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Determination of Seal Stresses for Geothermal Applications in The Netherlands: Methodology and Model

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Outline

1. Introduction & Application
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4. Results in 1-D geo-mechanical models including tectonics
5. Estimation of maximum horizontal stress from model and break-outs
6. Conclusions
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1 Introduction

- The geo-mechanical data acquisition for the geothermal development in The Netherlands within the SCAN programme was presented at the GET2024 (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, strength, friction and thermal expansion).
- We present results of the *in-situ* minimum and maximum horizontal stresses for 5 wells for the seal of potential geothermal low-enthalpy acquifers/reservoirs (Hettema, 2022)
- Calibration to a plane-strain model understand the origins of the stresses, allowing lateral extrapolation within the basin.

Application of the results

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

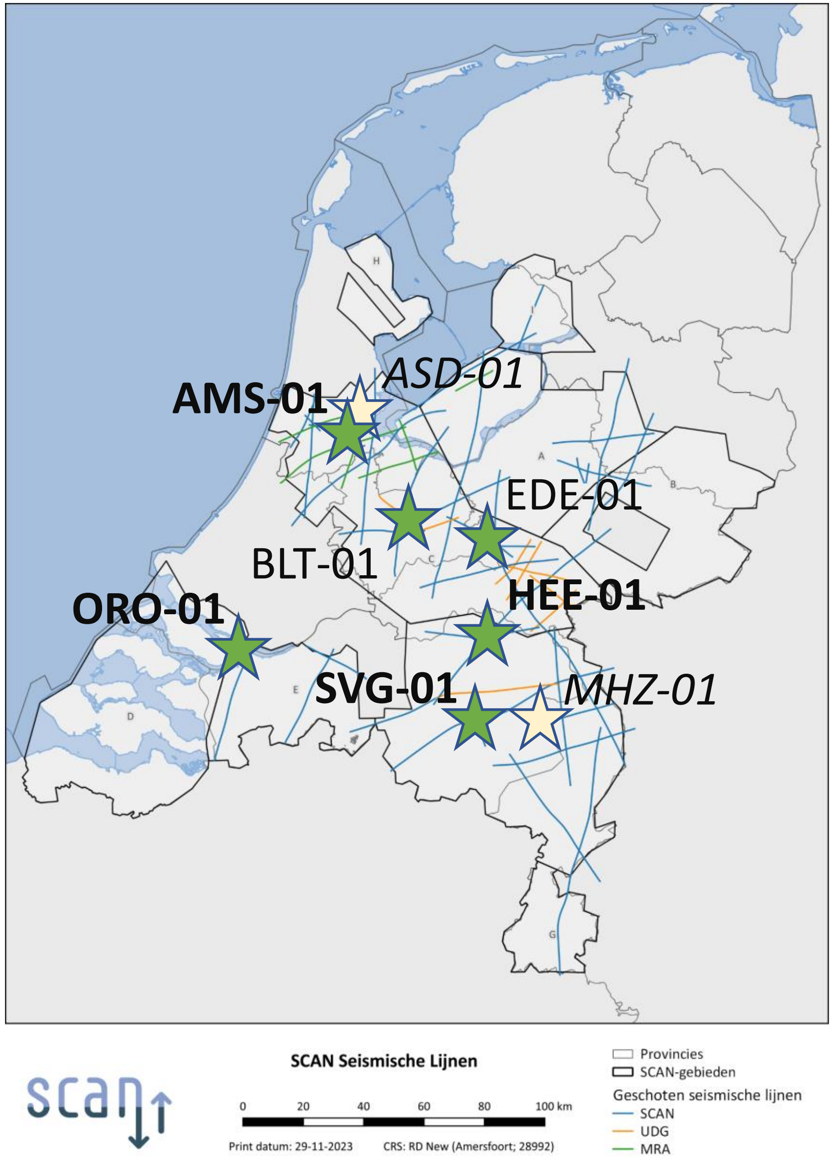
1. Develop, calibrate and update the **1-D geomechanical** model to assure safe and efficient drilling
2. Analyse the **reservoir integrity** to determine the maximum safe injection conditions to prevent out-of-zone injection and seismicity
3. Assess if **thermal fracturing** occurs, how it will affect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

Overview of SCAN wells XLOTs interpreted (work in progress)

Wellbore	Completion / pump	Start test	Fluid	XLOT 1 [cycles]	XLOT 2 [cycles]	XLOT 3 [cycles]
AMS-01	C&P / CMT	10/12/2023	Brine	Main Claystone [3]	Vlieland claystone [5]	Asse Claystone [4]
ORO-01	C&P / CMT	18/05/2024	Brine	Asse claystone [3]	Boom Claystone [3]	-
HEE-01	C&P / CMT	18/12/2024	Brine	Rogenstein clayst. [3]	Emscher limestone [3]	Landen Clay [3]
BLT-01	C&P / CT	24/03/2025	Brine	Main Claystone [3]	Röt Claystone [3]	Holland Marl [3]
EDE-01	C&P / CT	12/07/2025	Brine	Vlieland claystone [3]		
SVG-01	C&P / CMT-CT	09/05/2025	Brine-Gel	Veldhoven Claystone [4]	Breda FM Sand(stone)	

Cenozoic | Cretaceous | Triassic

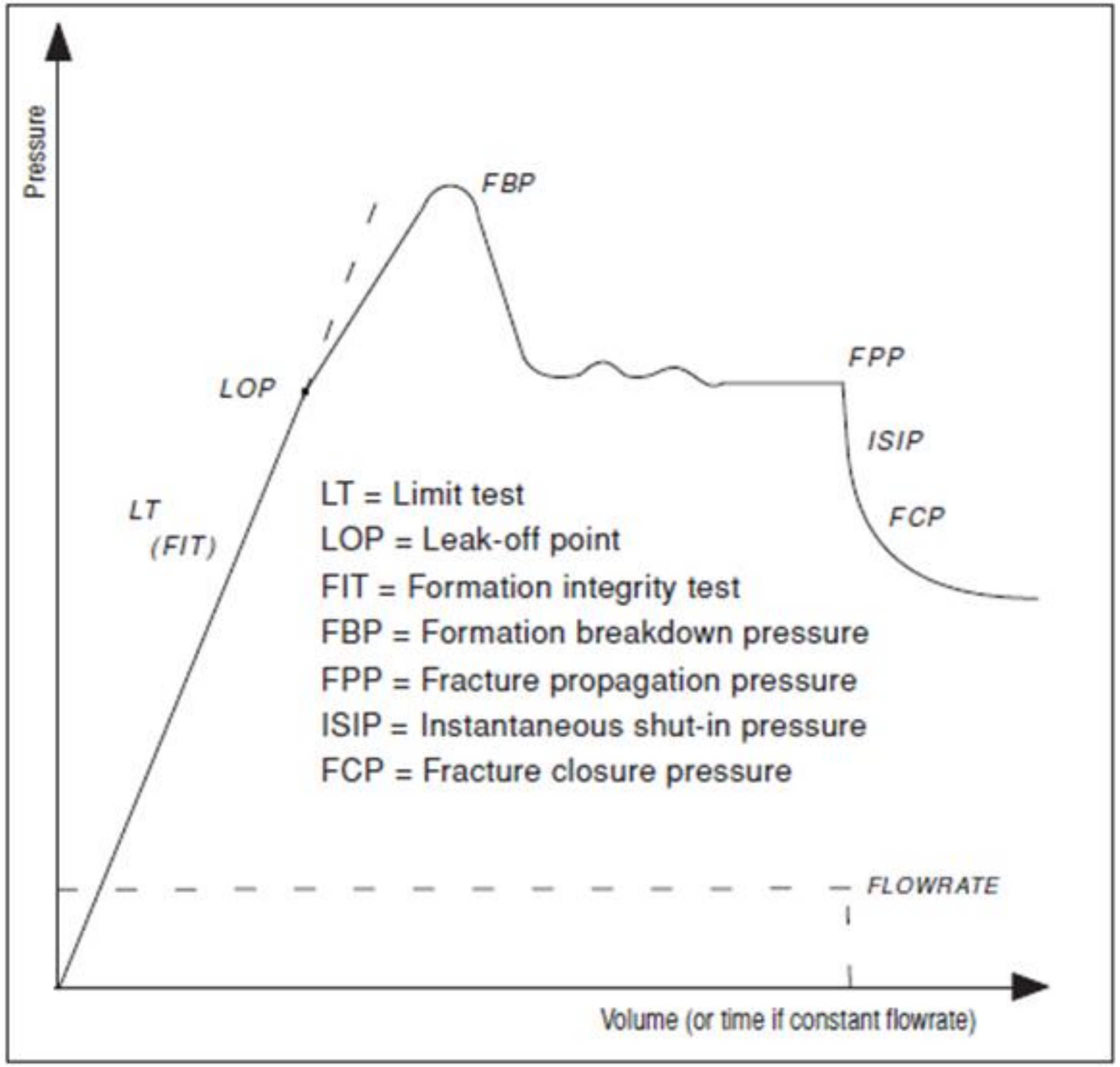
Map location of the SCAN wells XLOT-tested



XLOT testing performed

XLOT testing planned

Test overview XLOT and nomenclature (eg. Gaarenstroom)



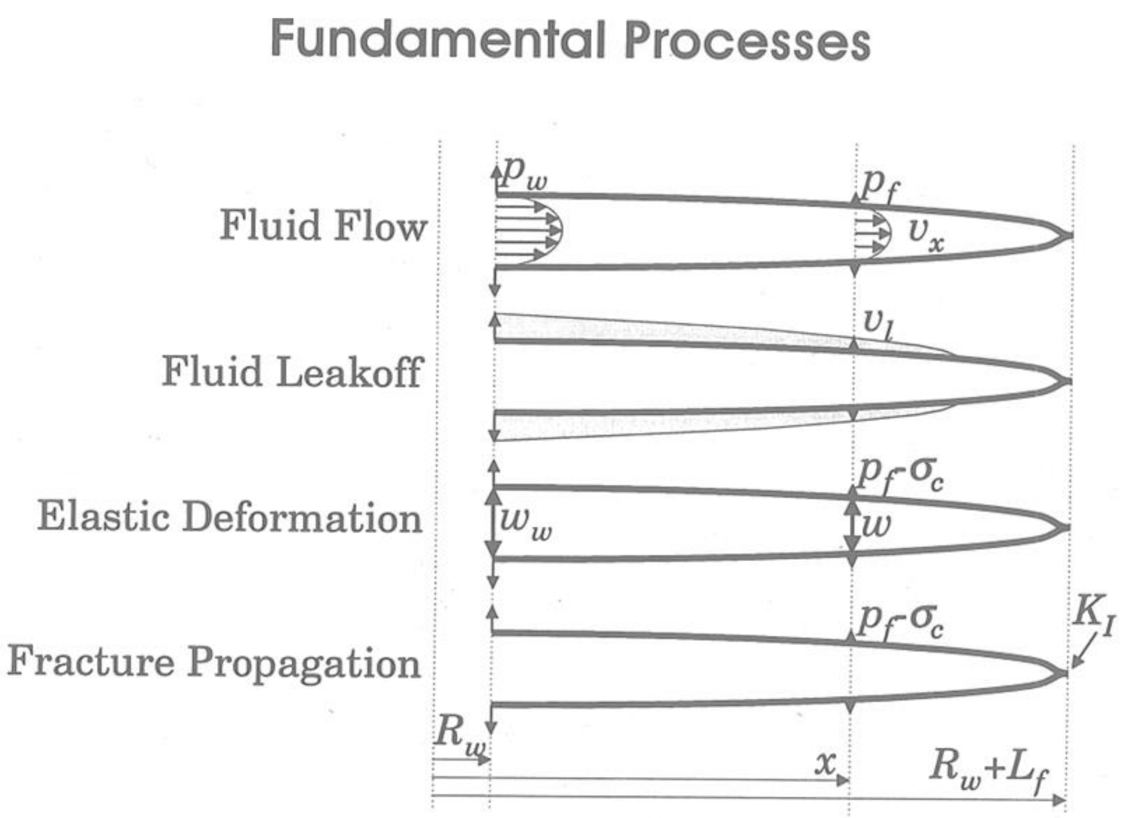
Analyses

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: Initial shut-in, post shut-in deviation
FCP: Fracture closure pressure

Two XLOT test stages interpreted

Analysis	Minimum stress	Confidence / Challenges	Assumptions
Fracture propagation FPP	From net-frac. pressure model calculations	Medium / Geometric model? Power-law viscosity Leak-off	Geometric models: GdK, PKN, Radial Stable (dp/dt=0)
Post shut-in ISIP & FCP	From post shut-in analysis	High / Details in slide 14	Details in slide 14

Four fundamental processes understanding *FPP*



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

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:

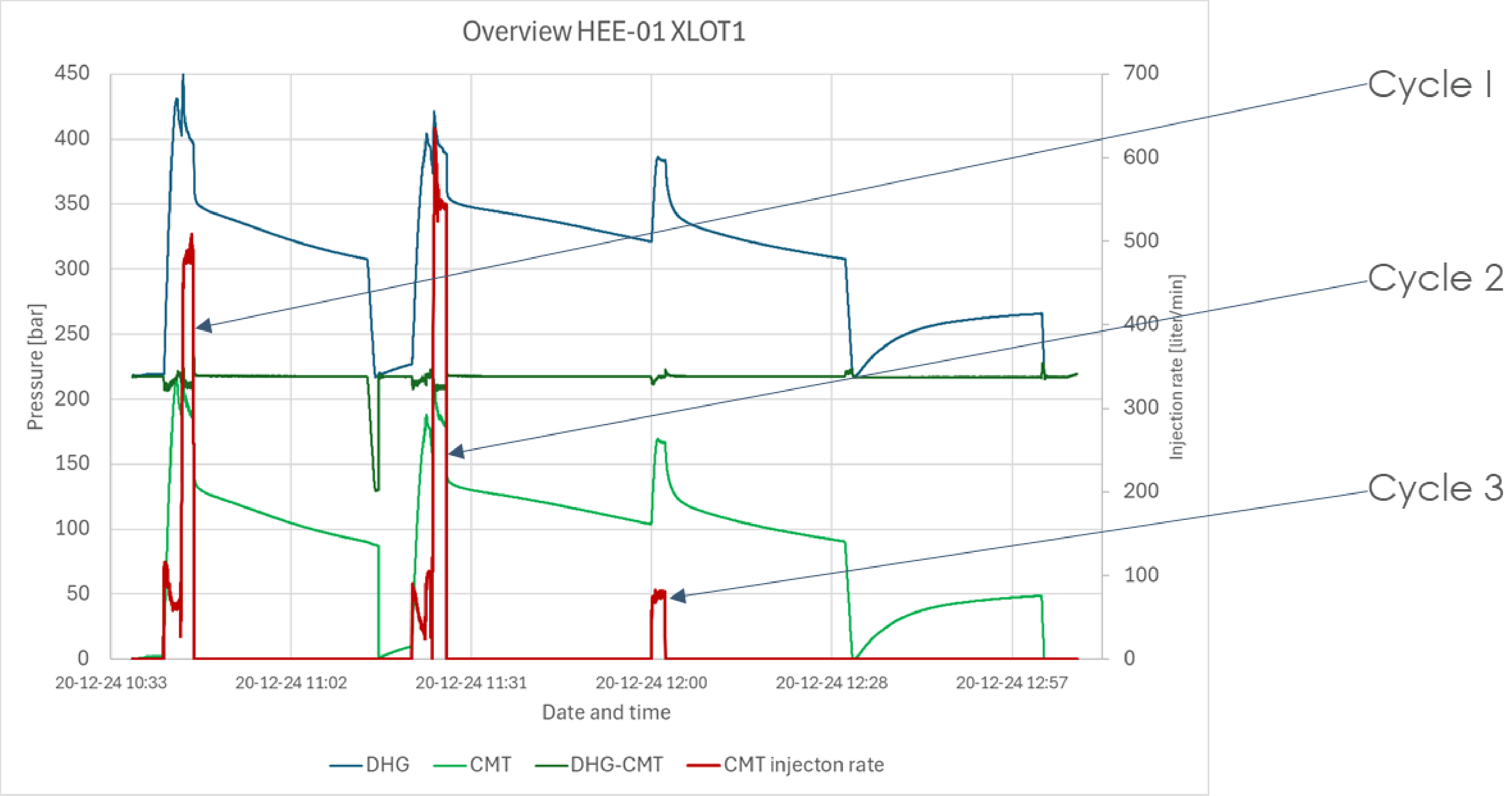
$$\eta V_{inj} = V_{frac} = \frac{4}{3}\frac{R_f^3}{E'}(p_f - \sigma_\perp)$$

Some methodologies used for post shut-in analysis

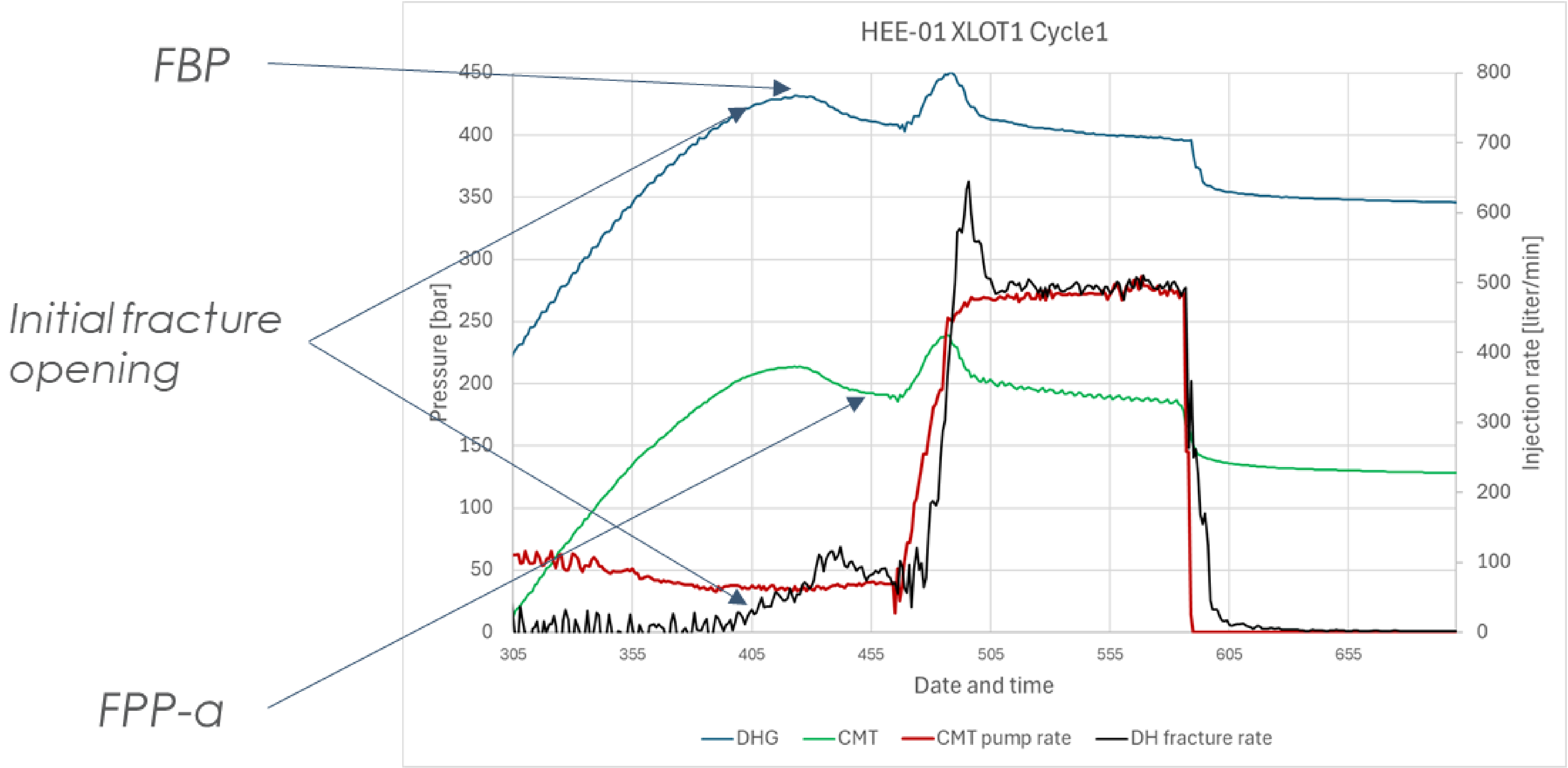
Most methodologies were developed for hydraulic fracture diagnostics for production optimization in shale reservoirs. Barree et al (2009) discuss several analysis methods

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)

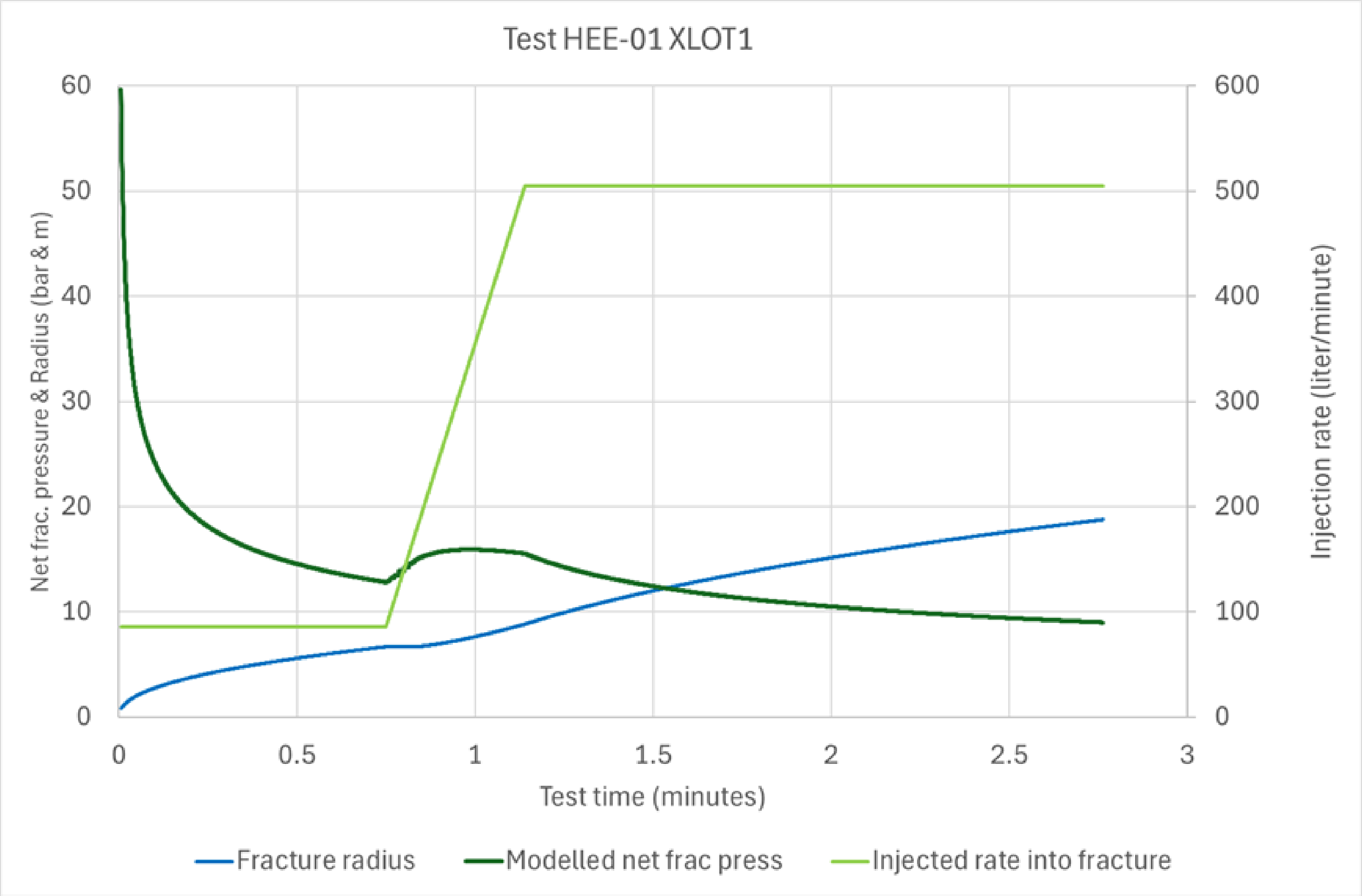
Test overview HEE-01 XLOT1



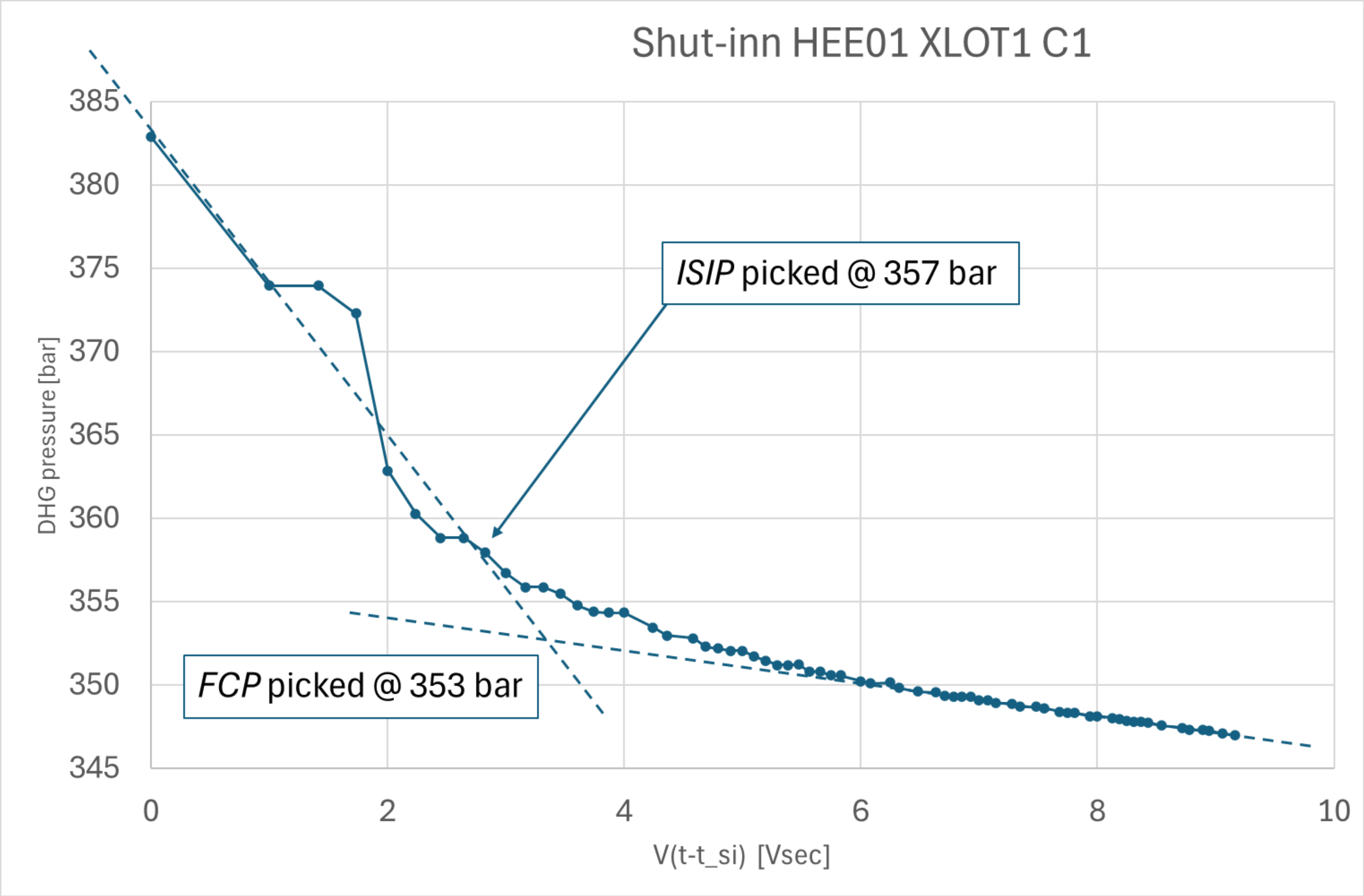
Data HEE-01 XLOT1 Cycle 1



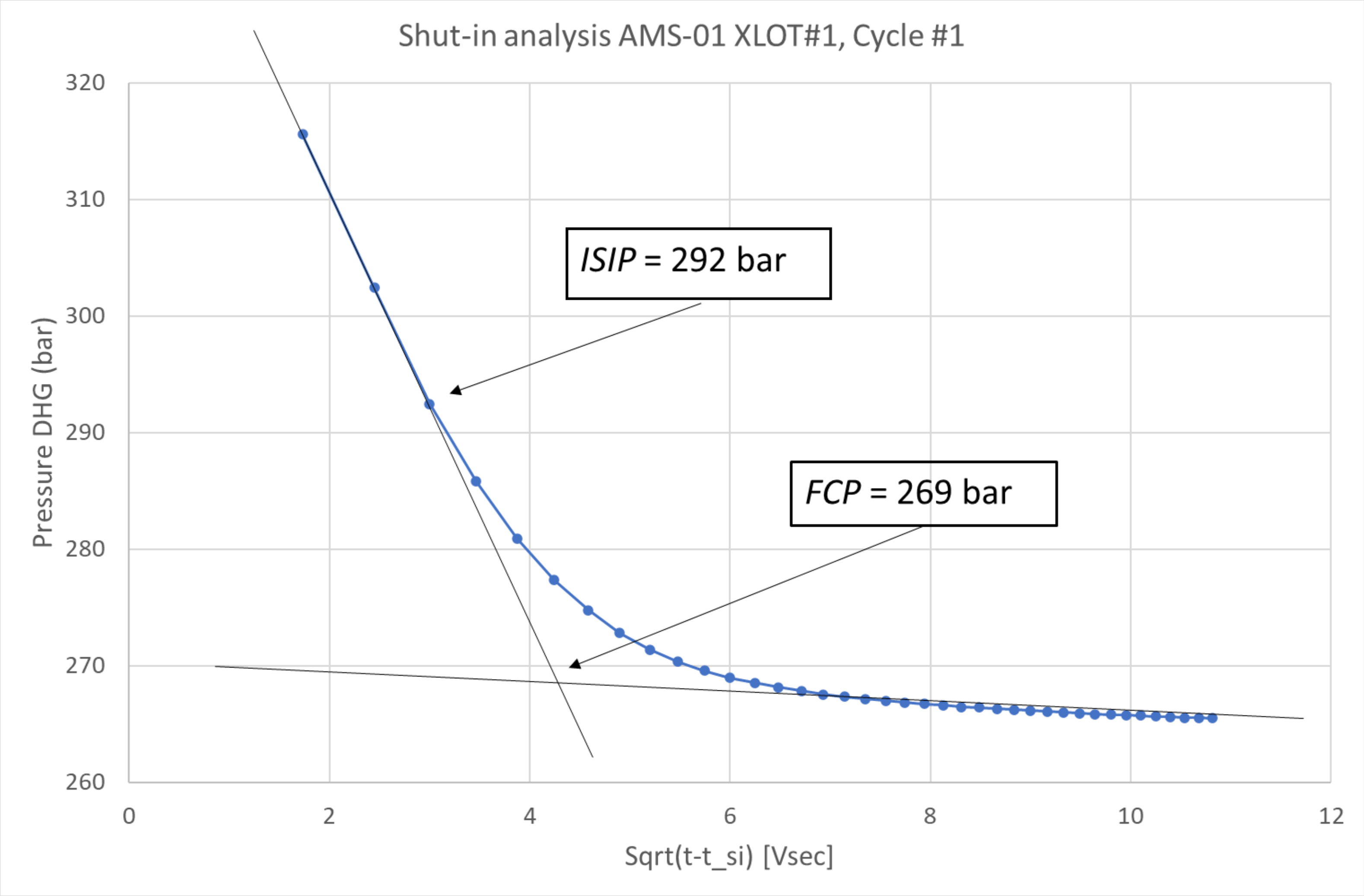
3 FPP modelling: radial extension and p-net



Shut-in analysis cycle 1



Shut-in analysis AMS-01 XLOT1 Cycle1 (textbook example)



3 Stress limits NF-stress regime, based on effective stress ratio

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

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 The plane-strain stress model: Passive basin + tectonic strain

The plane strain stress model for a normal-faulting stress regime has been shown by Hettema (2022).

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

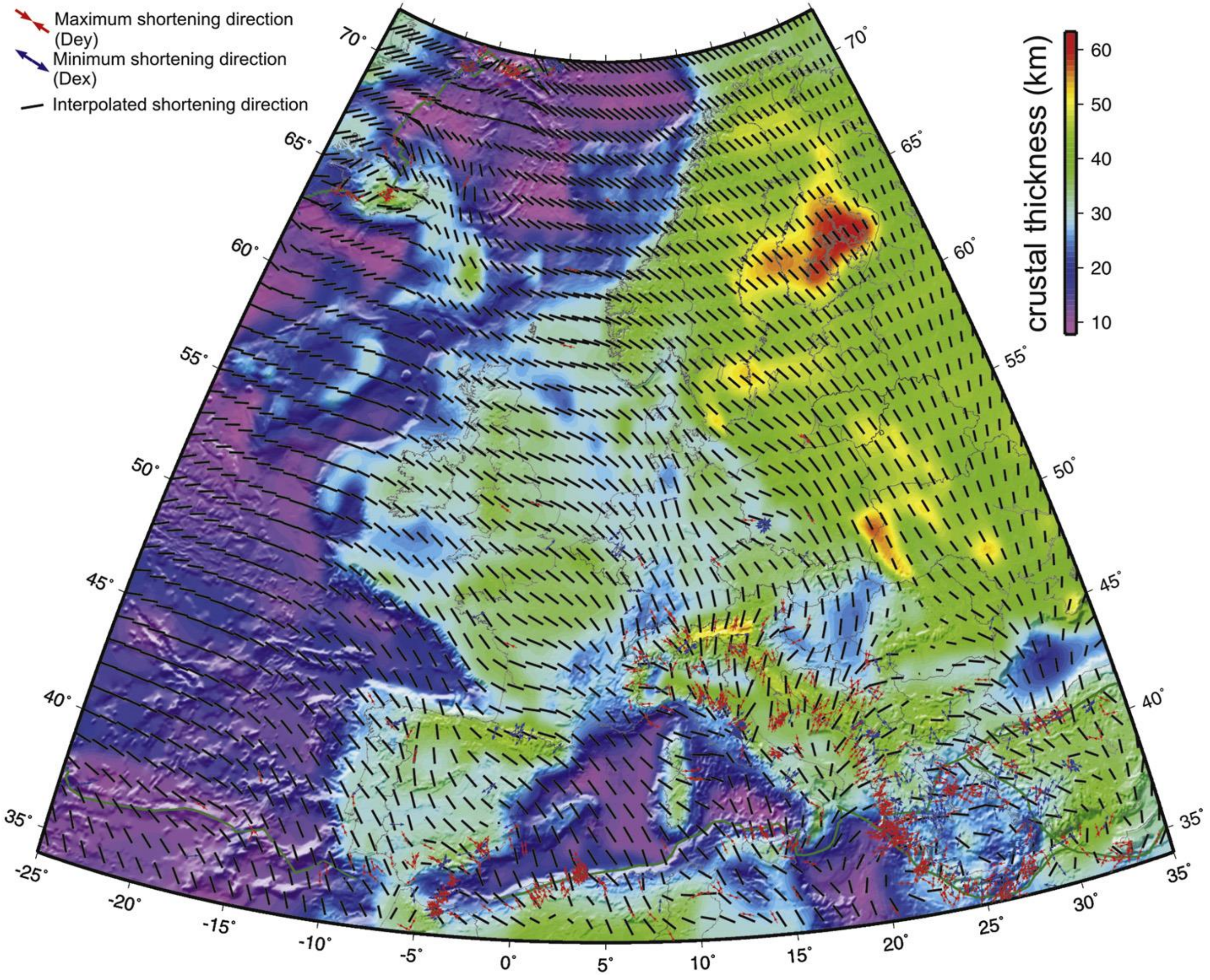
$$\sigma_H = K_0\sigma_v + (1 - K_0)p + \frac{2G}{1-\nu}(\varepsilon_H + \nu\varepsilon_h)_{tectonic}$$

The difference between the maximum and minimum horizontal stress becomes:

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

If there is only **one dominant tectonic compressive strain** present: $\varepsilon_H > 0; \varepsilon_h = 0$

4 An European tectonic strain/stress map (Oliaz et al., 2009)



The map is calibrated with inversion of moment tensors. The strain/stress regime is analyzed by the ratio of maximum over vertical compressive strain (their Table 1):

$$k' = \frac{\varepsilon_H}{\varepsilon_Z}$$

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

Natural Earthquakes are also investigated based on displacements

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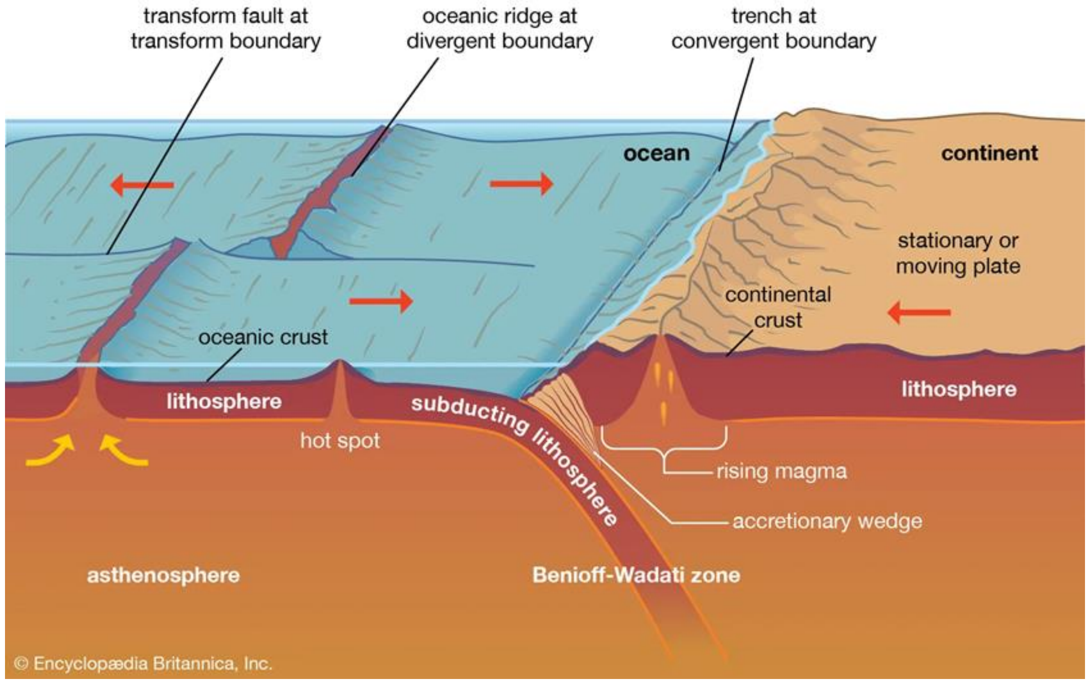
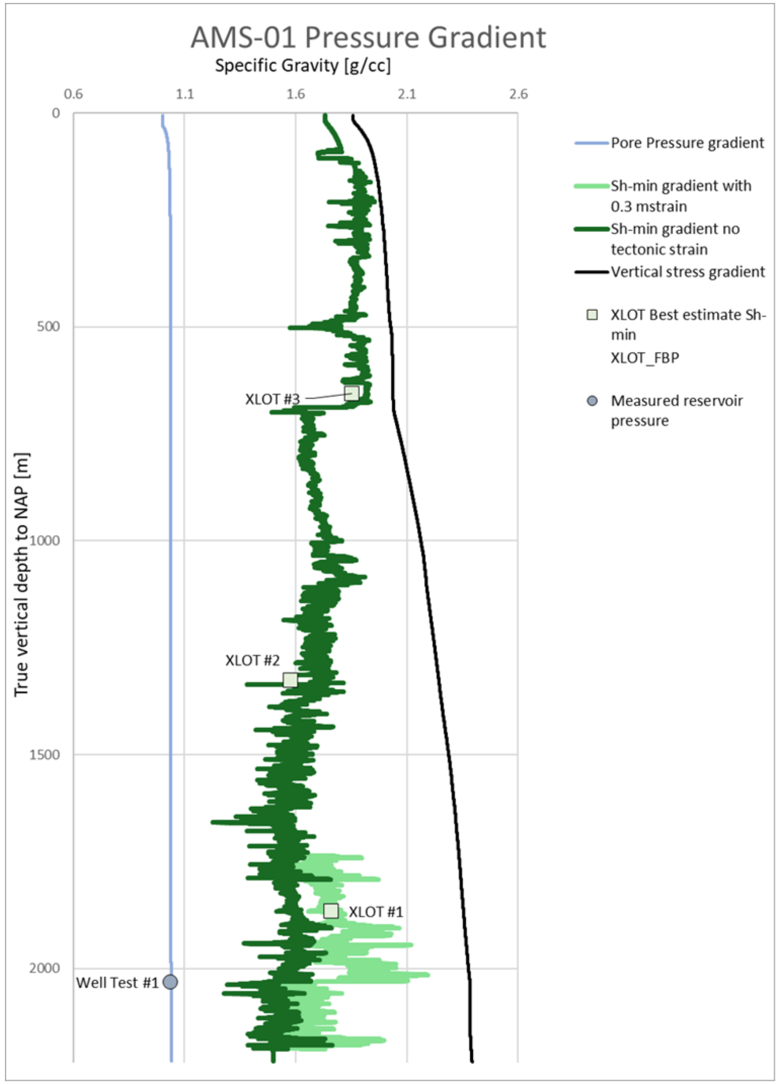
- Divergent (Iceland)
- Strike-slip (San Andreas)
- Convergent (subduction) (Chili, 1960, M=9.5)

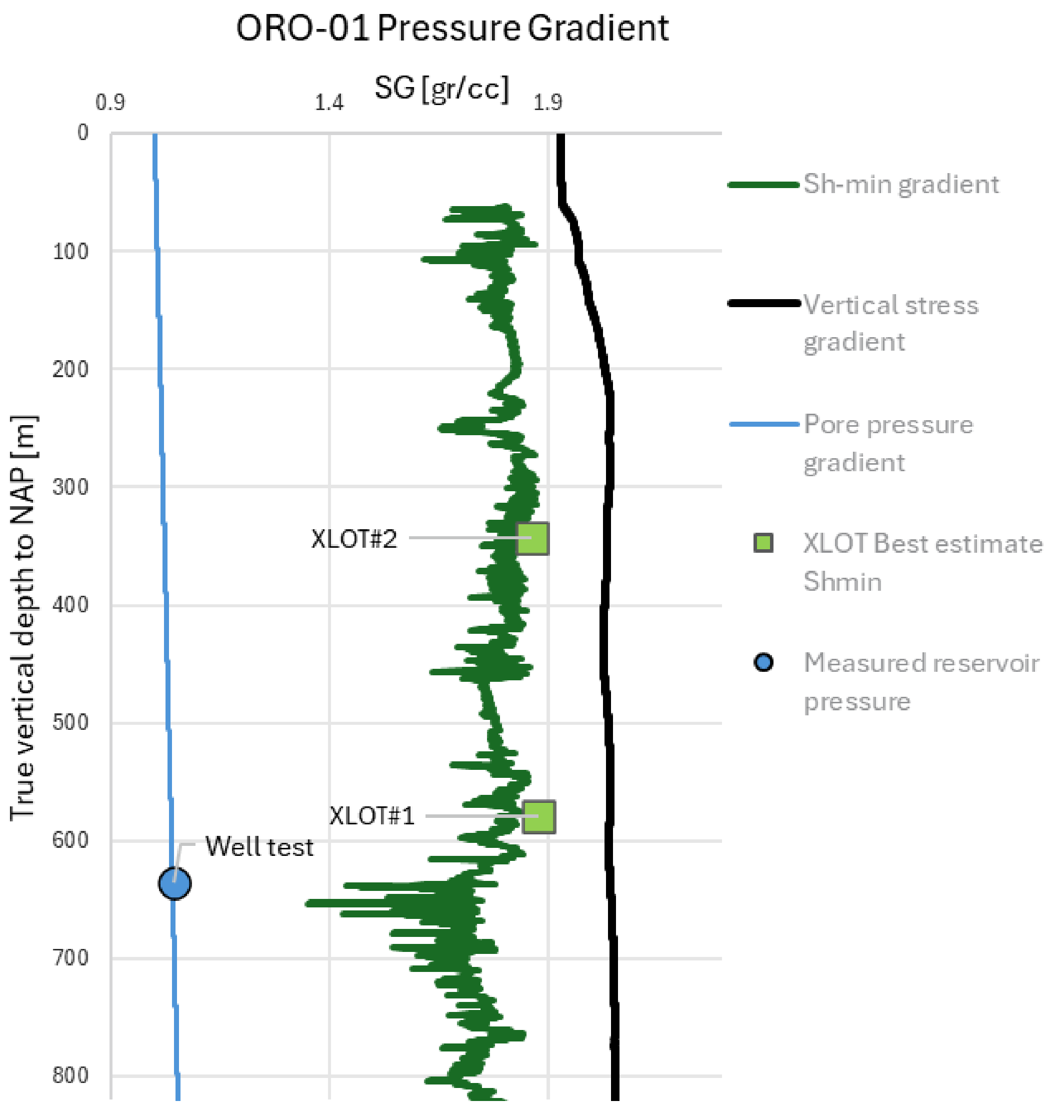


All related to related to (relative) displacement (strain)

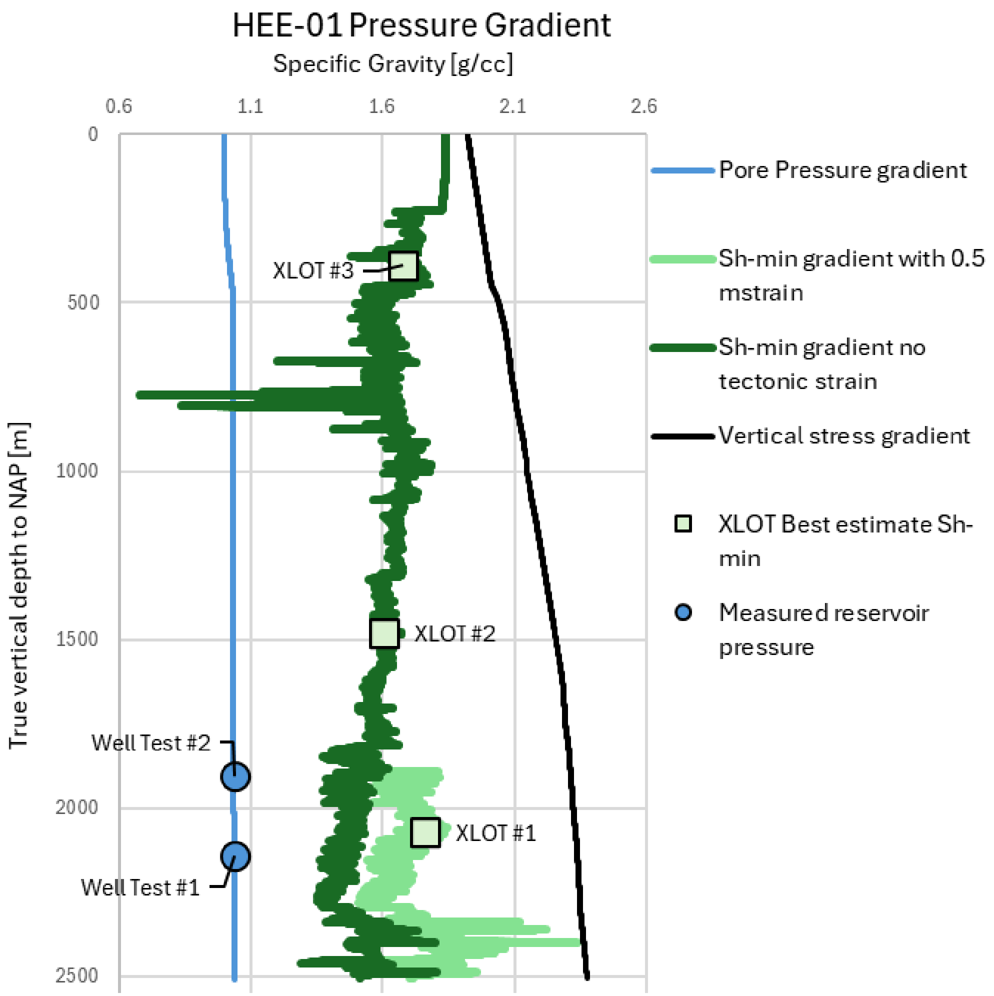
4 Results for AMS-01, including a tectonic strain component



4 Results for ORO-01, without a tectonic strain component



4 Results for HEE-01, including a tectonic strain component



Summing-up the results for the minimum stress

Wellbore	XLOT 1	XLOT 2	XLOT 3
AMS-01 Stress / Depth [TVD] **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 mstrain	Asse Claystone 120 bar / K=0.84 / 0 mstrain
ORO-01 Stress / Depth [TVD] **K / Tectonic strain**	Asse claystone 106.6 bar / 579 m K=0.83 / ≃ 0 mstrain	Boom Claystone 62.6 bar / 342 m K=0.83 / 0 mstrain	-
HEE-01 Stress / Depth [TVD] **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 mstrain	Landen Clay 64.1 bar K=0.62 / 0 mstrain
EDE-01 Stress / Depth [TVD] **K / Tectonic strain**	Vlieland claystone 175.5 bar / 1081 m K=0.66 / 0 mstrain		
SVG-01 Stress / Depth [TVD] **K / Tectonic strain**	Veldhoven Claystone 193.5 bar / 1018 m K=0.58 / 0 mstrain		

Cenozoic | Cretaceous | Triassic

Estimation of the maximum horizontal stress from breakout widths

The maximum horizontal stress magnitude can be estimated from the break-out width by (Barton et al., 1988; Zoback, 2007, eq. 7.7):

$$S_{Hmax} = \frac{\left(C_0 + p_p + p_w\right) - S_{hmin}\left(1 + 2cos(2\theta_b)\right)}{\left(1 - 2cos(2\theta_b)\right)}$$

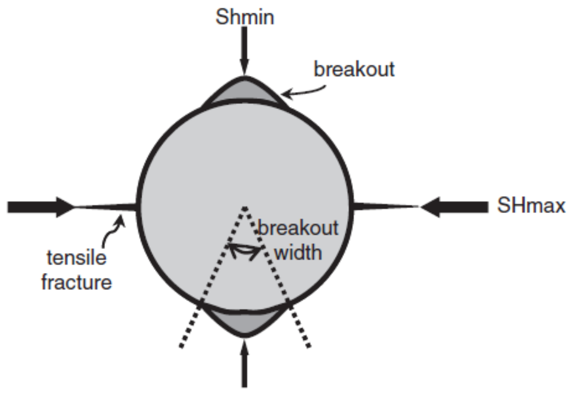
Here: $C_0 = UCS$ [MPa]

p_w [MPa] is the wellbore wall, non-penetrating mud pressure

p_p [MPa] is the formation pore pressure

The angle θ_b is defined by the full break-out width angle φ_{bo}:

$$2\theta_b = \pi - \varphi_{bo}$$



Trautwein-Bruns et al., 2020

Example of image logs showing break-outs (well AMS-01)

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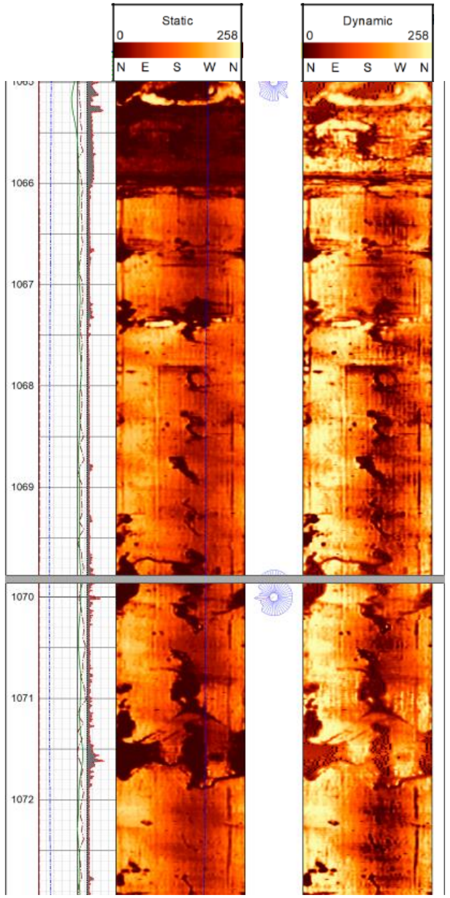
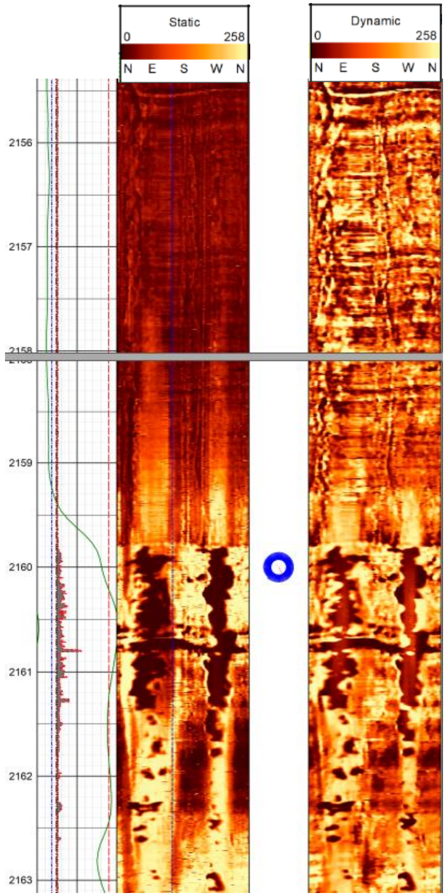
1. SHmax NW-SE (122° +/- 3°) in shallow section, consistent with published regional orientation
2. SHmax N-S (179° +/- 3°) in deep section
3. Appears to be a rotation of horizontal stress between with Vlieland Claystone and Zechstein Group
4. The break-out directions will be added to the World Stress Map

Breakouts in Vlieland Claystone Fm (1070mMDRT)

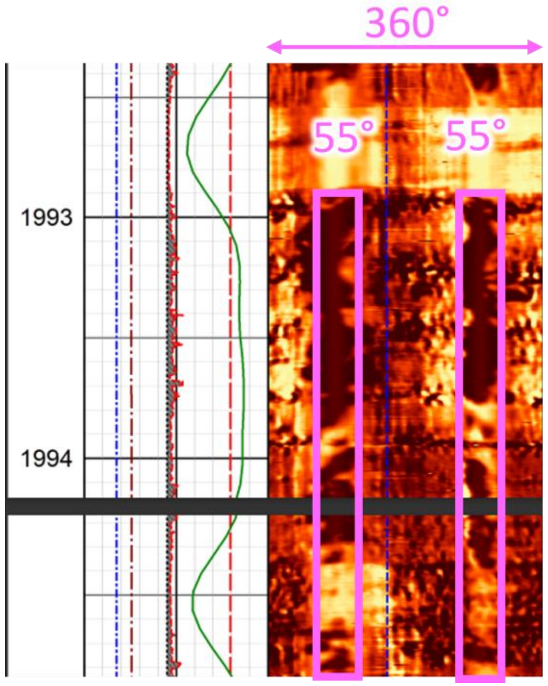


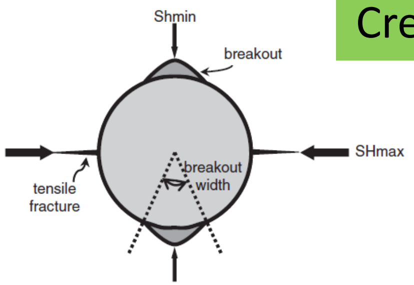
Tensile fractures in Slochteren Fm and breakouts in Limburg Gp (2160mMDRT)



Maximum horizontal stress from breakout widths well AMS-01

Borehole breakout widths in Permian Z1 Middle Claystone

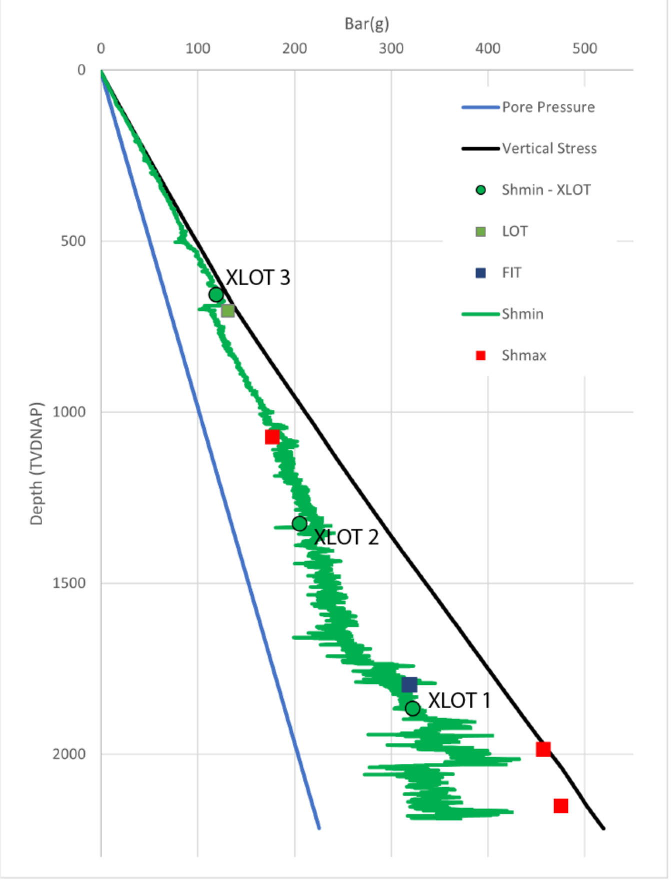




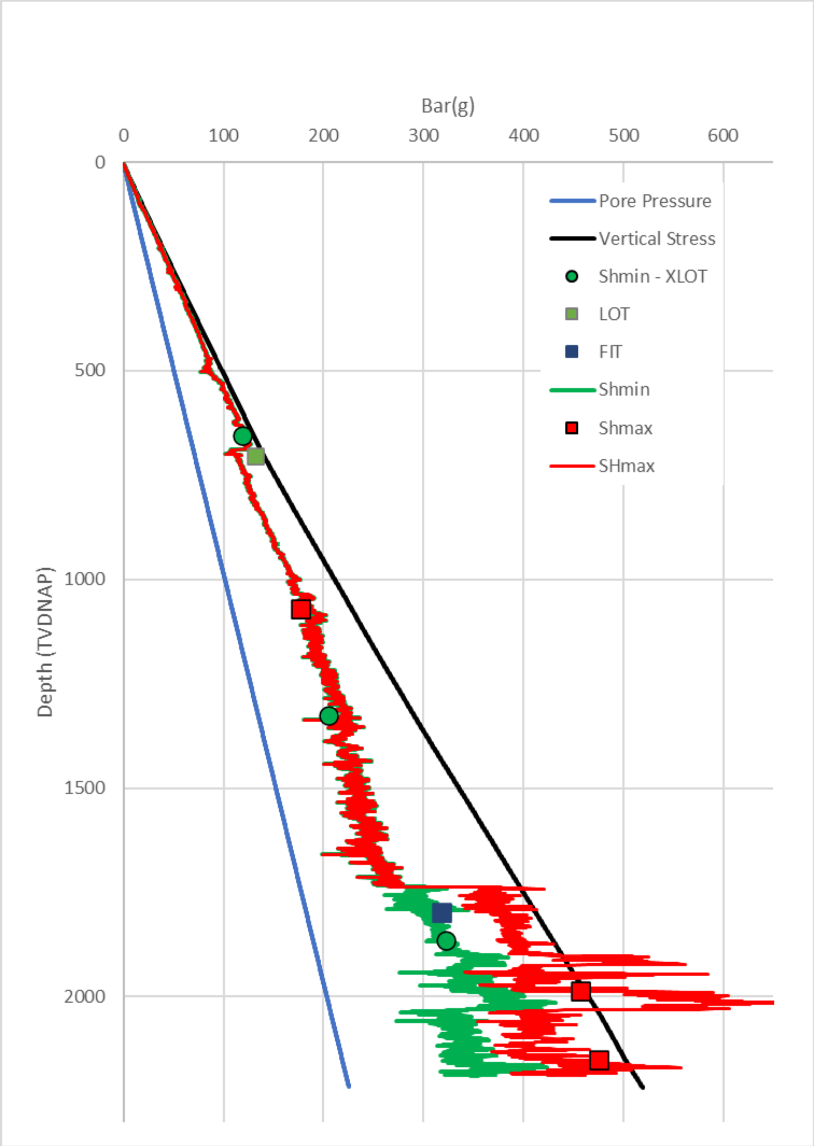
Trautwein-Bruns et al., 2020

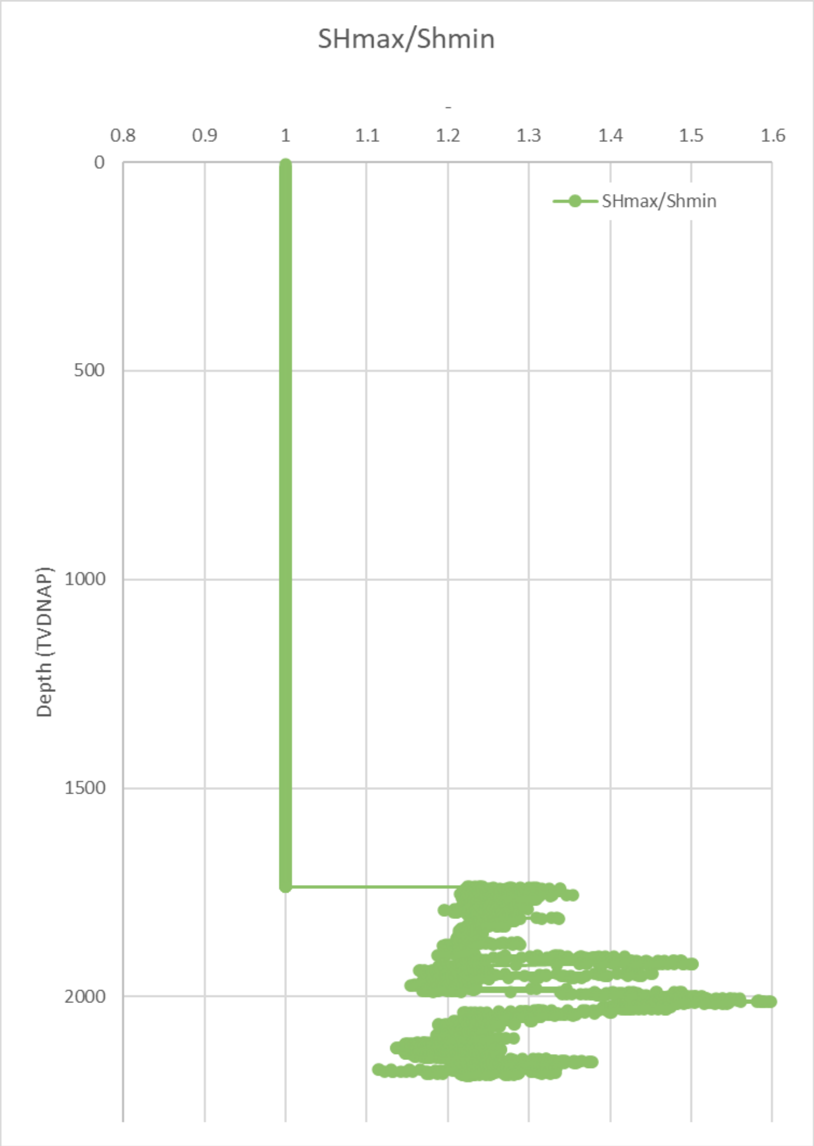
Formation	Depth	BO Width	C_0	P_W	P_P	S_{hmin}	S_{Hmax}
	M TVDNAP	[°]	[MPa]	[Mpa]	[Mpa]	[Mpa]	[Mpa]
Vlieland Claystone	1071.4	57	12	12.4	10.9	18.6	**17.7**
Z1 Middle Claystone	1985.1	55	50	22.6	20.2	36.3	**45.7**
Maurits	2150.4	70	40	24.5	21.9	35.9	**47.5**

Cretaceous | Permian | Carboniferous

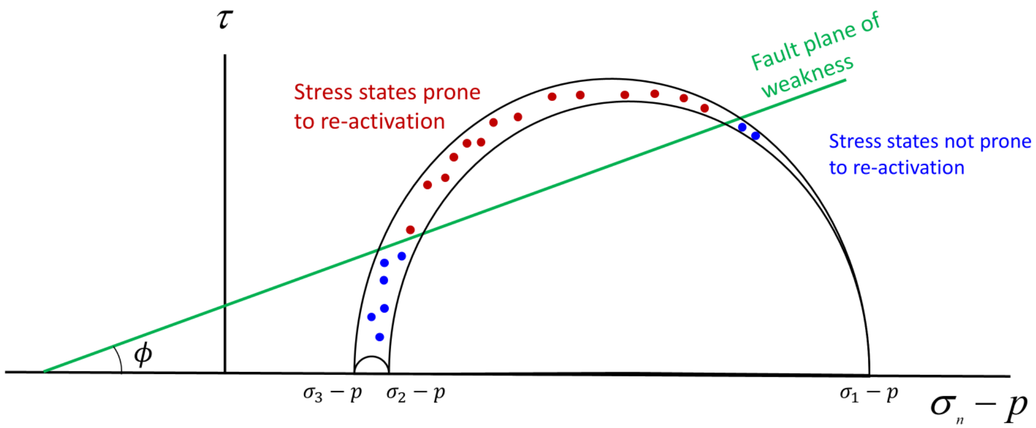


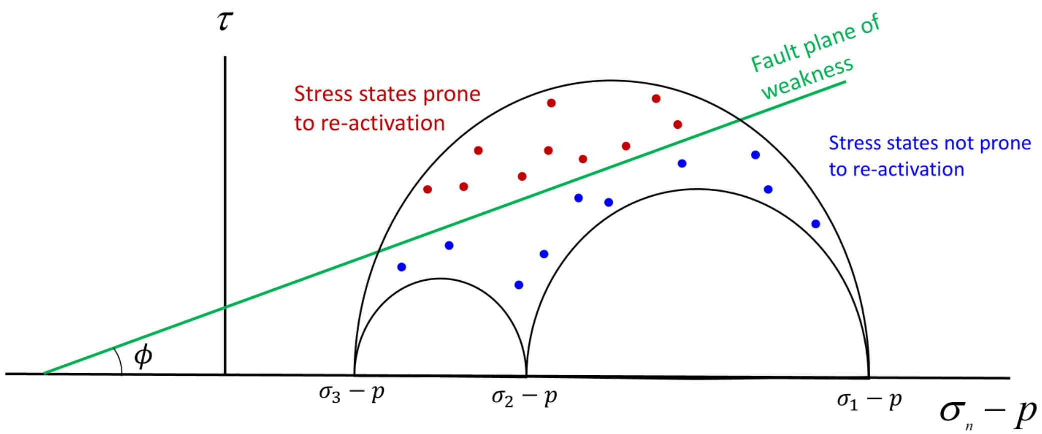
Independent maximum horizontal stress from plane strain model





5 Tectonic stress has major consequences for faults having potential Earthquake risk





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

Conclusions

1. Our interpretation of the minimum stress tests for the first five 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. If there is a tectonic strain/stress required to model the minimum stress, this is an indication of its presence. Absence of this requirement is no proof of absence of tectonic strain/stress.
5. Work in progress: Comparison of the plane-strain model-based stress magnitude of the maximum horizontal stress to analysis of break-out widths observed in image-logs of AMS-01.

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