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MINIMUM STRESS TESTING XLOT IN SEALS OF GEOTHERMAL SCAN WELLS: METHODOLOGY AND MODELS

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Outline

1. Introduction & Application
2. Test overview, data processing and methodologies
3. Interpretation of the XLOT test minimum stress
4. Results in 1-D geo-mechanical models including tectonics
5. Overview of minimum stress results
6. Conclusions and outstanding work

1 Introduction

- The geo-mechanical data acquisition for the geothermal development in The Netherlands within the SCAN programme was presented: *Geomechanical data acquisition in SCAN wells*, Janszen et al, GET2024.
- The extensive data collection program entails both wellbore logging, coring and well testing, to obtain the reservoir performance flow parameters and geo-mechanical parameters (stiffness and friction).
- This study focusses on determination of the *in-situ* minimum stress to calibrate the one-dimensional geo-mechanical model (Hettema, 2022)
- Calibration to physical models to understand the origine of the stresses, allowing lateral extrapolation within the basin.

1 Application of the results

These XLOT results are used to study the geo-mechanical challenges for geothermal developments:

1. Develop, calibrate and update the 1-D geomechanical well model to assure safe and efficient drilling
2. Analyse the reservoir integrity to determine the maximum safe injection conditions to prevent out-of-zone injection and seismicity
3. Assess if thermal fracturing occurs, how it will affect the safety and long-term injectivity of the system.

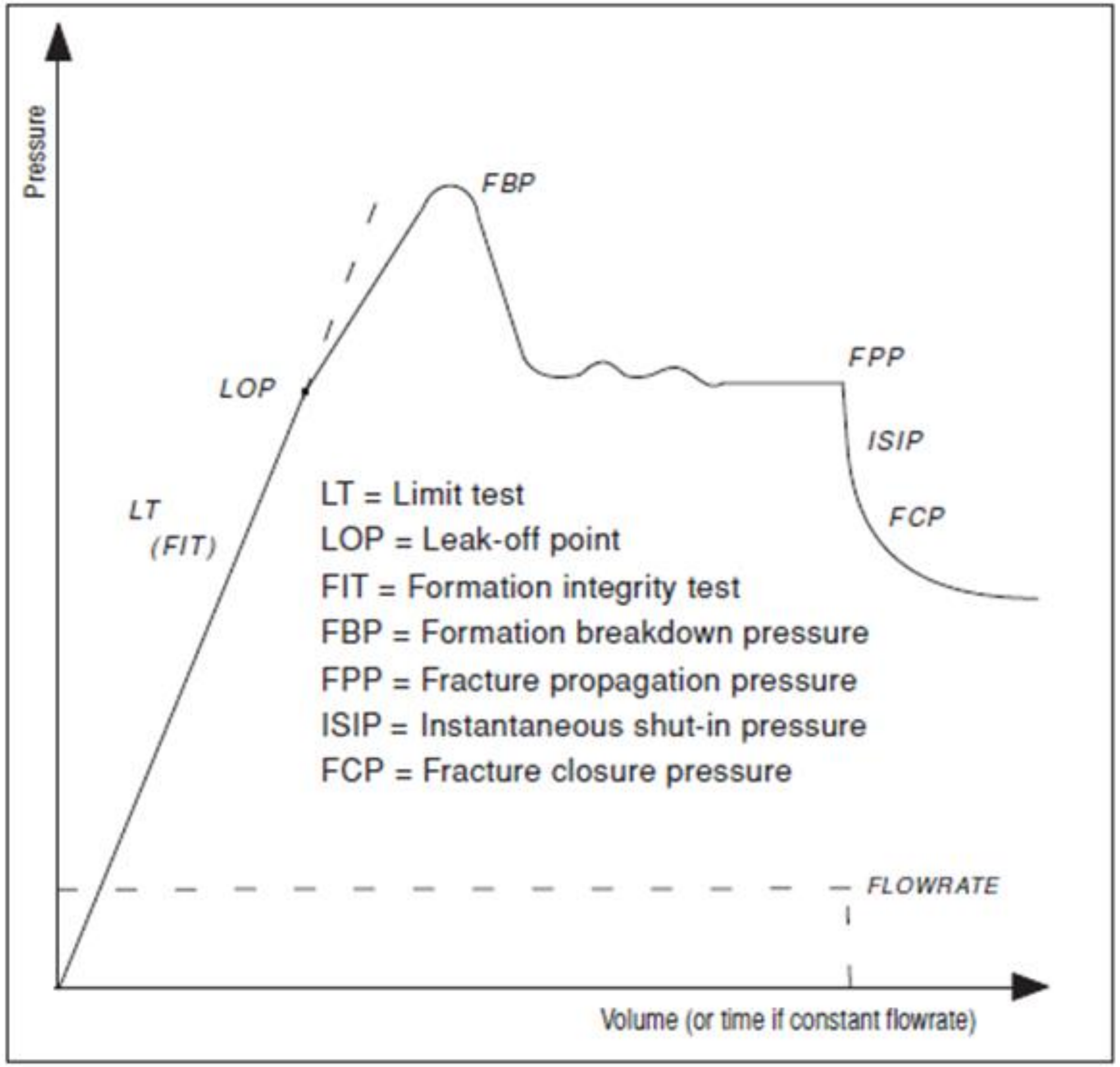
2 Overview of SCAN wells XLOT sealtests interpreted (work in progress)

Wellbore	Completion	Start test	XLOT 1 [cycles]	XLOT 2 [cycles]	XLOT 3 [cycles]
AMS-01	Cased and Perforated	10/12/2023	Main Claystone [3]	Vlieland claystone [5]	Asse Claystone [4]
ORO-01	Cased and Perforated	18/05/2024	Asse claystone [3]	Boom Claystone [3]	-
HEE-01	Cased and Perforated	18/12/2024	Rogenstein clayst. [3]	Emscher limestone [3]	Landen Clay [3]

2 Data processing

1. Surface data acquired from cement-unit or coil-tubing are the pumping rate and (wellhead) pressures. All tests had a downhole gauge located as close as possible to the top of the perforations.
2. The brine properties were obtained from the measured density and the salinity from the water sample, while applying the in-situ pressure and temperature conditions (Batzle and Wang, 1993).
3. The downhole flowrate is determined from the measured pump rate by applying a linear wellbore storage factor, which was in most cases confirmed from analysis of the pre-lot volume versus pressure plot

2 Test overview XLOT and nomenclature



Analyses

Pre-LOP: Determination of wellbore storage
Post-LOP: Initiation of fracture volume or hydraulic leak-off?
FBP: Defined as the maximum pressure
FPP: Stable fracture propagation if dP/dt -> 0
ISIP: Post shut-inn deviation
FCP: Fracture closure pressure

2 Three XLOT test stages interpreted

Method	Result [method certainty for minimum stress]	Results compared with pre-drill prognosis	References
FBP **Breakdown**	Wellbore stability, minimum stress [low]	Max. pressure (well design) Applying/calibration of 1-D geomech. model	Andrews et al., 2016
FPP **Propagation**	Minimum stress from net frac. pressure [medium], volume limit for safety	Minimize risk for out-of-zone injection	Geertsma & de Klerk, 1 Perkins & Kern, 1961 Nolte & Smith, 1981
ISIP & FCP **Closure**	Minimum stress [high]	1-D geomech. model	Hettema, 2022

2 FBP analysis, important to understand influence of well/perf angle, near-wellbore stresses, fluid/rock conditions, LOT

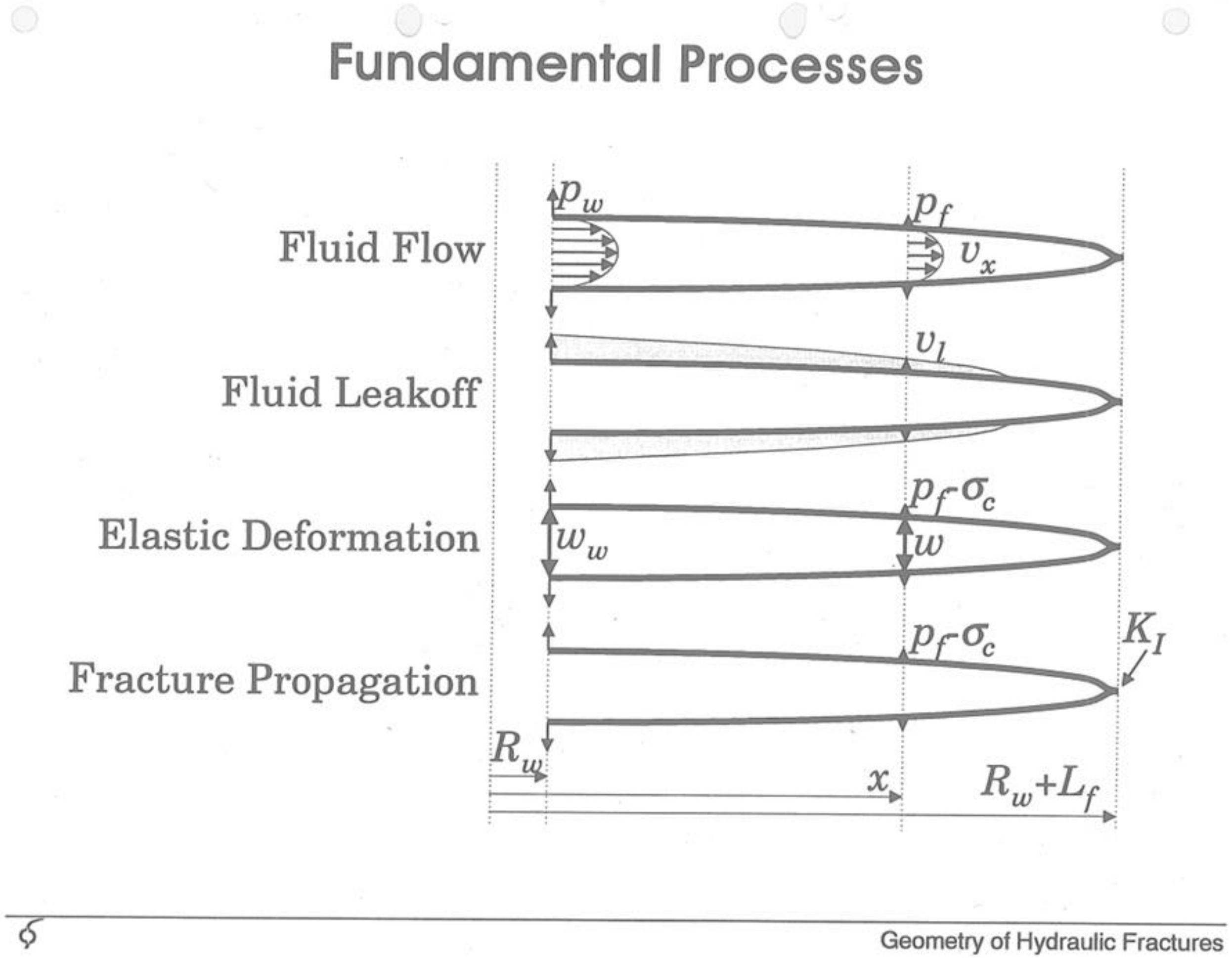
Andrews et al (2016) calibrated with high quality XLOT data the relationship for *FBP* for an inclined well (wells/perfs with inclination *i*):

$$FBP = (2 + \sin^2 i)\sigma_{hmin} - \sigma_v \sin^2 i - p_0 + T_0$$

Inversion allows determination of the minimum stress:

$$\sigma_{hmin} = \frac{FBP + \sigma_v \sin^2 i + p_0 - T_0}{(2 + \sin^2 i)}$$

`2 *FPP* four fundamental processes



Hans de Pater & PHD's performed at TU Delft large-scale block fracturing experiments and developed theory to understand the fracturing process (From Weijers, 1994)

2 *FPP* modelling based on *PKN*, *GdK* and radial models

1. The *FPP* is modelled through the net-fracture pressure from the basic literature (see Table 1):

$$p_{net} = p_{inj} - \sigma_3 > \Delta P_{fric}(q_i, \mu, w_{fr}) + \frac{K_{Ic}}{\sqrt{\pi L_{fr}}}$$

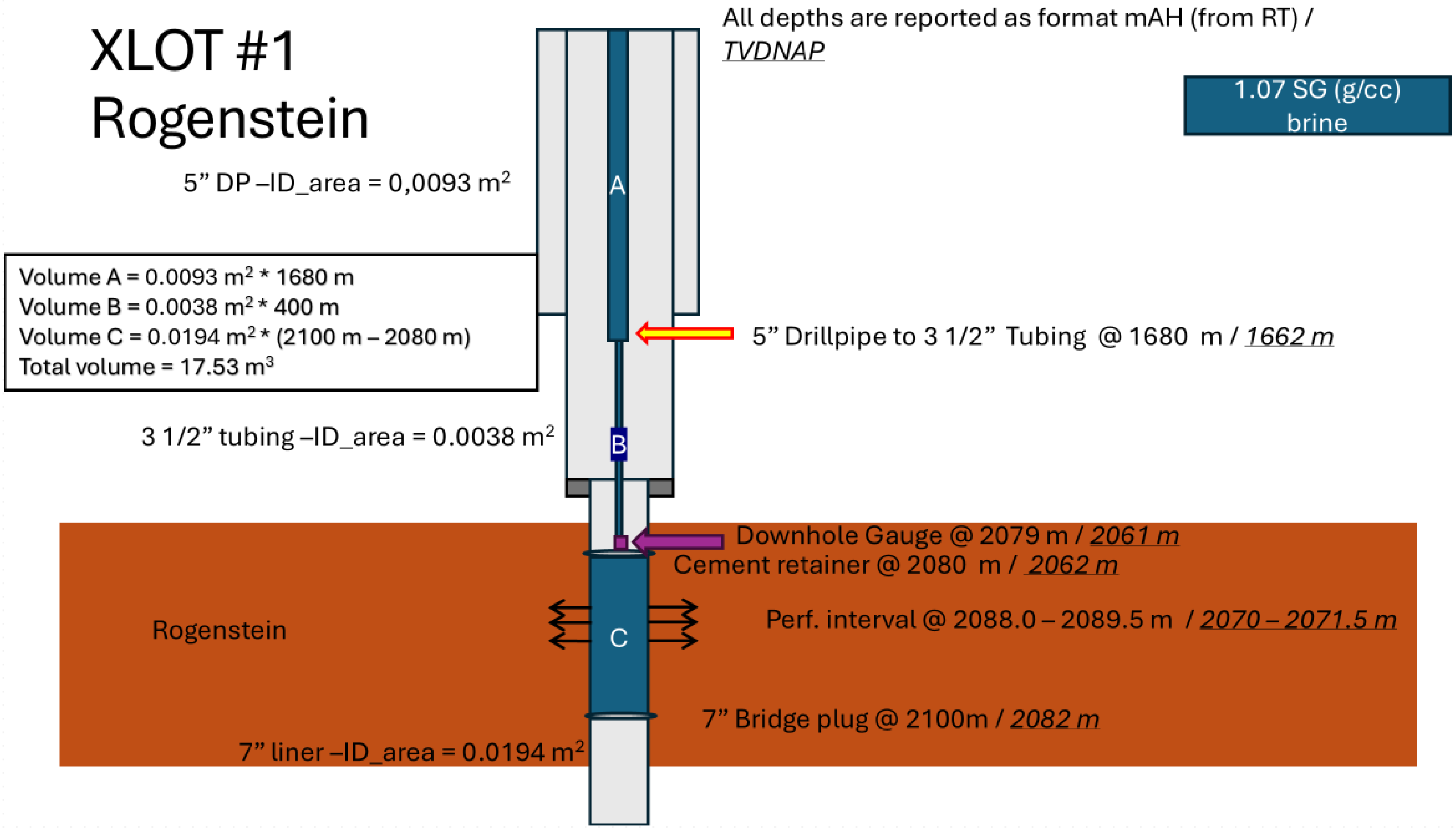
Since the seal is quite homogeneous and since for safety reasons we are interested in the maximum height-growth, the radial model has been used the determine the friction inside the fracture:

$$\Delta P_{fric}(q, R) = \left(\frac{E'}{R}\right)^{0.75} (\mu q)^{0.25}$$

Here q is the flow rate, μ the viscosity, E' the plane strain modulus and R the radius of the fracture. From the mass balance, the net-fracture pressure can be related to the fracture volume by:

$$\eta V_{inj} = V_{frac} = \frac{4}{3}\frac{R_f^3}{E'}(p_f - \sigma_\perp)$$

2 Well schedule XLOT #1, for wellbore storage calculation/verification

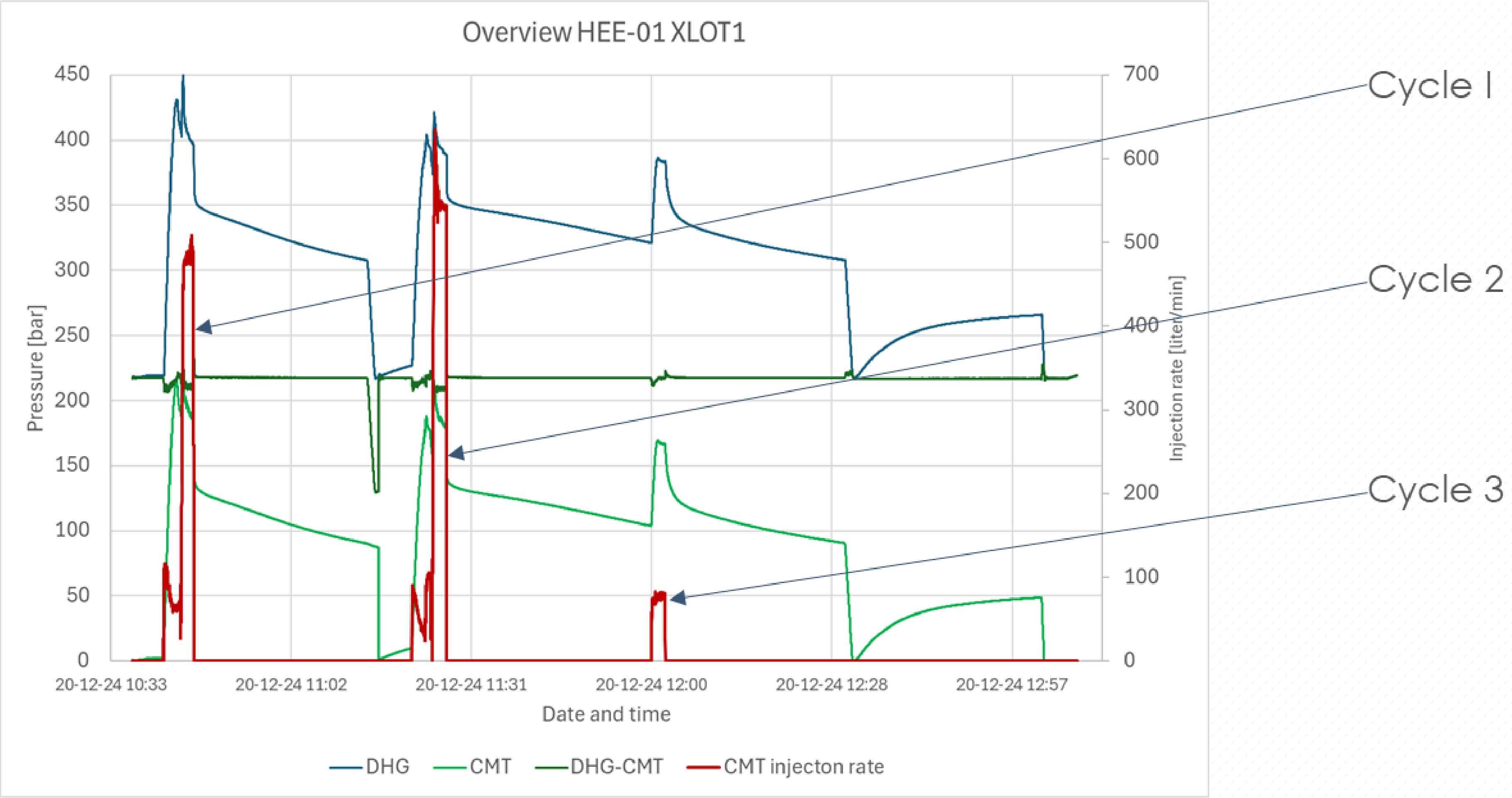


2 Post shut-in fracture closure analysis in seals

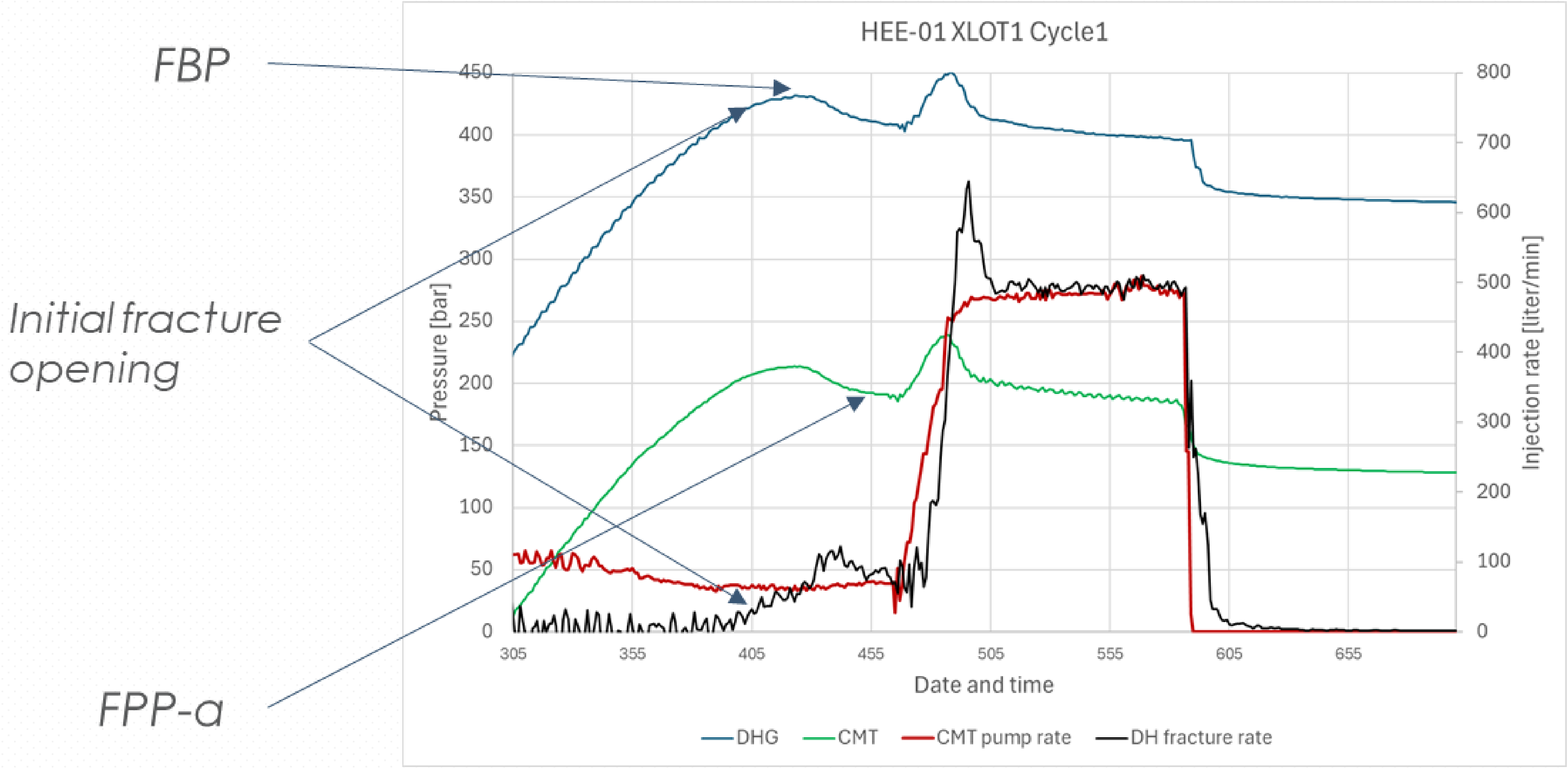
Most methodologies were developed for hydraulic fracture diagnostics for production optimization in shale reservoirs. Barree et al (2009) discuss several analysis methods:

Method	Basis	Remark +/-	Assumption	Reference
Root of time	Carter leak-off	+ Simple, direct data - Can lead to wrong interpretation (Raaen et al)	Constant: pressure fracture width	Carter (1957) Geertsma & Haafkens (1979)
G-function	Pressure decline analysis	+ Widely used - Complex, requires model choices	Fracture model	Nolte (1979)
System stiffness approach	Pump-in flow back	+ Elegant - Test design fixed (PIFB)	Sensitive to: leakage or gas present	Raaen et al (2001) Raaen (2006)

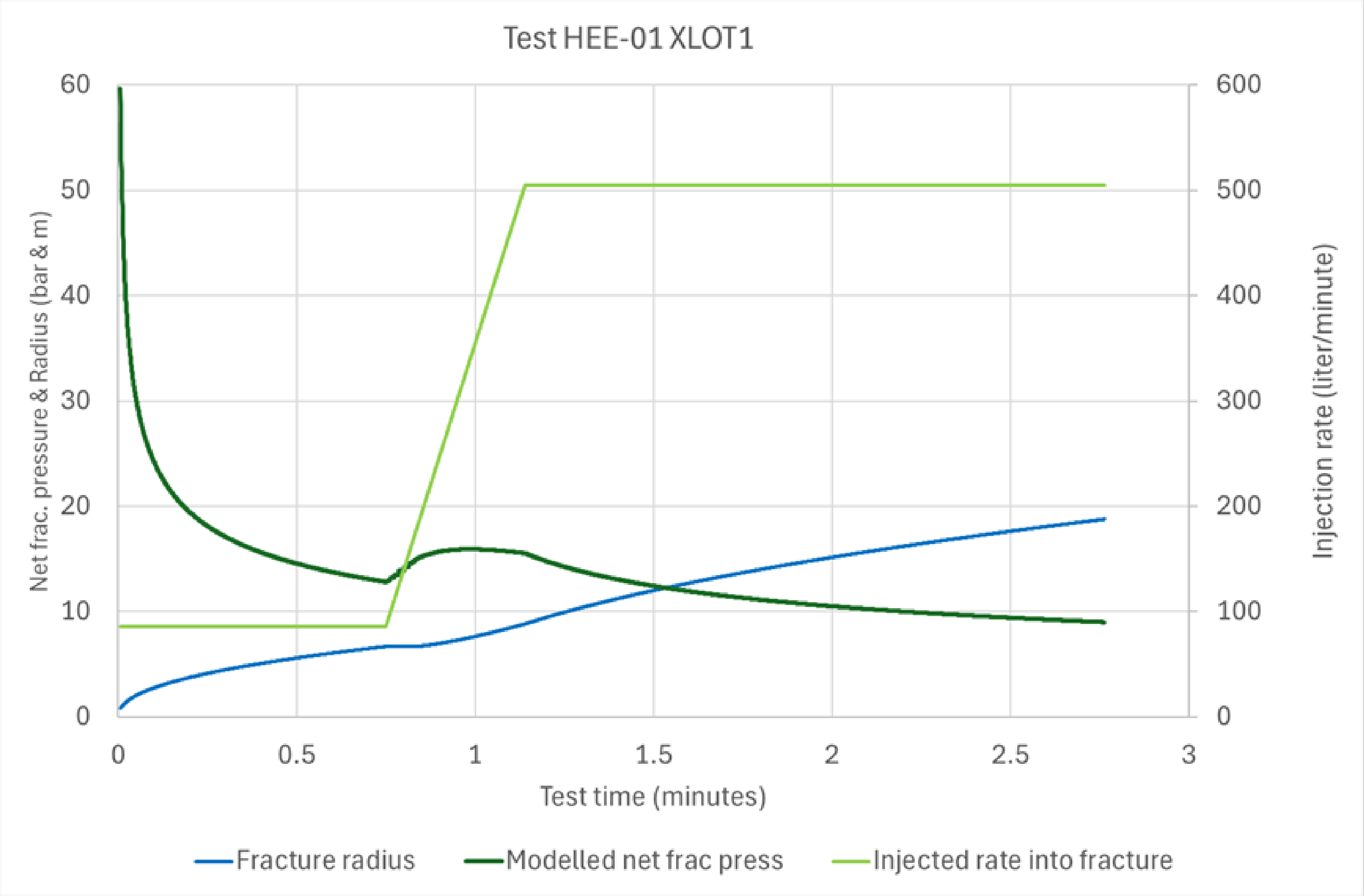
3 Minimum stress analysis for HEE-01 well



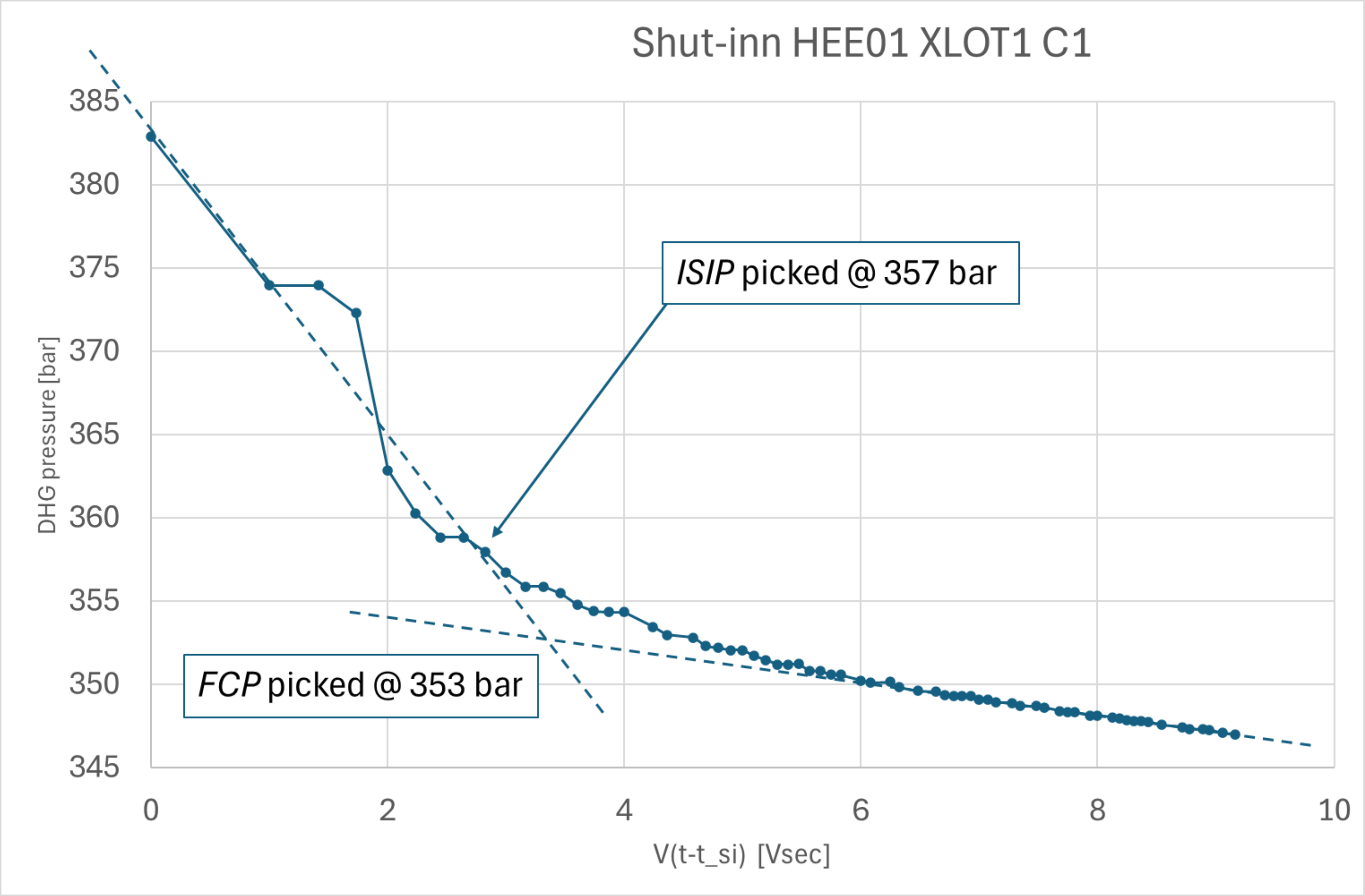
3 HEE-01, Cycle 1



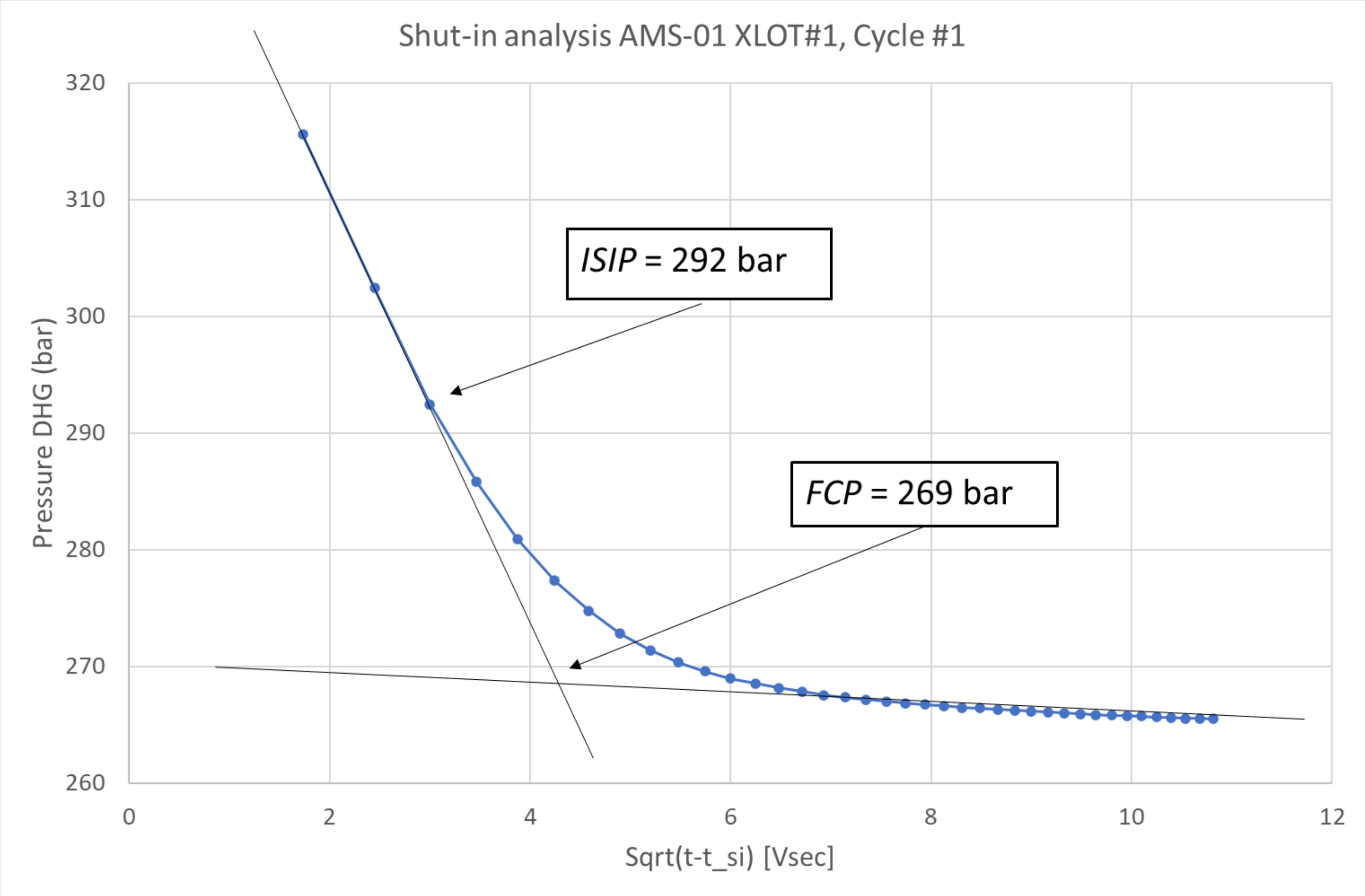
3 *FPP* modelling: Input flow and results



3 Shut-in analysis, cycle 1



3 Test AMS-01 XLOT1 C#1 behaves more textbook…



3 Models and stress limits are based on effective stress ratio *K*

$$K \equiv \frac{\sigma_h - p}{\sigma_v - p}$$

Friction model-based limits (see Hettema, 2022; Cohesionless, Zoback, 2007):

$$K_\phi = \frac{1}{\left[\sqrt{\mu^2+1}+\mu\right]^2} = \frac{1-\sin\phi}{1+\sin\phi}$$

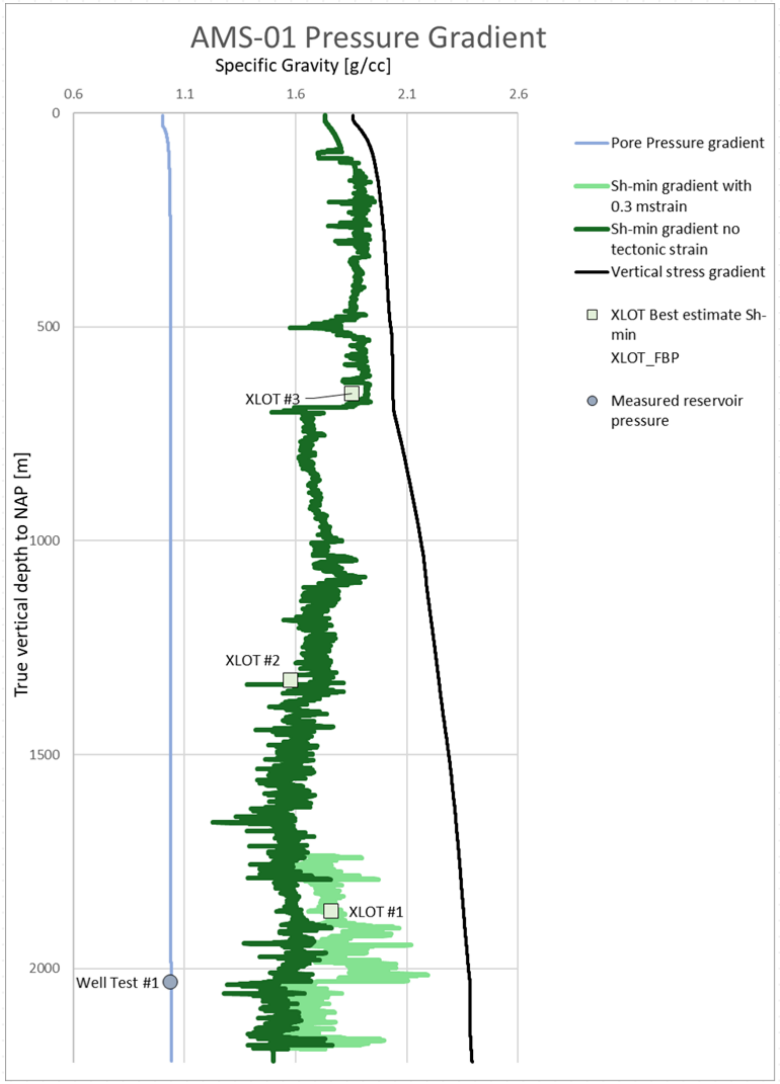
For seals, the plane-strain model without tectonic strain gives the limit (Hettema, 2022):

$$K_{0,ud}(z) = \frac{\nu_{ud}(z)}{1-\nu_{ud}(z)}$$

The stress limits for seals in case of the absence of a tectonic stress/strain are:

$$K_\phi < K < K_{0,ud}$$

4 Results in post-drill 1-D geo-mechanical model AMS-01, applying a tectonic strain-induced tectonic stress for XLOT#1



4 The minimum and maximum horizontal stresses based on the plane-strain model including a tectonic strain component

The plane strain stress model shown by Hettema (2022):

$$\sigma_h = K_0\sigma_v + \alpha(1 - K_0)p + \frac{E}{1 - \nu^2}(\varepsilon_h + \nu\varepsilon_H)_{tectonic}$$

$$\sigma_H = K_0\sigma_v + \alpha(1 - K_0)p + \frac{E}{1 - \nu^2}(\varepsilon_H + \nu\varepsilon_h)_{tectonic}$$

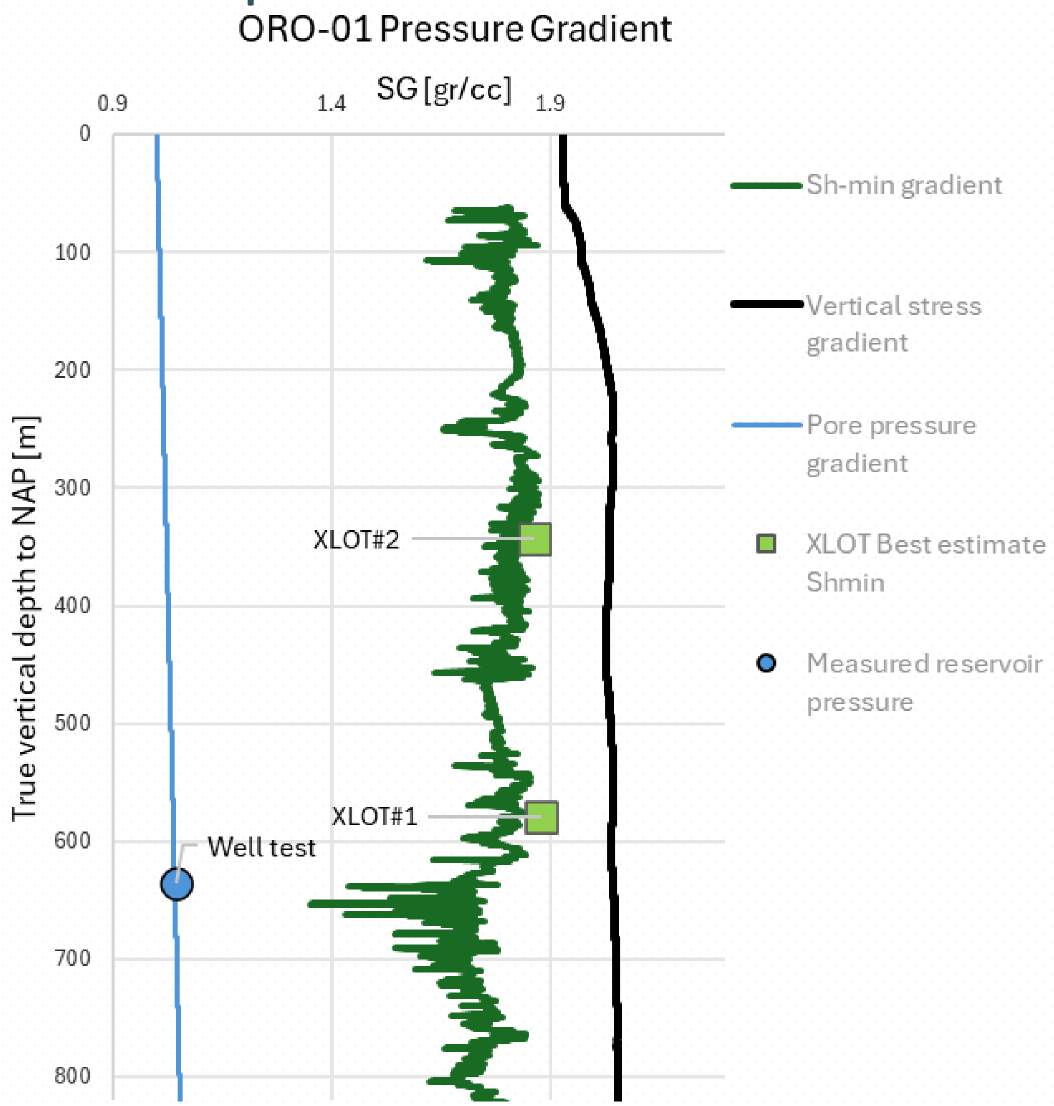
The model difference between maximum and minimum horizontal stress becomes:

$$\sigma_H - \sigma_h = 2G(\varepsilon_H - \varepsilon_h)_{tectonic}$$

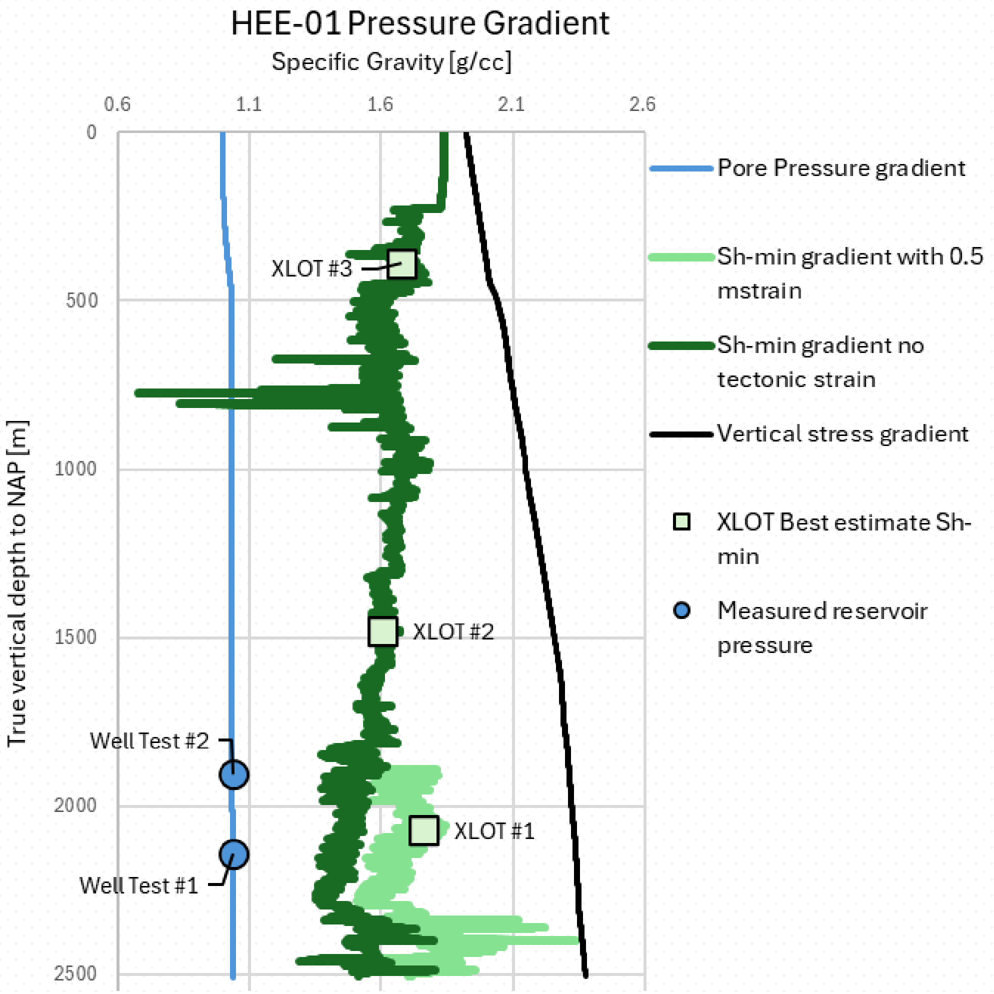
A European tectonic strain map has been produced by:
Olaiz, A.J., A. Munoz-Martin, G De Vicente, R. Vegas and S. Cloetingh. (2009). European continuous active tectonic strain-stress map. Tectonophysics 474, 33-40

If there is only one dominant tectonic compressive strain present, $\varepsilon_H > 0; \varepsilon_h = 0.$
The tectonic strain-map is in accorance to the world stress map maximum stress directions.

4 Results in the post-drill 1-D geo-mechanical model for ORO-01, without applying a tectonic stress component



4 Results in the post-drill 1-D geomechanical model, applying a tectonic strain-induced tectonic stress for XLOT#1



5 Overview of minimum stress results interpreted

Wellbore	XLOT 1	XLOT 2	XLOT 3
AMS-01 **[bar/m TVDnap]** **K / Tectonic strain**	Main Claystone 321 bar / 1873 m K=0.4 / 0.3 mstrain	Vlieland claystone 206 bar / 1325 m K=0.46 / 0	Asse Claystone 120 bar / K=0.84 / 0
ORO-01 **[bar/TVDnap]** **K / Tectonic strain**	Asse claystone 106.6 bar / 579 m K=0.83 / ≃ 0 (just)	Boom Claystone 62.6 bar / 342 m K=0.83 / ≃ 0 (just)	-
HEE-01 **[bar/m TVDnap]** **K / Tectonic strain**	Rogenstein claystone 357 bar / 391 m K=0.55 / 0.5 mstrain	Emscher limestone 232 bar/ 1497 m K=0.46/ 0	Landen Clay 64.1 bar K=0.62 / 0

6 Conclusions and outstanding work

1. Our interpretation of the minimum stress tests for the first three SCAN wells have been presented.
2. In general, the *FPP*-based minimum stress is higher than the *ISIP* and *FCP*-based.
3. The results fit well to the post-drill geo-mechanical models, some requiring a tectonic strain, giving confidence to extrapolation to nearby geothermal projects within the same basin.
4. Outstanding work: Compare the image-log interpreted maximum horizontal stress direction to the Word Stress Map
5. Compare the model-based stress magnitude of the maximum horizontal stress to analysis of break-out widths observed in image-logs.

7 References

- Andrews, J.S., Fintland, T.G. and Helstrup, O.A. Horsrud, P and Raaen, A.M., 2016. Use of Unique Database of Good Quality Stress Data to Investigate Theories of Fracture Initiation, Fracture Propagation and the Stress State in the Subsurface. **ARMA 16-887.**
- Barton, Colleen A., Mark D. Zoback and Kerry L. Burns, 1988. In-situ stress orientation and magnitude at the Fenton geothermal site, New Mexico, determined from wellbore breakouts. *Geophysical research letters*, Vol. **15**, No. 5. 467-470.
- Geertsma, J. and F. de Klerk, 1969. A Rapid Method of Predicting Width and Extent of Hydraulic Induced Fractures. Journal of Petroleum Technology, december 1969.
- Hettema, Marc. 2022. Practical workflow for assessment of seismic hazard in low enthalpy geothermal systems. Geomechanics and Geophysics for Geo-energy and Geo-resources. Springer Nature.
- Nolte, Kenneth G., 1979. Determination of fracture parameters from fracturing pressure decline. SPE 8341. Paper presented at the SPE ATC&E, Las Vegas.
- Nolte, Kenneth G. and Smith, Michael B., 1981. Interpretation of Fracturing Pressures. SPE AIME.
- Perkins, T. K. and L. R. Kern, 1961. Widths of Hydraulic Fractures. Paper presented at the annual fall meeting of SPE, oct. 8-11, 1961 in Dallas, Texas, USA.
- Zoback, 2007. Reservoir geomechanics. Cambridge University Press.