT	Leak-off test. #>1000	Same as above	Same as above	Tends to overestimate σ_{hmin}
MF	Mini-frac test (alt: micro-frac, Diagnostic Fracture Injection Test, DFIT) #<200	Usually in the reservoir as preparation for hydraulic fracturing.	Tight gas reservoirs or oil reservoirs. NLD: sandstone reservoirs.	Best estimate of σ_{hmin}

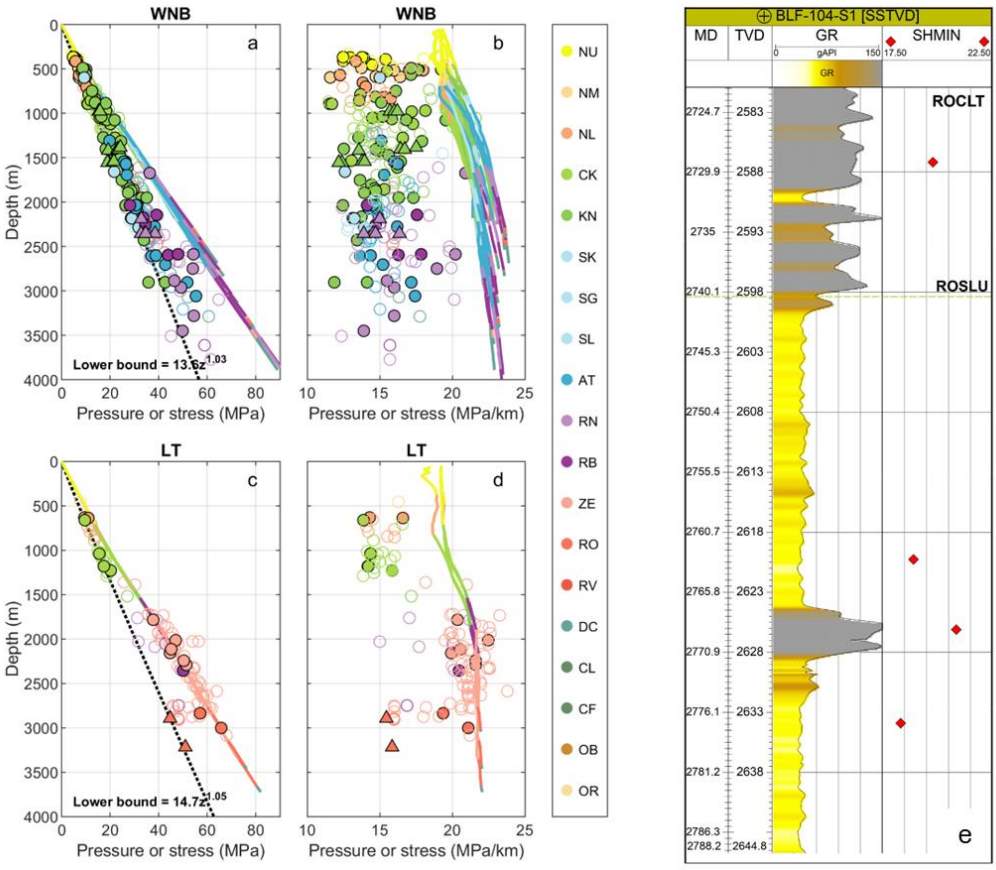


Figure 2. Extract of stress data in the Netherlands. a-d) Absolute minimum horizontal stresses and stress gradients from WNB: West Netherlands Basin in the southwest, and LT: Lauwerszee Trough, northern onshore. Data shown are FIT: hollow circles, LOP: solid circles, mini-frac tests: triangles. A lower bound power law fit to these data is also shown, with 80% of the measurements above the fit. Additionally, vertical stresses and stress gradients are shown (solid lines). The FIT, LOT, and mini-frac, as well as the vertical stress curves, are shaded according to the lithostratigraphic unit (see www.dinoloket.nl/stratigrafische-nomenclator for codes). e) Fracture Closure Pressure gradients in MPa/km from mini-frac measurements taken in a well in the northern onshore of the Netherlands, plotted together with the Gamma Ray log. ROCLT: Ten Boer Claystone Member, ROSLU: Upper Slochteren Member.

The vertical stress σ_v and σ_v-gradient varies laterally and with depth, as the thicknesses of formations vary laterally, and the densities of formations change with depth and lithology. Thick Cenozoic sediments or Zechstein evaporites cause relatively low gradients (e.g. see Figure 2d), and the presence of shallow carbonates or tectonic inversion causes high gradients (Buijze et al., 2024).

The most important observations for the σ_{hmin} are the following. Firstly, σ_{hmin} increase with depth, as do the σ_v gradients. Secondly, σ_{hmin} depends strongly on the lithology, due to e.g. differences in elastic moduli and/or creep. Lithologies such as clay and salt typically show high σ_{hmin} gradients. Observed stresses in the Zechstein salt were near-lithostatic, whereas those in the underlying Rotliegend Group were on the order of 16 MPa/km, which translates into a stress contrast of >10 MPa (RO and ZE in Figure 2c-d). The effect of lithology is also obvious in a stress profile measured in a well in the north of the Netherlands (Figure 2e). The stress gradient in the clay-rich caprock, and even within a thin (<5 m) clay-rich layer in the reservoir are 1-2 MPa/km larger than in the sandy reservoir rocks. Hence stress contrasts of several MPa may persist in claystone – sandstone sequences or sandstone – evaporite (salt or anhydrite) sequences. These contrasts will have a large effect on fault reactivation and caprock fracturing, and should therefore be accounted for. A third point to consider is that the horizontal stress depends on the amount of overpressure, with larger overpressures typically related to larger horizontal stresses (e.g. Engelder & Fischer, 1994). Hence, stress values from one location should not be blindly used at another location. In any case, for fault stability it is important to jointly consider the appropriate depth- and lithology-dependent σ_v and σ_{hmin}, and pore pressure.

4 NEW MEASUREMENT CAMPAIGNS TO MEASURE COOLING INDUCED STRESS CHANGES

4.1 Middenmeer Geothermie, the Netherlands

The Middenmeer Geothermie project (operator: Ennatuurlijk Aardwarmte) is situated in the northwest of the Netherlands. The target reservoir at Middenmeer is the Slochteren Sandstone Formation (Permian age), which is overlain by the anhydrites and clays of the Zechstein 1 Formation (Permian age), and underlain by clays, silts and sands of the Limburg Group (Carboniferous age). The reservoir top lies at a depth of 2.1 – 2.3 km (Figure 3a), and the reservoir has an initial temperature up to 94°C. A total of four doublets circulate formation brine through the reservoir at flow rates up to 150 – 350 m^3/hr per doublet, reinjecting the cooled brine at a temperature of ~35 °C. The doublet of interest for this study is Doublet #2, which was initially composed of wells MDM-GT-03-S2 (injector) and MDM-GT-04 (producer). The doublet produced from November 2014 to November 2024, circulating a total of $1.2 \cdot 10^7$ m^3 at an average flow rate of 136 m^3/hr. In 2025 these wells were redrilled by wells MDM-GT-11-S2 (new injector) and MDM-GT-07-S2 (new producer), which were both drilled sub-parallel to the two former wells. In the reservoir, the horizontal distance between the former injector and the new injector is 120 (top reservoir) to 220 (base reservoir) m (Figure 3b). Hence, MDM-GT-11-S2 provided a unique opportunity to probe the reservoir cooling due to 10 years of injection in MDM-GT-03-S2.

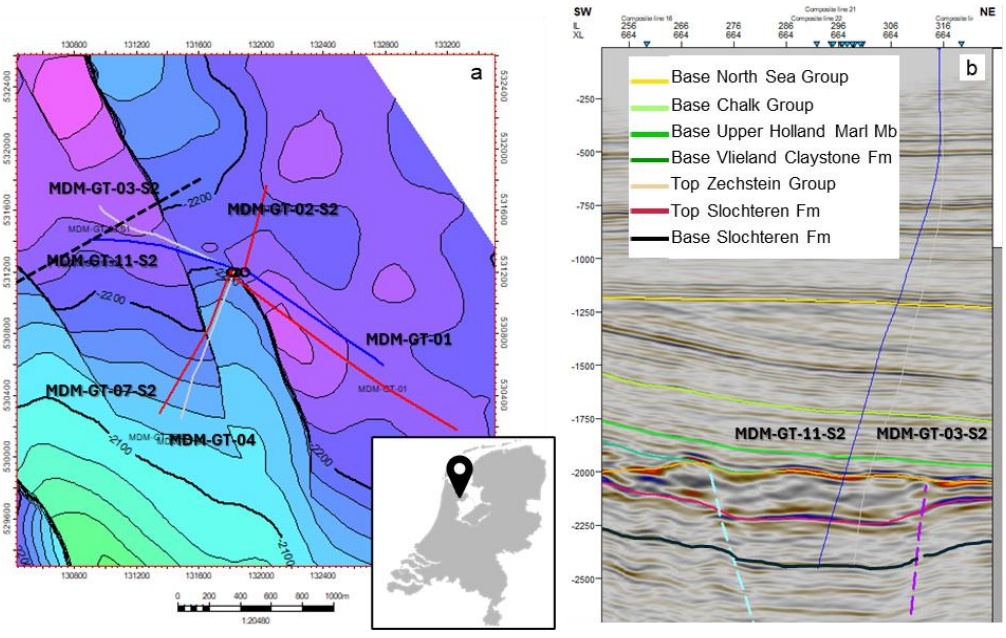


Figure 3. Overview of Middenmeer Geothermie project (from: Buijze et al., 2025). A) Plane view of the top reservoir depth and Doublet #2 with MDM-GT-03-S2/04 (old wells), MDM-GT-11-S2/07-S2 (new wells). B) Cross-section view through MDM-GT-11-S2, perpendicular to the main faulting orientation.

A logging and stress test campaign was performed in March 2025 to assess the effect of geothermal cooling on the state of stress in MDM-GT-11-S2. The campaign consisted of three runs, executed in the open hole section of the well 1-3 days after drilling of the final wellbore section was completed. The first two runs consisted of a Gamma Ray, dipole sonic, density, caliper and an image log, as well as accompanying PT measurements. During the third run, micro-frac tests were performed at three 1-m intervals along the open hole section. The logging results of the first two runs (see Buijze et al., 2025) formed the basis of selecting the stress test intervals. These were chosen based on 1) quality of the wellbore wall, 2) the absence of natural fractures, 3) low expected permeability, to ensure enough pressure build-up over the interval, and 4) the amount of cooling.

The intervals all targeted the lower permeability dune sandflat facies recognized in the image logs, but the amount of cooling varied with depth in the reservoir (Buijze et al., 2025) and hence over the tested intervals (Table 2). The initial temperature measurements during the first log runs showed a lower temperature within the bottom third of the reservoir with a minimum of 65 °C, whereas the top of the reservoir was hotter at 75°C. However, this temperature profile was heavily perturbed by the drilling process. A repeat temperature log taken 3 months after drilling still indicated cooling to be concentrated in the bottom third of the reservoir, but the temperature near the base of the reservoir was 52 °C and near the top 80 °C (Buijze et al. 2026). The amount of cooling from the initial reservoir temperature was thus 10-15 °C near the top and ~40 °C near the bottom of the reservoir.

Table 2. Overview of micro-frac tests in MDM-GT-11-S2. FCP: Fracture Closure Pressure; interpretations from SLB and Fenix Consultancy B.V. Temp1: temperature measurement 1-3 days after drilling. Temp2: temperature measurement 3 months after drilling.

Test #	Depth AH	Depth TVD	Temp1	Temp2	Porosity	Estimated Permeability	FCP SLB	FCP Fenix
	m	m	°C	°C	%	mD	MPa/km	MPa/km
ST#1	2636.8	2412.8	67-70	52-55	12	3	11.7-12.3	12.1-12.3
ST#2	2583.7	2362.3	67-68	77-83	12	4	12.2-12.4	12.6-12.8
ST#3	2462.0	2248.1	72-74	81	16	15	12.9-13.2	13.2-13.5

The micro-frac test was executed by SLB using the Modular Formation Diagnostic Tester (MDT) tool deployed on a wireline. Prior to deployment of the tool, a viscous pill was placed in the open hole section to increase the viscosity of the fluid used by the tool and allow higher pressure build-up during the micro-frac test. The test procedure at each interval started with a breakdown phase, where a strong packer was inflated over the selected open hole interval to initiate breakdown of the formation – a so-called sleeve frac or dry frac. This was done using multiple inflation and deflation cycles leading up to breakdown. Subsequently, the MDT tool was moved up, placing and inflating two other packers above and below the same pre-fractured interval. Wellbore fluids were pumped then through the tool into the isolated interval, pressurizing and reopening, propagating and closing the fracture over multiple pressurization cycles until a stable fracture closure pressure was reached.

Stress cycling at all three intervals was successful and yielded clear fracture closure pressures (

Figure 4). Two main observations were made. First, the absolute minimum horizontal stress gradients were ~12-13 MPa/km, a value that is lower than typical values (Section 3). The reduced horizontal stress is likely to reflect the influence of cooling around MDM-GT-03-S2. Even though the amount of cooling recorded at ST#2 and #3 is limited (~10°C), more cooling is expected around MDM-GT-03-S2 which could also reduce the horizontal stress further away through stress transfer. Follow-up stress tests in an uncooled part of the reservoir are planned to constrain the unperturbed state of stress and help with the interpretation. Second, the lowest horizontal stress gradients were observed in the zone with the largest amount of cooling (12 MPa/km at ST#1 vs 13.5 MPa/km at ST#3). Recalculated to the mid reservoir depth, this difference amounts to ~2.5 MPa of horizontal stress reduction for 40 °C of cooling (

Figure 4c). This is a two to three times smaller reduction in stress than would typically follow from estimates assuming a laterally extensive reservoir (Equation 1) using typical Slochteren values for elasticity (E = 15 GPa, v = 0.25, α_T = 1e-5 1/K), or from the SRIMA model estimate in Figure 1. This could be e.g. due to stress arching effects resulting from the observed heterogeneous cooling, or from reservoir plasticity or small scale thermal fracturing and resulting lower static 'elastoplastic' moduli. However, the results must be further interpreted and compared to more detailed models of cooling, taking into account the exact wellbore trajectories, permeability distribution, static and dynamic elasticity, a priori horizontal stress, over the reservoir and all related uncertainties. The results do present (one of) the first in-situ measurements of thermo-elastic stressing in a geothermal reservoir. If the findings are also representative of other Rotliegend reservoirs, this implies that

thermo-elastic stress and the potential for fault reactivation may be lower than is currently modeled in simplified geomechanical tools, and resulting limits on cooling may be relaxed (Fokker et al., 2023, TNO-AGE & EBN, 2023).

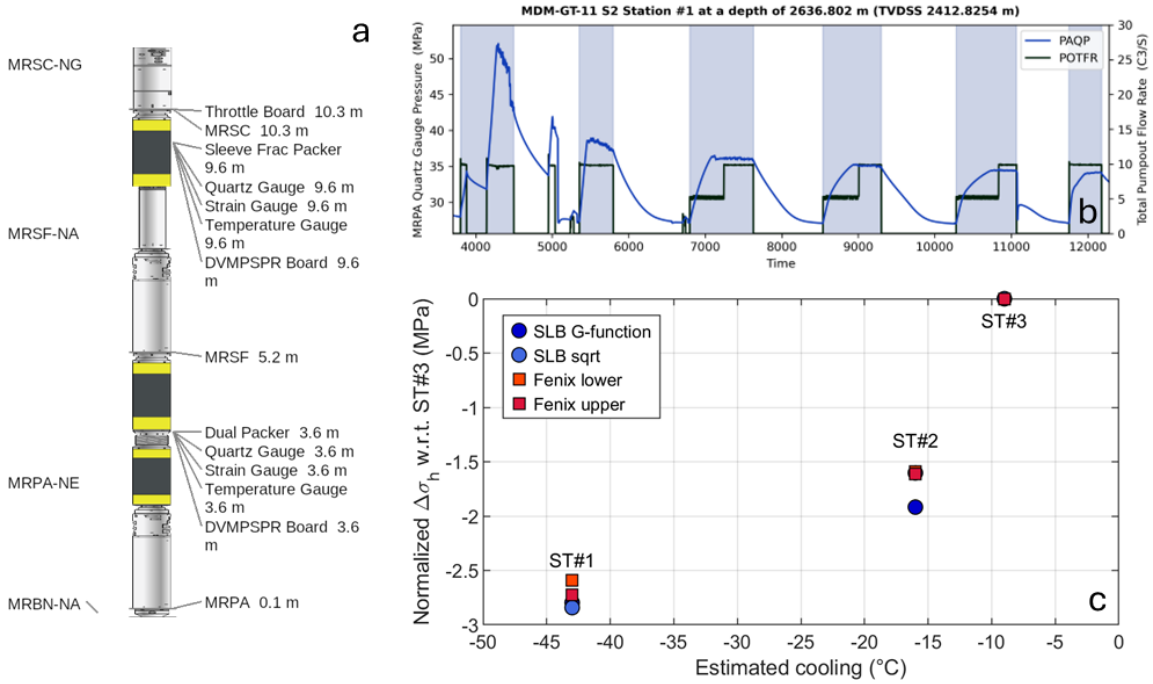


Figure 4. Overview of micro-frac procedure and results from Middenmeer. a) MDT tool for micro-frac testing, b) pressure and injection rate during micro-frac cycles at ST#1, measured at the interval between the two lower packers, c) difference in FCP between the 3 stations, recalculated from the gradients to the mid reservoir depth, and relative to the ST#3.

4.2 Geothermie Delft, Delft, the Netherlands

The Geothermie Delft project (operator: GTD) is situated in the west of the Netherlands. It is designed with dual aims of operating commercially and as a research site (Vardon et al., 2024a). The target reservoir is the Delft Sandstone Formation (early Cretaceous age), which is overlain by the Rodenrijs Claystone Member and underlain by the Alblasserdam Member (both also early Cretaceous age). The reservoir top lies at a depth of 2.0 – 2.2 km (Figure 5a), and the reservoir has an initial temperature of up to 80 °C. The Delft Sandstone formation is known to be of coastal plain origin and has a complex interlayered structure of sands and clays. The project began producing in December 2025, with flow rates projected to reach a maximum of 350 m^3/hr when demand is sufficient on both the university campus (existing heat network) and part of the city of Delft (new heat network under construction).

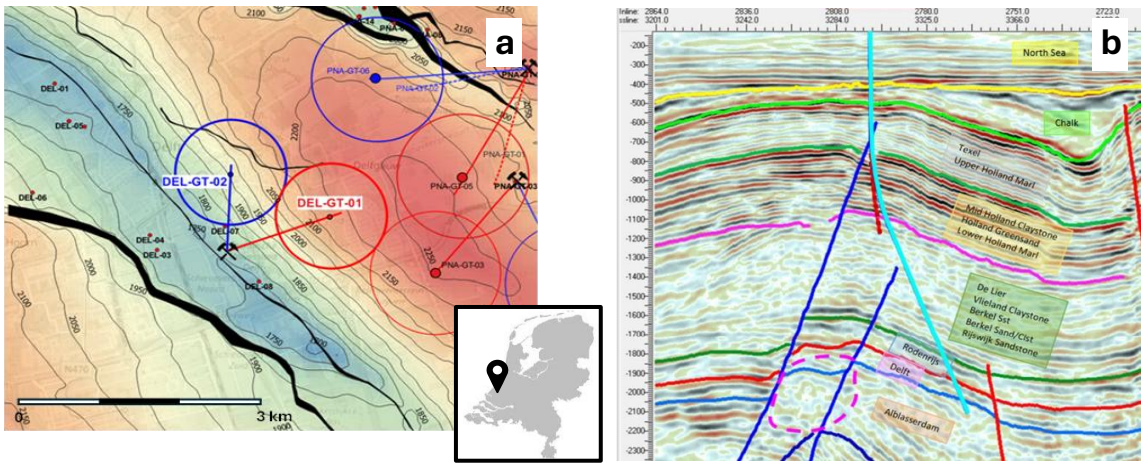


Figure 5. Overview of Geothermie Delft project. A) Plane view of the top reservoir depth with producer DEL-GT-01 and injector DEL-GT-02, and adjacent wells. B) Cross-section view through DEL-GT-02.

A comprehensive data collection programme including coring, logging, and sampling was carried out during drilling in 2023 (Vardon et al., 2024b, which contains links to download the data) and will continue throughout the lifetime of the project. For more information on the wider scope, see https://tudelft.nl/geothermalwell.

In November 2025, an initial cased hole logging programme in DEL-GT-02-S2 (injector) was carried out in conjunction with perforating the well, i.e. in a cased well. These logs provide the first set of logs for a timelapse series to investigate the evolution of the reservoir and also will allow a comparison with the logs carried out in open hole conditions during installation. As part of this campaign, micro-frac stress tests were carried out. These tests were designed to capture the initial (un-cooled) stress state in the reservoir and caprock, with the intention to return and test the same location after several years of cooling. A major advantage of doing these tests in cased hole conditions is the ability to easily locate and test the same location in the future in the same conditions. The perforations were carefully designed on the basis of the initial logging such that productive sandstone zones and desired stress test locations were perforated with unperforated sections left 2.4 m above and below stress test locations to ensure packers could seal against the casing.

The logging campaign consisted of four runs. The first run consisted of gamma ray and an ultrasonic imager with the primary objective of ensuring the location of the perforations, the second run consisted of the micro-frac tests including a gamma ray to aid accurate location, the third run was a pulsed neutron and the fourth a dipole sonic log.

The locations of the stress tests were chosen based on 1) the availability of sampled material so complementary laboratory tests can be carried out, 2) quality of the wellbore wall, 3) the absence of natural fractures and 4) a predicted local stress contrast so that a fracture would propagate away from the wellbore. Initially, a range of shales and sandstones in the reservoir were chosen to be investigated. The fluid in the wellbore was formation brine and it was anticipated to be a challenge to build up sufficient pressure to fracture the high permeability sandstones (predicted to be up to 1.2D), therefore tanks of highly viscous fluid were included in the logging toolstring. However, even with this contingency, it was not possible to build up sufficient pressure to fracture the sandstones.

The resulting stress test intervals are summarized in Table 3, which are all in shalesTable 2. The temperatures are consistent with the known thermal gradient and consistent with the well being left in static conditions for almost 2 years.

Table 3. Overview of micro-frac tests in DEL-GT-02-S2. FCP: Fracture Closure Pressure interpretations from Baker Hughes.

Test #	Depth AH	Depth TVD	Temp1	Porosity	Permeability	FCP
	m	m	°C	%	mD	MPa/km
ST#1	2267.4	1978.8	74.1	<5	<10	17.9
ST#2	2506.7	2166.4	77.6	<5	<10	17.4
ST#3	2365.1	2062.6	76.0	<5	<10	18.6

The tests were carried out with the Baker Hughes Reservoir Characterization eXplorer (RCX) tool, deployed on a wireline, which has the same principle as the MDT tool. The test procedure followed a different initial procedure due to the cased hole condition. The tool was first positioned in place via live correlations with a gamma ray tool included in the RCX toolstring and the gamma ray included in the ultrasonic imager tool string which could visualize the actual perforations. This eliminated any potential positioning errors due to wireline cable stretch. Two packers were inflated above and below the perforated interval. For the tests reported here, a breakdown injection cycle was initiated with the well-bore fluid, pressurizing the zone until a fracture was seen to open and propagate. The fluid was allowed to leak off naturally (with a low-rate pump available if needed to pump out of the tested zone) and a characteristic pressure drop off with a change in shape indicating that fracture closure pressure had been reached. Multiple pressurization and fracture reopening, propagating and fracture closing cycles were undertaken until a stable fracture closure pressure was reached.

Results from one of the tests (ST#1) are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**Figure 6. In the first cycle, a higher injection pressure is reached than in later cycles as expected, indicating the fracture developing towards the direction of the minimum stress (formation breakdown), rather than overcoming the tensile strength due to the existing perforations. The fracture closure pressure decreases in subsequent cycles

and was observed to become constant after the third cycle, indicating that the fracture had reached beyond the zone of influence of the wellbore.

The stress tests showed a consistent minimum horizontal stress with past observed trends (see Figure 2 and Figure 6) and with the stress gradient increasing slightly with depth and being above the lower bound previously identified. A stress gradient of 1749-18.6 MPa/km was measured. The variation of the values away from a linear trend, is consistent with being an interlayered reservoir. The planned tests after cooling from operation in several years will be able to test the same locations, and therefore the findings would not be impacted by this heterogeneity. The findings confirm that using the lower bound values from past LOT and FIT could be conservative.

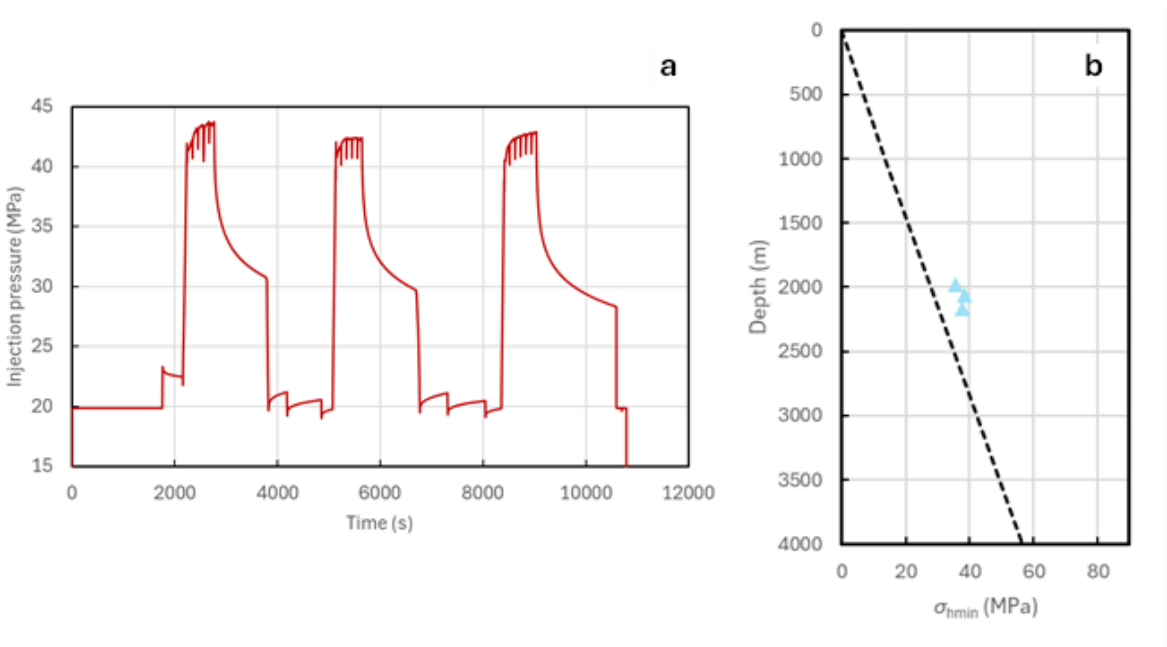


Figure 6. Overview of micro-frac results from Delft. a) pressure during micro-frac cycles at ST#1, b) measured stresses plotted alongside the lower bound shown in Figure 2 for the West Netherlands Basin.

5 DISCUSSION, FUTURE PLANS AND IMPLICATIONS

The measurement of in-situ stresses in geological conditions in two key geothermal plays in the Netherlands allows further analysis and contributes to the body of work on the operational safety of geothermal projects. Initial indications are that in-situ stresses are above identified lower bounds (from the Delft results), and further testing can confirm the hypothesis that a higher 'lower bound' could be used in operational safety analyses to safely expand the operational window. The impact of cooling on stresses also appears to be smaller than initially expected (Middenmeer results) which again with more confirmation could be used to safely expand the operational window. Both initial findings will be tested via upcoming tests at the respective sites. At Middenmeer, tests are planned to be carried out in another well which is planned to be drilled in reasonable proximity and does not intersect a cold plume. At Delft, the same locations will be again tested after a few years of cooling. The future Middenmeer tests will measure undisturbed in-situ stresses in the near future, yet will have some influence of spatial heterogeneity, while the future Delft tests will eliminate the impact of spatial heterogeneity although can only take place after a significant period of cooling.

These data can provide the basis for improved and less conservative geomechanical analyses that are used to assess, for example, the likelihood of cooling-induced seismicity. However, further validation of the findings is valuable (yet costly). Analysis of seismic monitoring and laboratory tests will also further add to the knowledge basis and can open the door to knowing when the operational window (i.e. being able to reduce injection temperatures) can be safely carried out, with a result of more profitable projects.

6 CONCLUSIONS

In-situ stresses and cooling-induced stress changes are both vital to determine operational safety of geothermal projects, yet both are rarely measured. Measurement campaigns have been carried out in two sites in the Netherlands in conjunction with their operations. In the Middenmeer Geothermie site, a doublet was being redrilled with the new well 120-220 m away from a former injector that had been injecting for 10 years.

Temperatures and stresses were measured at various depths inside the cooled plume in open hole conditions. The results show:

- Cooling of the reservoir was heterogeneous with depth and varied between -40 and -10° C over the tested intervals.
- The absolute minimum horizontal stresses that were measured were 12-13 MPa/km which is relatively low compared to regional estimates. This may reflect the influence of cooling at the well location as well as the nearby cooled reservoir volume.
- The minimum horizontal stress gradient showed a consistent decrease with the amount of cooling.
- The minimum horizontal stress change with temperature was less than expected from thermo-elastic stress changes computed using simplified models with default geomechanical input parameters.

In the Geothermie Delft site, cased hole stress tests have been carried out in a well prior to operation, identifying stresses above the lower bound conditions compiled from LOT, FIT and a limited number of micro-frac tests. These same locations will be retested after a few years of operation, eliminating any uncertainty of spatial variability on the test results.

Acknowledgements

The authors gratefully acknowledge the Geo4All project, carried out with a PPP program allowance subsidy from the Ministry of Economic Affairs and Climate for TKI Nieuw Gas, Topsector Energy (www.topsectorenergie.nl) and the EPOS-NL/EPOS-eNLarge projects funded from the Dutch Research Council (NWO) via the Dutch national research infrastructure for solid Earth sciences (project numbers 184.034.005 and 184.036.007) and from Delft University of Technology.

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