



ARBEITSBERICHT NAB 24-19

In-Situ Stress Field in the Siting Regions
Jura Ost, Nördlich Lägern and
Zürich Nordost

October 2024

**Nagra | National Cooperative for the
Disposal of Radioactive Waste**

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KEYWORDS

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

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Executive summary

The in-situ stress field is a relevant state variable for the design of underground structures and for the assessment of the long-term stability of a deep geological repository.

During the deep borehole drilling (TBO) campaign between 2019 and 2022, a large number of new stress data were acquired from 9 boreholes in the siting regions Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO). In particular, the availability of stress magnitude data was improved substantially with a total of 139 new microhydraulic fracturing (MHF) tests, compared to only 15 directly from the siting regions before 2019 (Nagra 2014).

The magnitude of the minimum horizontal stress (S_{hmin}) has been successfully measured from 121 MHF test intervals, 27 of them in the Opalinus Clay. The magnitude of the maximum horizontal stress (S_{Hmax}) has been derived from 65 sleeve reopening (SR) tests, 19 of them in the Opalinus Clay. The S_{Hmax} orientation was interpreted from borehole failures (borehole breakouts and drilling-induced tensile fractures) and from the MHF-induced fractures. The information on the horizontal stress magnitudes complements the estimates of the vertical stress (S_v) from integrated rock density and a few direct measurements.

The prevailing S_{Hmax} orientation derived from the borehole data in the Mesozoic sediments of the siting regions is NNW-SSE ($166 \pm 12^\circ$), in agreement with the regional and large-scale trend and the results prior to the new exploration campaign (Heidbach & Reinecker 2013). Importantly, the S_{Hmax} orientation shows no variation with depth beyond the standard deviation between the basement and the Mesozoic sedimentary pile, and especially across the Opalinus Clay and its confining units.

While the new stress data confirm the dominant S_{Hmax} orientation, important new insights have been gained into the stress magnitudes and the stress regime at the different siting regions. This is mainly due to two factors: 1) a very high density of MHF and SR results acquired in the new TBO campaign, and 2) improved testing equipment and testing protocols. For the Opalinus Clay, a fairly consistent gradient with depth is observed for both S_{hmin} and S_{Hmax} , irrespective of the siting region. The new data demonstrates that the prevailing stress regime in the Opalinus Clay at the borehole locations is normal faulting ($S_v \geq S_{\text{Hmax}} \geq S_{\text{hmin}}$) for all three siting regions, and not strike-slip faulting ($S_{\text{Hmax}} \geq S_v \geq S_{\text{hmin}}$) as anticipated before the TBO campaign.

The richness of new stress magnitude data, as well as rock mechanical properties from core testing and petrophysical logging, allowed a more robust calibration of site-specific, geomechanical-numerical 3D “stress models”. These models were built for all three siting regions and describe the spatial distribution of the entire stress tensor from surface to a depth of 2,000 m below sea level. The models are used to predict the in-situ stress field away from the boreholes where MHF and SR tests were conducted, and to explore the effects of mechanical layering, topography and of major fault zones on the local in-situ stress field.

From field data and model results, four main conclusions can be drawn:

1. The MHF and SR test data from the boreholes reveal that the Opalinus Clay exhibits very consistent depth gradients of the horizontal stress magnitudes, irrespective of siting region.
2. The contemporary 3D in-situ stress field can be predicted spatially using geomechanical-numerical models with a similar degree of reliability in all three siting regions.
3. Characteristics of the in-situ stress field are similar in all three siting regions, with depth and mechanical layering coupled to tectonic loading controlling the stress magnitudes.
4. Faults incorporated in the models indicate no relevant influence on the in-situ stress field in the far-field (a few hundred metres away from the faults).

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List of Acronyms

BEN	Benken borehole
BO	Borehole breakout
BAC1-1	Bachs-1-1 borehole (TBO campaign)
BOZ1-1	Bözberg-1-1 borehole (TBO campaign)
BOZ2-1	Bözberg-2-1 borehole (TBO campaign)
BUL1-1	Bülach-1-1 borehole (TBO campaign)
DEF	Drilling-enhanced fracture (naturally existing prior to drilling)
DITF	Drilling-induced tensile fracture; also termed A-DITF when aligned parallel to the borehole axis, or E-DITF when en-échelon sets of fractures at an angle to the borehole axis
FMI	Formation Micro Imager
FP	Fracture potential
GR	Gamma-ray (wireline logs)
GTPT	Gas-threshold pressure test
HF	Hydro frac test, in contrast to MHF performed with hydraulic test equipment
HTPF	Hydraulic tests of pre-existing fractures
ISIP	Instantaneous shut-in pressure
JO	Jura Ost siting region
MAR1-1	Marthalen-1-1 borehole (TBO campaign)
MDT	Modular dynamic formation tester, equipment used for MHF
MHF	Microhydraulic Fracturing
NF	Normal faulting stress regime ($S_v > S_{Hmax} > S_{hmin}$)
NL	Nördlich Lägern siting region
OPA	Opalinus Clay
PC	Petal-centreline fracture
Pi	Interval pressure
P _f	Fluid pressure in fracture
P _{SR}	Sleeve re-opening pressure
RHE1-1	Rheinau-1-1 borehole (TBO campaign)
RIN	Riniken borehole
RSR	Regime stress ratio
S ₁	Maximum principal stress magnitude
S ₂	Intermediate principal stress magnitude
S ₃	Minimum principal stress magnitude

BEN	Benken borehole
SED	Swiss Seismological Service
SF	Sleeve fracturing
S_{hmin}	Minimum horizontal stress magnitude
S_{Hmax}	Maximum horizontal stress magnitude
SQRT	Square-root of time (shut-in)
SR	Sleeve reopening
SRT	Step-rate test
SS	Strike-slip faulting stress regime ($S_{Hmax} > S_v > S_{hmin}$)
STA2-1	Stadel-2-1 borehole (TBO campaign)
STA3-1	Stadel-3-1 borehole (TBO campaign)
S_v	Vertical stress magnitude
TBO	Nagra's deep borehole campaign, nine boreholes drilled in the years 2019 – 2022
TF	Thrust faulting stress regime ($S_{Hmax} > S_{hmin} > S_v$)
TRU1-1	Trüllikon-1-1 borehole (TBO campaign)
TVD	True vertical depth
UBI	Ultrasonic Borehole Imager
VSLR	Very slow reopening
WEI	Weiach borehole
WSM	World stress map project
ZNO	Zürich Nordost siting region

1 Introduction

1.1 Goal of the report

The overall goal of the report is to quantify the contemporary 3D in-situ stress field in the rock volume of the siting regions Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO). The backbone of this task is provided by the stress data from the analysis of a wide collection of stress measurements and stress indicators that allow determination of individual components of the stress tensor, and the distribution of rock properties in the siting regions. The synthesis of all stress data, especially in integrating the new data from Nagra's 9 deep borehole (TBO) campaign, resulted in a unique, comprehensive and high-quality dataset.

In particular, the report summarises the analysis of the orientation of the stress tensor using the orientation of the maximum horizontal stress (S_{Hmax}) from different stress indicators, and the measurement of the magnitude of the minimum horizontal stress (S_{hmin}) using microhydraulic fracturing (MHF) tests in combination with sleeve reopening (SR) tests that allow the magnitude of the maximum horizontal stress S_{Hmax} to be estimated. Each method used is briefly explained in this report.

Furthermore, the report presents the set-up and key results of geomechanical-numerical 3D “stress models” for each siting region that provide a continuous description of the stress tensor. These models are calibrated with the stress magnitude data and allow a prediction of all relevant stress components at the planned repositories for high-level and long-lived intermediate-level waste where no a priori in-situ information is available.

1.2 Stress tensor definitions and terminology

Physically, stress is defined as an external force acting on a plane. Thus, it has SI units of force per area (N/m^2), which is commonly referred to as Pascal (Pa). To describe the stress state at a particular point, the Cauchy stress tensor σ with nine components is used. It consists of three forces that act on three planes that are perpendicular to each other (Fig. 1-1a). Due to the symmetry of the stress tensor one can always rotate the coordinate system in such a way that the three forces are perpendicular to the sides (Fig. 1-1b). This is a so-called principal axis system with three principal stresses. Regardless their orientation in space, the maximum principal stress is labelled as S_1 , the intermediate principal stress as S_2 , and the minimum principal stress as S_3 (Fig. 1-1b).

In geosciences, it is often assumed that the vertical stress S_v is a principal stress. With this assumption, S_{Hmax} and S_{hmin} are also principal stresses (Fig. 1-1c). This so-called reduced stress tensor has only four unknowns: the orientation of S_{Hmax} as well as the magnitudes of S_{hmin} , S_{Hmax} and S_v . Note that, due to convention, the orientation of S_1 , S_2 and S_3 are not fixed in space, but can change abruptly by 90° (Fig. 1-1e).

In this report, the terminology of the reduced stress tensor is used as this is also used throughout the literature. However, it should be noted that, for the estimation of stress magnitudes, the MHF tests measure the magnitude of S_3 and the SR test allows derivation of the magnitude of S_2 or S_1 , depending on which of these two stresses is closer to the S_{Hmax} orientation (Fig. 1-1e).

Note that all methods used to determine individual components of the stress tensor, except for the MHF tests, do not measure stress directly but use either indirect observations of strain or model assumptions. Thus, except for the MHF tests, use of the term stress measurement is avoided. For more technical and physical details, reference should be made to comprehensive reviews and textbooks (e.g. Amadei & Stephansson 1997, Jaeger et al. 2007, Schmitt et al. 2012, Zang & Stephansson 2010, Zoback 2010).

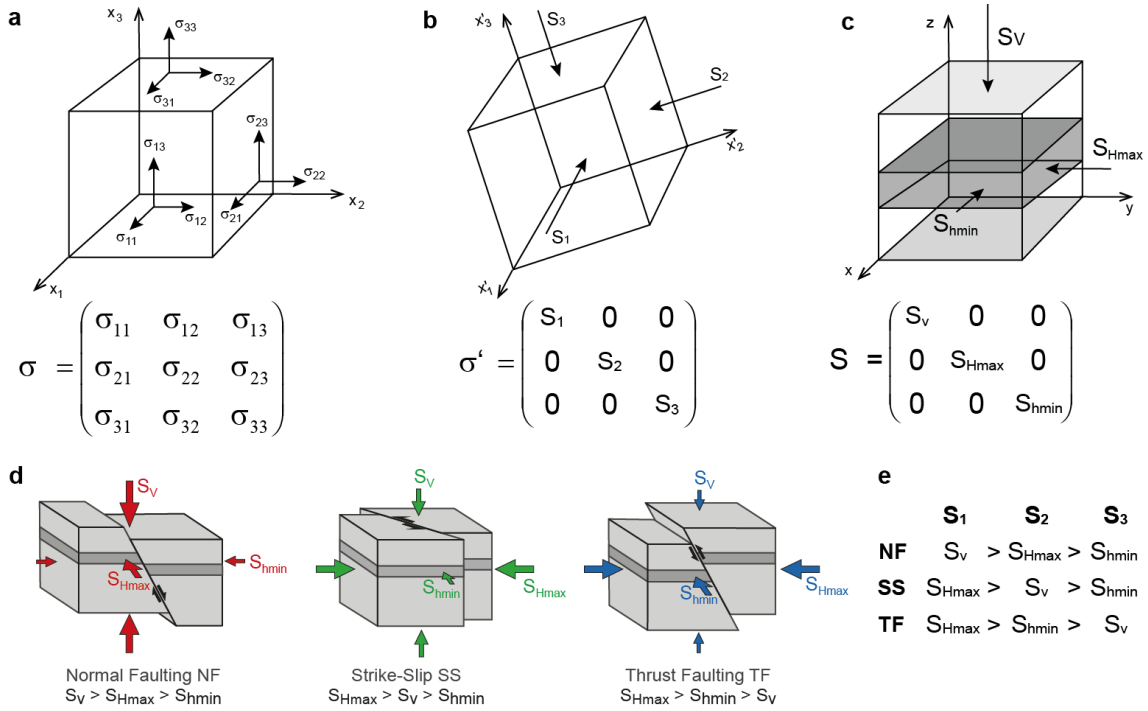


Fig. 1-1: Definition of the stress tensor and the tectonic stress regime

(a) The stress tensor at a particular point is described as three forces acting on three perpendicular faces of an infinitely small cube. b) Due to the stress tensor symmetry, a coordinate system exists where the three forces are perpendicular to the three cube faces. In this principal axis system, the three forces are termed principal stresses S_1 , S_2 , and S_3 with $S_1 > S_2 > S_3$. c) Assuming that the vertical stress S_v is a principal stress, the minimum and maximum horizontal stresses S_{Hmin} and S_{Hmax} , respectively, are also principal stresses. d) The tectonic stress regime is defined by the relative magnitudes of the principal stresses. e) Note that S_1 , S_2 and S_3 change their orientation abruptly with respect to a geographical coordinate system when the tectonic stress regime changes.

This report should also be set in the context of the frictional limit framework which is often also referred to as the critically stressed crust concept. Originally this framework was described by (Sibson 1974), which in turn is based on the general faulting concept of (Anderson 1905, 1951). It can be applied to any mature fault with negligible cohesion and describes the frictional behaviour with the linear failure criterion $\tau > \tau_f = \mu \sigma_n$ where τ is the applied shear stress τ_f the frictional resistance to shear, μ the static friction coefficient, and σ_n the fault normal stress. Thus, the concept only applies to the fault itself, i.e. the width of the fault core and to a lesser extent to the fault damage zone. Beyond the damage zone, the strength of the rock volume is significantly higher and controlled by the rock cohesion and the internal friction angle of intact rock.

Assuming that the width of damage zones of mature faults with reduced strength is smaller than 100 m, the volume in which the crust is critically stressed is $<1\%$. For the rest of the volume the critically stressed crust concept does not apply as the strength of intact rock is higher. Furthermore, elastic stresses that are built up due to plate tectonics are released by co-seismic fault slip. For moderate earthquakes in intraplate settings, the stress build-up and release are a few MPa at the fault during the seismic cycle, but decay quickly with distance (King et al. 1994). These stress changes are small compared to the total stress level and localised at the fault and its near-field (Reiter et al. 2024). The consequence of this first order description is that faulting keeps the volume between the crust strong (Townend & Zoback 2000). This results in large rock volumes

at distance from faults where sediments experience little or no internal deformation over tens of millions of years. The stress data and 3D geomechanical models presented in this report confirm these general statements.

1.3 Distinction and link to other reports

A first analysis of the stress orientation using the image logs of the TBO campaign was provided in Dossier V of the borehole-specific data reports (Tab. 1-1). However, these were only rush jobs for a provisional assessment of the boreholes to guide in-situ testing execution (i.e. packer seats for hydraulic packer tests and MHF tests). In this report, the final analysis is presented based on the World Stress Map (WSM) guidelines and quality assignment in agreement with Heidbach & Reinecker (2013) and Reinecker & Heidbach (2016). Furthermore, the new data records for the S_{Hmax} orientation from the TBO campaign are integrated into the existing ones to provide a comprehensive dataset.

The same holds for the stress magnitude analysis of the MHF and SR tests. Dossier VI (see Tab. 1-1) contains the pressure-time and reconciliation plots – although these plots are only from quick-look interpretations, pre-vs. post-MHF borehole images, as well as likely ranges for the closure stress. This report presents the final analysis of the MHF tests in order to estimate S_{hmin} magnitude ranges and the interpretation of the SR tests that provide S_{Hmax} magnitude ranges.

Tab. 1-1: Nagra's 9 deep boreholes (TBO) drilled 2019 – 2022, including references to data reports

Each of the TBO data reports consists of several Dossiers (I to XI).

Siting region	TBO name	Abbreviation	Data report	Nagra NAB No.
JO	Bözberg-1-1	BOZ1-1	Nagra (ed.) 2022a	NAB 21-21
JO	Bözberg-2-1	BOZ2-1	Nagra (ed.) 2022b	NAB 21-22
NL	Bülach-1-1	BUL1-1	Nagra (ed.) 2021a	NAB 20-08
NL	Stadel-3-1	STA3-1	Nagra (ed.) 2022d	NAB 22-01
NL	Stadel-2-1	STA2-1	Nagra (ed.) 2022c	NAB 22-02
NL	Bachs-1-1	BAC1-1	Nagra (ed.) 2023a	NAB 22-04
ZNO	Trüllikon-1-1	TRU1-1	Nagra (ed.) 2021c	NAB 20-09
ZNO	Marthalen-1-1	MAR1-1	Nagra (ed.) 2021b	NAB 21-20
ZNO	Rheinau-1-1	RHE1-1	Nagra (ed.) 2023b	NAB 22-03

2 Stress orientation data

Stress orientation data refer here to the S_{Hmax} orientation as defined in Fig. 1-1. This parameter can be estimated with a wide variety of stress indicators that sample different rock volumes (Ljunggren et al. 2003). For Northern Switzerland, data records are interpreted from borehole logs and earthquake focal mechanisms, following the guidelines and quality assignment of the World Stress Map (WSM) project (Heidbach et al. 2010, Heidbach et al. 2016).

2.1 Stress indicator from borehole wall failure analysis

Drilling of boreholes in a pre-stressed rock essentially generates a free surface (i.e. borehole wall) where there is no shear stress. This results in a redistribution of the stresses (Kirsch 1898, Schmitt et al. 2012) and the circumferential stress or hoop stress at the borehole wall may result in failure when the compressive or tensile strength of the intact rock is exceeded (Fig. 2-1). These stress-induced failures are known as borehole breakouts (BOs) and drilling-induced tensile fractures (DITFs) and both are well-established methods for providing reliable indicators of the present-day in-situ S_{Hmax} orientation (Bell & Gough 1979, Schmitt et al. 2012). The elongation of the cross-sectional shape of the wellbore is therefore the direct result of compressive shear failure on intersecting conjugate planes, which causes pieces of the borehole wall to spall off. The maximum circumferential stress around a vertical borehole is perpendicular to the orientation of S_{Hmax} . Hence, BOs form perpendicular to the S_{Hmax} orientation. BOs are observed as relatively wide, often poorly resolved zones on opposite sides of the borehole wall (Fig. 2-1).

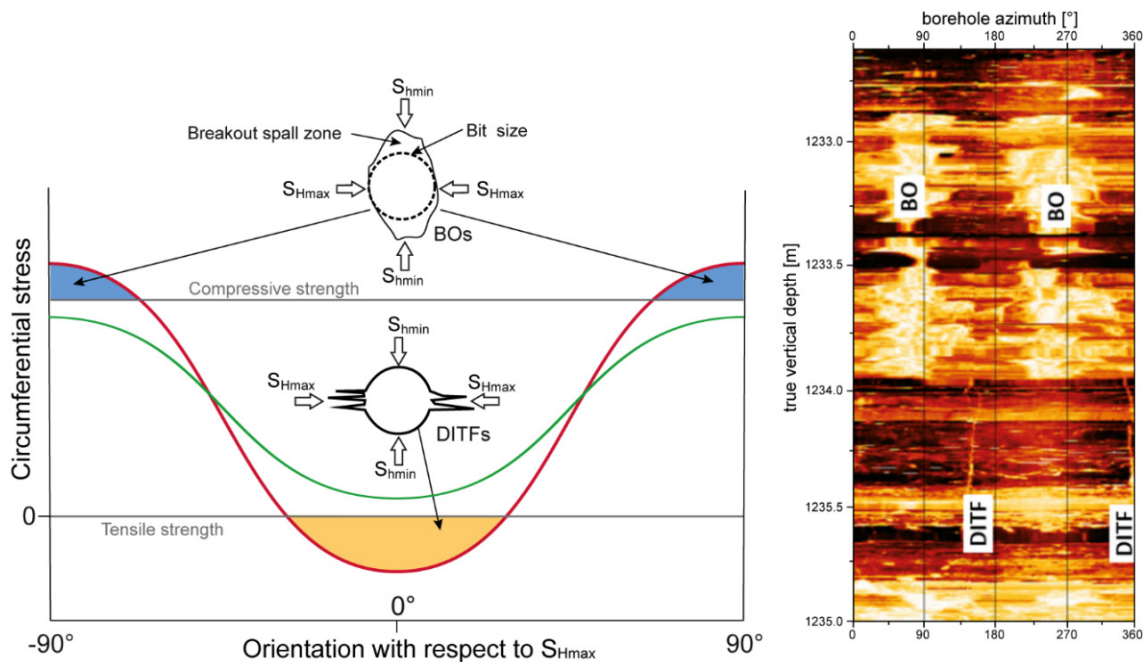


Fig. 2-1: Stress-induced failure modes at the wall of a near vertical borehole

Left side shows the orientation of borehole breakouts (BOs) and drilling-induced fractures (DITFs) with respect to the circumferential stress around the wellbore. Right side shows an image log of the borehole wall where typical BOs and DITFs are identified in a 3.4 m long section of borehole BAC1-1 in the Zeglingen Formation between 1,232.7 m and 1,235 m true vertical depth. Both indicate an S_{Hmax} orientation of approximately 170°N.

DITFs are caused by tensile failure of the borehole wall and form when the minimum circumferential stress exceeds the tensile strength of the intact rock. DITFs commonly appear as axisymmetric pairs of fractures parallel or en-echelon with respect to the borehole axis on the image. In vertical boreholes with one principal stress being parallel to the borehole, DITFs will be aligned parallel to the borehole axis in the orientation of S_{Hmax} and on opposite sides of the borehole (A-DITF; Fig. 2-1 left). When principal stresses are not coaxial with the borehole, DITFs may form as en-echelon sets of fractures at an angle to the borehole axis along a line of minimum circumferential stress on both sides of the borehole (E-DITF). These features can be a proxy for the change in the stress regime or low horizontal differential stress.

A third stress-induced feature observed at the borehole wall (and on cores) is a petal-centreline fracture (PC). PCs form just ahead of the drill bit due to concentration of stress at the bottom of the borehole. They nucleate near the margins of the bottom of the borehole and propagate into the plane perpendicular to the least compressive stress. As the petal fracture grows and curves towards the borehole axis, it becomes parallel with it to define a centreline fracture. Whereas the petal part does not reflect the regional stresses, the centreline can be used as an indicator of the stress orientation. Although centreline fractures form in response to relatively broad regions of enhanced tensile stress ahead of the bit and thus need not be coaxial with the borehole, they can continue to propagate as classical borehole wall tensile fractures after the drill bit drills through them (Davatzes & Hickman 2010). However, only co-axial (180° apart) PCs are picked as proxies for the orientation of S_{Hmax} .

Another stress-induced feature is the enhanced opening of natural pre-existing fractures in tensile mode in S_{Hmax} orientation. This feature is called a drilling-enhanced fracture (DEF) and may also be used as stress indicator, but with less confidence than DITFs and PCs. For the sake of completeness, these features were also picked, but, due to their potentially ambiguous interpretation, they are not used for the estimation of the S_{Hmax} orientation.

BOs, A-DITFs and E-DITFs are formed post-drilling, whereas PCs are formed during drilling ahead of the drill bit. DITFs, PCs and DEFs are tensile features, whereas BOs are compressive features. Note that compressive and tensile features can form at the same depth in orthogonal orientations (Fig. 2-1 right).

Other indicators for the S_{Hmax} orientation in boreholes are the orientations of the induced fractures that result from the MHF tests. These fractures are comparable to the DITFs and are accurate stress orientation indicators for the S_{Hmax} orientation as well.

2.2 Stress orientation data along borehole trajectories

In comparison to the rush analysis of the stress-induced failures at the borehole wall presented in Dossier V of the TBO boreholes (see Tab. 1-1), the guidelines of the WSM project are followed strictly here to ensure comparability with the re-analysis of the old data and newly acquired boreholes (Heidbach & Reinecker 2013, Reinecker & Heidbach 2016). The individual length of each picked stress-induced borehole failure was also recorded to apply a length-weight estimation of the mean S_{Hmax} orientation. Due to more conservative picking rules, the number of picks is lower compared to the rush analysis, but the resulting mean S_{Hmax} orientations of the borehole failure features are in overall agreement.

Fig. 2-2 shows as an example the individually picked BOs, DITFs, PCs and DEFs from the logs of the Ultrasonic Borehole Imager (UBI) and the Formation Micro Imager (FMI) in the STA3-1 borehole. Furthermore, the DITFs are distinct in A-type DITFs and E-type DITFs. The latter occur mainly in the Opalinus Clay and the formations of the Upper Dogger. E-type DITFs either indicate that the principal stresses are not aligned with the borehole axis and that a stress regime change takes place or that the horizontal differential stress is low.

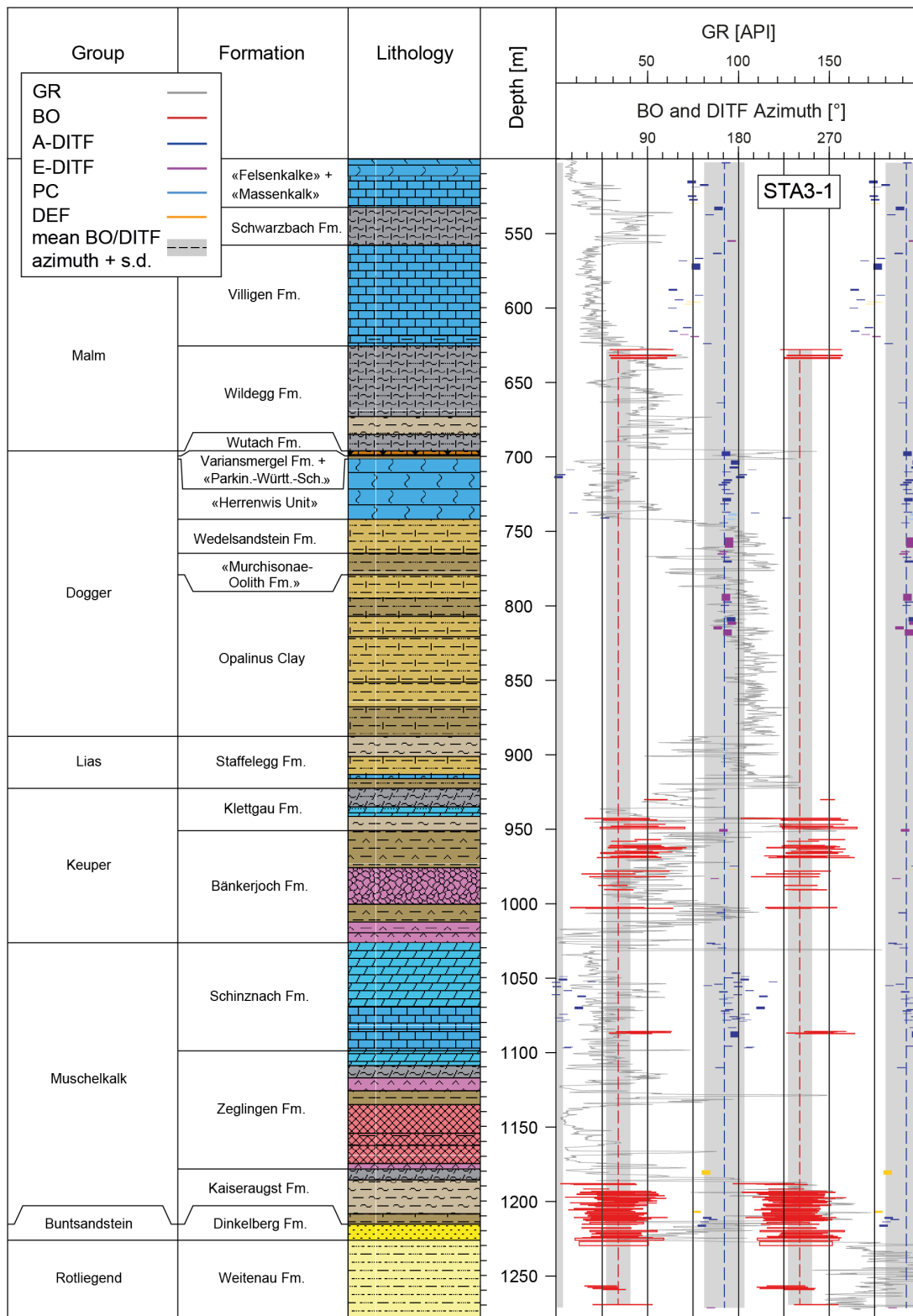


Fig. 2-2: Borehole failure modes along the STA3-1 borehole trajectory

The lateral extent of the red lines is the picked width of the BOs. The three picked PCs are located at 740 m depth in the «Herrenwis Unit», E-type DITFs are picked at 13 locations. Most of these are in the Wedelsandstein Formation and the Opalinus Clay. Grey line shows the Gamma Ray (GR) log.

The rose diagram of Fig. 2-3 shows the orientation of the individual picks of the BOs, DITFs and PCs. The mean orientation of the BOs is 62°N , with a standard deviation of $\pm 12^{\circ}$ resulting in a mean $S_{H\text{max}}$ orientation of 152°N . The mean orientation of the DITFs and PCs is 167°N ($= S_{H\text{max}}$ orientation) with a standard deviation of $\pm 20^{\circ}$. The mean orientations are also presented in Fig. 2-2 with blue (DITFs/PCs) and red (BOs) dashed vertical lines. The grey shaded areas around these lines denote the standard deviations of the mean orientations.

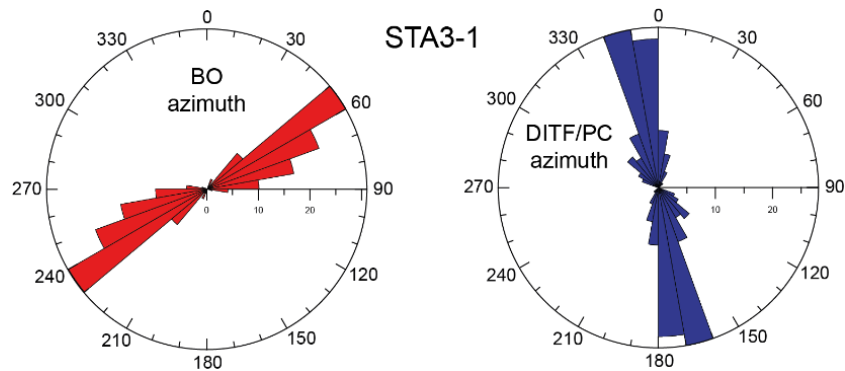


Fig. 2-3: Rose diagrams of borehole failure orientations at STA3-1

Rose diagrams show only the orientations of the individual picks of the borehole failures. For the estimation of the mean orientation, weights are used according to the length of the picks.

2.3 Local deviations of stress orientation data along borehole trajectories

The results for the other boreholes are very similar and do not show any significant variation with depth. They are documented in the same way as above in App. A. The only exception is detected in borehole TRU1-1. Here the rose diagram already indicates that there are subsets of DITFs/PCs with distinct orientations at approximately 145° and 175° (Fig. 2-4).

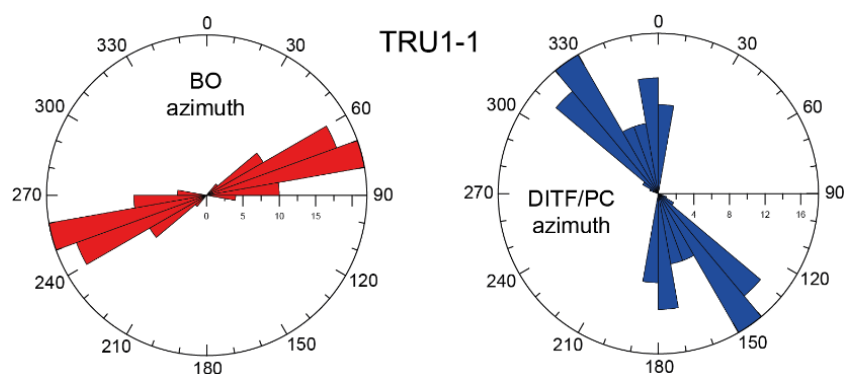


Fig. 2-4: Rose diagrams of borehole failure orientations in TRU1-1

Rose diagrams show only the orientations of the individual picks of the borehole failures. For the estimation of the mean orientation, weights are used according to the length of the picks.

Fig. 2-5 reveals that, within the Malm at 608 m TVD and across the evaporites of the Zeglingen Formation (Muschelkalk) below 1,212 m, a significant rotation occurs. The rotation in the Malm is interpreted as a local phenomenon associated with a fault zone. The rotation across the Zeglingen Formation has previously also been observed in the Herdern-1 borehole (20 km to the southeast) and in boreholes GTB Sonnengarten-1 and Schafisheim, south of the Folded Jura (Heidbach & Reinecker 2013). This observation may indicate a mechanical decoupling, possibly affecting the south-eastern part of the ZNO siting region but not the siting regions JO and NL (both north of the Jura Main Thrust).

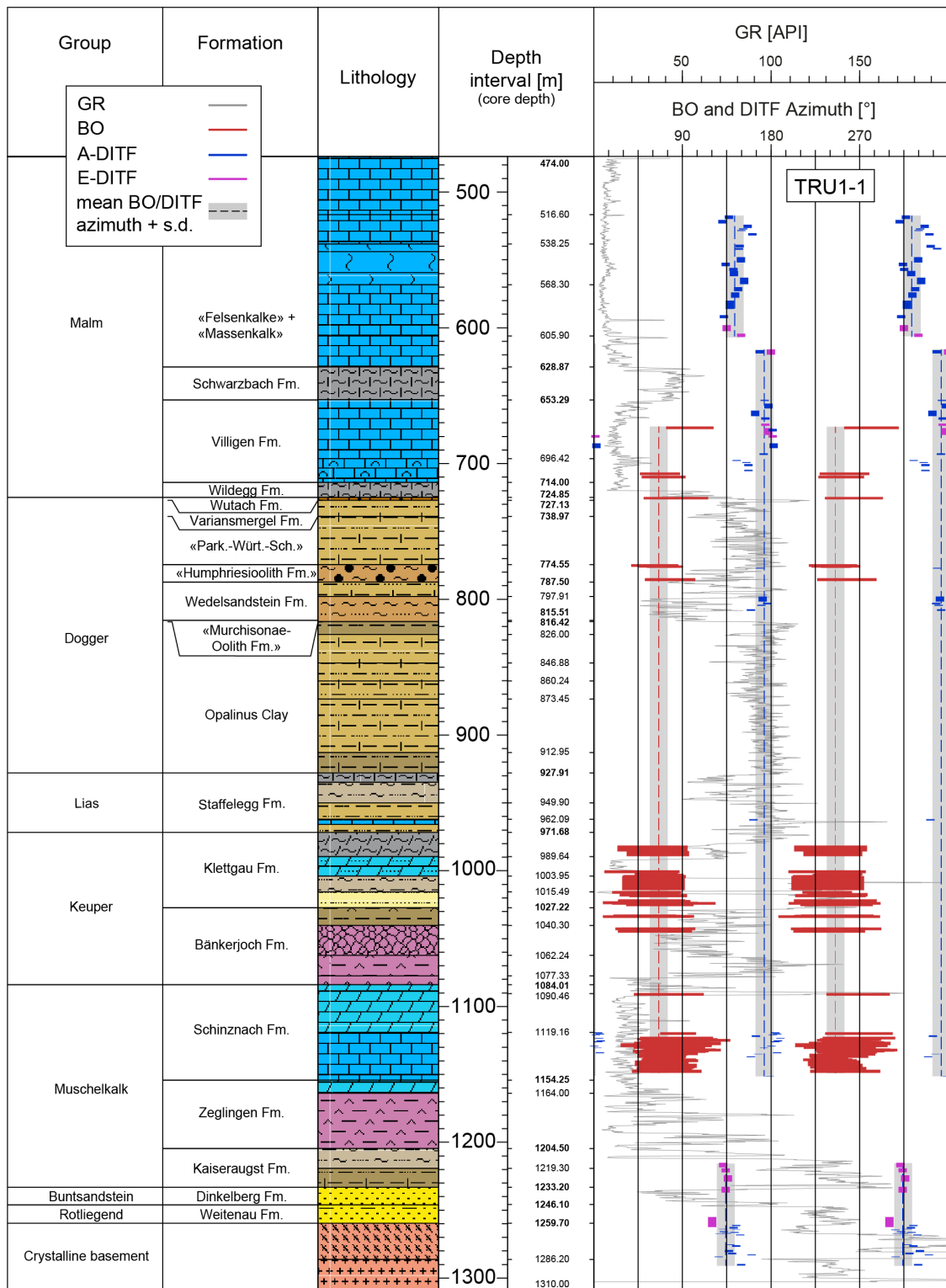


Fig. 2-5: Borehole failure modes along the TRU1-1 borehole trajectory

Horizontal red lines denote the width of the picked BOs. Note the change in the orientation of the DITFs and PCs above 608 m and below 1,212 m. Both sections in which these rotations occur have E-type DITFs that are expected when the principal stress orientations are not aligned with the vertical borehole axis or when horizontal differential stresses are low. Grey line shows the Gamma Ray (GR) log.

2.4 Stress map of Northern Switzerland

The updated stress map of Northern Switzerland presents a dataset of 86 data records of the S_{Hmax} orientation (Fig. 2-6). Within the Mesozoic sediments, 42 data records result from the analysis of borehole data. For the depth range between 2 and 22 km in the crystalline basement, 44 data records use the principal strain axes of earthquake focal mechanisms as a proxy for the principal stress orientations. Details of the procedure for deriving the S_{Hmax} orientation and the assignment of a stress regime from earthquake focal mechanisms can be found in the guidelines of the WSM project (Heidbach et al. 2016) and in key publications (McKenzie 1969, Zoback 1992).

The borehole data records for S_{Hmax} orientation result from the analysis of the nine TBO campaign boreholes, the re-analysis of the previous Nagra boreholes in the three siting regions and additional boreholes in the greater area (Heidbach & Reinecker 2013, Reinecker & Heidbach 2016). The earthquake focal mechanisms were provided by Tobias Diehl from the Swiss Seismological Service (SED) covering the observation period of greater Switzerland between March 1976 and August 2023. This dataset contains 484 focal mechanisms based on first-motion polarities. Moment tensor inversion is in most cases not possible since more than 90% of the events have moment magnitudes $M_w < 4.0$.

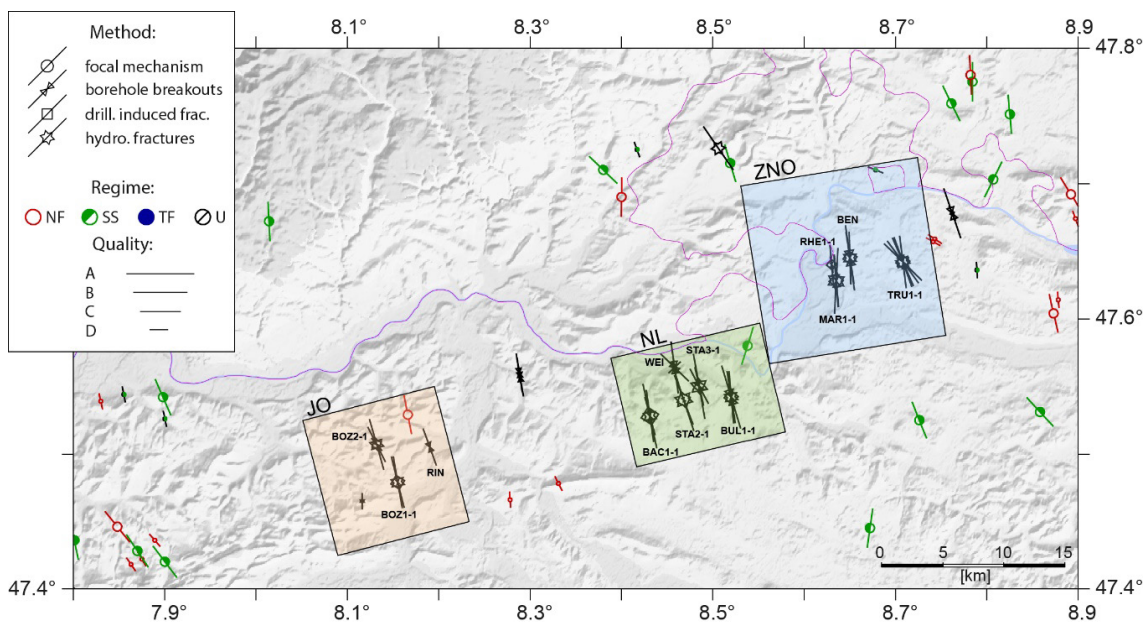


Fig. 2-6: Stress map of the S_{Hmax} orientation data in Northern Switzerland

The map shows the compilation of 86 stress orientation data records with A-D quality from boreholes ($n = 42$) and earthquake focal mechanisms ($n = 44$). Data are assigned to different qualities according to the WSM quality ranking scheme (Heidbach et al. 2010). Line length is proportional to data quality and colours indicate the stress regime with NF = normal faulting (red), SS = strike-slip (green), TF = thrust faulting (blue), and U = Unknown (black). Rectangles show the area of the 3D geomechanical-numerical stress models JO, NL and ZNO (see Chapter 4). Abbreviations of the boreholes are given in Tab. 1-1, RIN, WEI, and BEN are the Riniken, Weiach and Benken boreholes, respectively.

Each data record is assigned to a quality between A and E following the WSM quality ranking scheme that has been developed to make data records from different stress indicators for the S_{Hmax} orientation comparable. A-quality means that the S_{Hmax} orientation is accurate to within $\pm 15^\circ$, B-quality to within $\pm 20^\circ$, C-quality to within $\pm 25^\circ$, and D-quality to within $\pm 40^\circ$. E-quality data records do not provide sufficient information or have standard deviations greater than 40° . These data records are kept only for bookkeeping purposes, i.e. to show that these data have been processed. For most methods, these quality classes are defined through the standard deviation of S_{Hmax} . Further details of the WSM quality ranking scheme are presented in the WSM Technical Report 16-01 (Heidbach et al. 2016) and in key publications (Heidbach et al. 2010, Sperner et al. 2003, Zoback 1992). Note that, due to the limited reliability of stress orientations derived from earthquake focal mechanisms, they always receive C-quality or D-quality when the earthquake magnitude is lower than M 2.5.

The rose diagrams presented in Fig. 2-7 compare the S_{Hmax} orientations for the two datasets of borehole data records in the Mesozoic sediments and the ones derived from earthquake focal mechanisms located in the basement between 2 – 22 km depth. They show that there is no significant difference in the mean S_{Hmax} orientation from the two datasets. However, the rose diagram of the S_{Hmax} orientations derived from focal mechanisms reveal that the results have a higher fluctuation compared to the dataset of S_{Hmax} orientations from borehole data. This reflects the fact that S_{Hmax} orientations derived from earthquake focal mechanisms are less reliable in general due to the inherent uncertainty when the principal strain axes from the focal mechanisms are used as proxies for the principal stress orientations (McKenzie 1969).

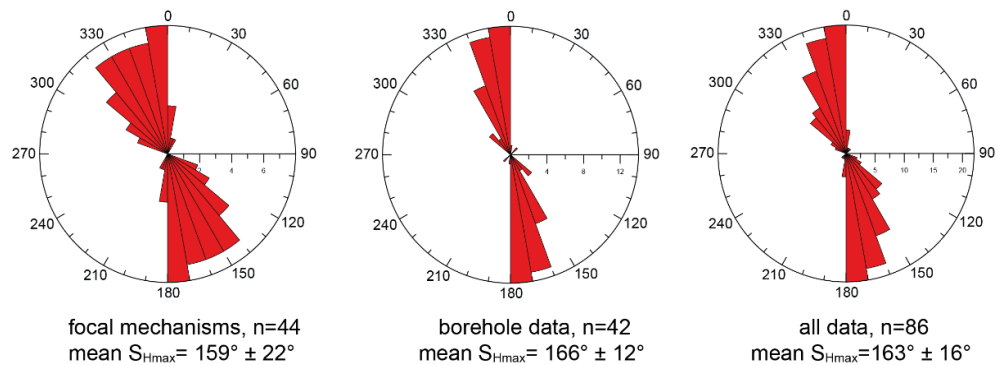


Fig. 2-7: Rose diagrams of S_{Hmax} orientation datasets in Northern Switzerland

Rose diagrams show only the S_{Hmax} orientations of the individual data records with A- to D-qualities without reflecting their assigned quality according to the WSM quality ranking scheme (see Tab. 2-1). For the estimation of the mean S_{Hmax} data qualities are used as weights.

The mean S_{Hmax} orientation and standard deviation for each dataset is estimated with the statistics of bi-directional data (Mardia 1972) using the assigned data qualities as weights. The mean S_{Hmax} orientation in the Mesozoic sediments based on borehole data records is 166° N with a standard deviation of $\pm 12^\circ$, whereas the mean S_{Hmax} orientation in the basement based on earthquake focal mechanism data records only is 159° N with a standard deviation of $\pm 22^\circ$. The mean S_{Hmax} orientation for the combined dataset ($n = 86$) is 163° N with a standard deviation of $\pm 16^\circ$.

From a statistical point of view, the two datasets do not reveal a systematic rotation of the stress orientation between the Mesozoic sediments and the basement. Section 2.2 shows the stress orientation along a borehole in detail and Section 2.3 the results along the borehole trajectory of TRU1-1 where local deviations from the prevailing trend were detected.

Tab. 2-1 shows the summary of the analysis of borehole failures (borehole breakouts BOs, drilling-induced tensile fractures DITFs and induced fractures from the MHF tests) for each of the nine new boreholes of the TBO campaign. For each different borehole failure type, a mean S_{Hmax} orientation is estimated using the mean of the orientations of the picked stress-induced borehole failure zones. Furthermore, weight according to the individual length of the picked stress-induced borehole failure zone is applied to avoid a potential overrepresentation of short borehole failure zones. However, a comparison with a number-weighted estimation of the mean S_{Hmax} orientation has been performed and resulted in difference of a few degrees only.

Tab. 2-1: Summary of borehole failure analysis from the nine TBO boreholes

FMI stands for Formation Micro Imager, UBI for Ultrasonic Borehole Imager. SD is the standard deviation of the mean S_{Hmax} orientation, n is the number of individually picked stress-induced borehole failure zones or the number of induced fractures during the MHF tests that are used for the mean S_{Hmax} orientation estimation. The total length is the sum of all picked stress-induced borehole failure zones. Depth range denotes the distance between the first (top) and last (bottom) picked stress-induced borehole failure zone. Colour indicates the three siting regions as shown in Fig. 2-6.

Bore-hole	Type	Log/test	S_{Hmax} orientation [°]	SD [°]	n	Total length [m]	Depth range MD [m]	WSM quality
BOZ2-1	BO	FMI/UBI	139	3.9	18	11.0	108 – 288	D
	DITF	FMI	153	18.2	35	27.0	202 – 603	C
	HF	MHF	164	17.1	9	-	316 – 595	B
BOZ1-1	BO	FMI/UBI	167	13.5	34	7.0	494 – 984	D
	DITF	FMI	166	13.1	41	105.9	305 – 1,018	B
	HF	MHF	170	12.4	15	-	290 – 829	B
BAC1-1	BO	FMI/UBI	165	11.0	72	30.4	515 – 1,244	C
	DITF	FMI	168	7.0	50	182.2	519 – 1,304	A
	HF	MHF	172	13.2	8	-	562 – 1,290	B
STA2-1	BO	FMI/UBI	156	7.5	34	8.1	525 – 779	D
	DITF	FMI	159	12.8	96	93.5	478 – 1,288	B
	HF	MHF	162	11.1	15	-	544 – 1,281	A
STA3-1	BO	FMI/UBI	152	11.5	97	26.6	628 – 1,268	C
	DITF	FMI	167	19.6	105	107.5	446 – 1,270	C
	HF	MHF	170	10.8	15	-	483 – 1,264	A
BUL1-1	BO	FMI/UBI	163	5.0	257	160	643 – 1,364	A
	DITF	FMI	175	10.0	17	44	586 – 1,307	B
	BO	Caliper	173	8.0	11	17	808 – 1,112	D
	HF	MHF	171	13.1	15	-	558 – 1,332	B
RHE1-1	BO	FMI/UBI	170	18.6	18	7.8	54 – 686	D
	DITF	FMI	175	15.0	15	27.2	157 – 739	C

Tab. 2-1: Cont.

Bore-hole	Type	Log/test	S_{Hmax} orientation [°]	SD [°]	n	Total length [m]	Depth range MD [m]	WSM quality
MAR1-1	BO	FMI/UBI	175	14.0	74	45.2	338 – 849	B
	DITF	FMI	176	13.0	108	94.0	321 – 1,052	B
	HF	MHF	3	7.9	12	-	387 – 726	A
TRU1-1	BO	FMI/UBI	156	9.0	66	34.8	674 – 1,148	C
	DITF	FMI	151	19.0	74	133.5	520 – 1,291	C
	DITF sub-set I	FMI	143	9.0	19	52.5	520 – 602	B
	DITF sub-set II	FMI	173	9.0	34	47.5	614 – 1,152	B
	DITF sub-set III	FMI	134	9.0	21	33.5	1,212 – 1,291	C
	HF	MHF	160	12.9	16	-	515 – 1,054	B

For each borehole and each stress indicator type, one mean S_{Hmax} orientation was estimated (see Section 2.2). The only exception is the TRU1-1 borehole where the DITFs above 608 m TVD and below 1,212 m TVD show a clear rotation (Fig. 2-4). Therefore, the DITFs result for this borehole in three data records from the DITF subsets I, II and III (Tab. 2-1). As a result, this separation lowers the standard deviation for each subset to 9.0° compared to the standard deviation of 19° for the mean S_{Hmax} orientation based on all DITFs from this borehole.

To compare the mean S_{Hmax} orientation within the Mesozoic sediments in each siting region, the borehole data are used within the rectangles shown in Fig. 2-6. These rectangles denote the lateral extent of the stress models that are presented in Chapter 4. The mean S_{Hmax} orientation is quite similar with a small clockwise rotation of 7° from east to west following the regional and large-scale trend. Further east, the prevailing S_{Hmax} orientation is N-S (Heidbach & Reinecker 2013, Reinecker et al. 2010) and to the west S_{Hmax} has a 140 – 150° orientation (Heidbach & Reinecker 2013), following the trend of the topography of the Alps that are the key driving force for the S_{Hmax} orientation in forelands (Heidbach et al. 2007, Reiter et al. 2014).

The mean S_{Hmax} orientation in the Jura Ost (JO) siting region is 163°N, 166°N for Nördlich Lägern (NL) and 170°N for Zürich Nordost (ZNO). These values hardly change when the data from the re-analysed older Nagra boreholes Riniken, Weiach and Benken are included, which shows the consistency of the logging and analysis procedure (Tab. 2-2). Note that some of the other older Nagra borehole logging data either did not result in reliable S_{Hmax} estimates during the re-analysis (Böttstein, Kaisten, Leuggern) or are outside the rectangular boxes (Schafisheim, Siblingen).

Tab. 2-2: Summary of borehole failure analysis in the three siting regions

The dataset is based on the new TBO campaign boreholes in each siting region. For comparison, the mean S_{Hmax} orientation including the re-analysis of the old Nagra boreholes reported in Heidbach & Reinecker (2013) is also given.

Siting region	Number of boreholes	Number of data records	Mean S_{Hmax} orientation [°]
JO	3 including Riniken	6 (7 including Riniken data)	$163^{\circ}N \pm 8^{\circ}$ ($163^{\circ} \pm 8^{\circ}$)
NL	5 including Weiach	13 (16 including Weiach data)	$166^{\circ}N \pm 6^{\circ}$ ($166^{\circ} \pm 11^{\circ}$)
ZNO	4 including Benken	8 (11 including Benken data)	$170^{\circ}N \pm 11^{\circ}$ ($172^{\circ} \pm 9^{\circ}$)

3 Stress magnitude data

This chapter focuses on the determination of the magnitude of the principal stresses.

Sections 3.1 to 3.4 present the various methods that were used during the TBO campaign to determine stress magnitudes. Section 3.1 presents how ranges of the S_{hmin} magnitude can be determined from the microhydraulic fracturing (MHF) tests. Section 3.2 presents how sleeve reopening (SR) tests can provide ranges for the S_{Hmax} magnitude. Section 3.3 focuses on the case where MHF tests can estimate the vertical stress. Section 3.4 details other tests that are also conducive to estimating stress magnitudes.

Because of the very unusual extent of the stress measurement campaign during the TBO project, Section 3.5 describes the test statistics in detail, discussing the coverage of the lithological column over the three regions.

Section 3.6 presents and discusses stress magnitudes from the entire campaign, while Section 3.7 is focused on the Opalinus Clay formation.

3.1 Microhydraulic fracturing (MHF) tests for estimating S_{hmin} magnitudes

MHF tests are the most robust method for determining stress magnitudes at great depth. The principle underlying the measurement is that a hydraulic fracture will eventually propagate perpendicularly to the minimum principal stress S_3 . Furthermore, the fluid pressure at which the fracture opens and closes is an integral measurement of the normal stress acting on the fracture surface, providing an avenue to measure the far-field S_3 magnitude. More details can be found in (Haimson & Cornet 2003) and references therein. Note that, in the following, S_{hmin} and S_{Hmax} are used instead of S_3 and S_1 or S_2 to be consistent with the literature (see Section 1.2).

The MHF technique, combined with SR tests, allows access to both the S_{hmin} and S_{Hmax} stress magnitudes. A successful example for the determination of the stress tensor in the lithological column of interest for the siting of a radioactive waste repository – prior to the TBO campaign – can be found in Wileveau et al. (2007).

Similarly to the campaign reported in Wileveau et al. (2007), a wireline conveyed formation testing tool was used here. Furthermore, sleeve fracturing (SF) was performed prior to the MHF to focus the hydraulic test at a desired location by creating vertical starter fractures. The toolstring has been customised for stress testing; of particular importance is the presence of a downhole pump that can deliver constant injection rates regardless of pressure. The toolstring was further optimised as the campaign unfolded to provide the best possible test sequence for a particular lithological column, with the use of special packers, chambers to carry fracturing fluid downhole, etc. (Desroches et al. 2023). The optimised toolstring also facilitated the real-time redesign of each MHF/SR test.

To maximise the number of high-quality stress measurements, as well as the sampling of the formations of interest, an iterative planning process was deployed, from pre-planning (months before testing) down to real-time adjustment of each individual test. More details can be found in (Desroches et al. 2021).

3.1.1 Closure stress determination

Closure stress is the average magnitude of the stress acting normal to the fracture surface. The aim of an MHF test is to determine the value of the closure stress with as much accuracy as possible, and to ensure that the closure stress is as representative as possible of a far-field principal stress magnitude.

During an MHF test, an interval is isolated with inflatable packers, and fluid is injected into the interval to create and propagate a small hydraulic fracture into the formation. The fracture extension into the formation is typically of the order of 1 metre. An MHF test consists of a series of fluid injection / withdrawal phases. The protocol is tailored in real time to prove hydraulic isolation, ensure that a fracture was created, and ensure that the fracture has extended sufficiently into the formation that the far-field stress is mostly sensed by the fracture (Desroches et al. 2023).

An example from the TBO campaign is presented in Fig. 3-1 to illustrate the tailoring of an MHF test to achieve the two aims described above. The top panel presents interval pressure as a function of time, as well as injection rate as a function of time, just after the packers have been inflated and a hydraulic seal was confirmed. Fracture initiation is indicated by a sharp drop after a maximum pressure has been reached (“breakdown” pressure). The presence of a hydraulic fracture – and not of a high-pressure packer bypass – is confirmed by a slamback / rebound test. The pressure immediately after shut-in, or ISIP (Instantaneous Shut-In Pressure) is an upper bound for the closure stress.

As mentioned previously, the fluid pressure inside the fracture at which the width of the fracture is zero is an integral measure of the stress acting perpendicularly to the surface of the fracture. However, a hydraulic fracture does not close uniformly on itself, and the fluid pressure is never uniform in the fracture. There are therefore several methods for estimating when the fracture width is “zero”, either from an open fracture to a closed fracture (from falloff – during which fluid leaks from the fracture into the formation, or from flowback tests – during which fluid is slowly removed from the fracture), from a closed fracture to an open fracture (from reopening – during which fluid is pumped from the borehole, or from rebound – during which fluid from the tip of the fracture is equilibrating after a fast depressurisation of the borehole), or from extrapolation of a fracture propagated under different conditions (step-rate test). Each of these methods provides an estimate of the closure pressure, i.e. the pressure at which the fracture is at the limit between being open and closed. Each estimate responds to a different way to interrogate the fracture, and, as the size of the fracture increases, all estimates should converge to the value of the closure stress.

The middle panel of the figure presents the interval pressure and the injection rate as a function of time during the third and part of the fourth cycle, which were designed to respond to the absence of a clear estimate of closure pressure during the falloffs of the first and the second cycle: the focus was shifted to estimates that make use of fracture reopening instead of closure.

In the bottom panel, all test estimates of closure pressure are presented as a function of cycle number, also known as a reconciliation plot (Desroches & Kurkjian 1999). The test continues until convergence is observed from one cycle to the next, ensuring that the fracture has propagated sufficiently into the formation to mostly sense the far-field stress. The last few cycles are designed to shrink the difference between the various closure pressure estimates for a particular cycle as much as possible.

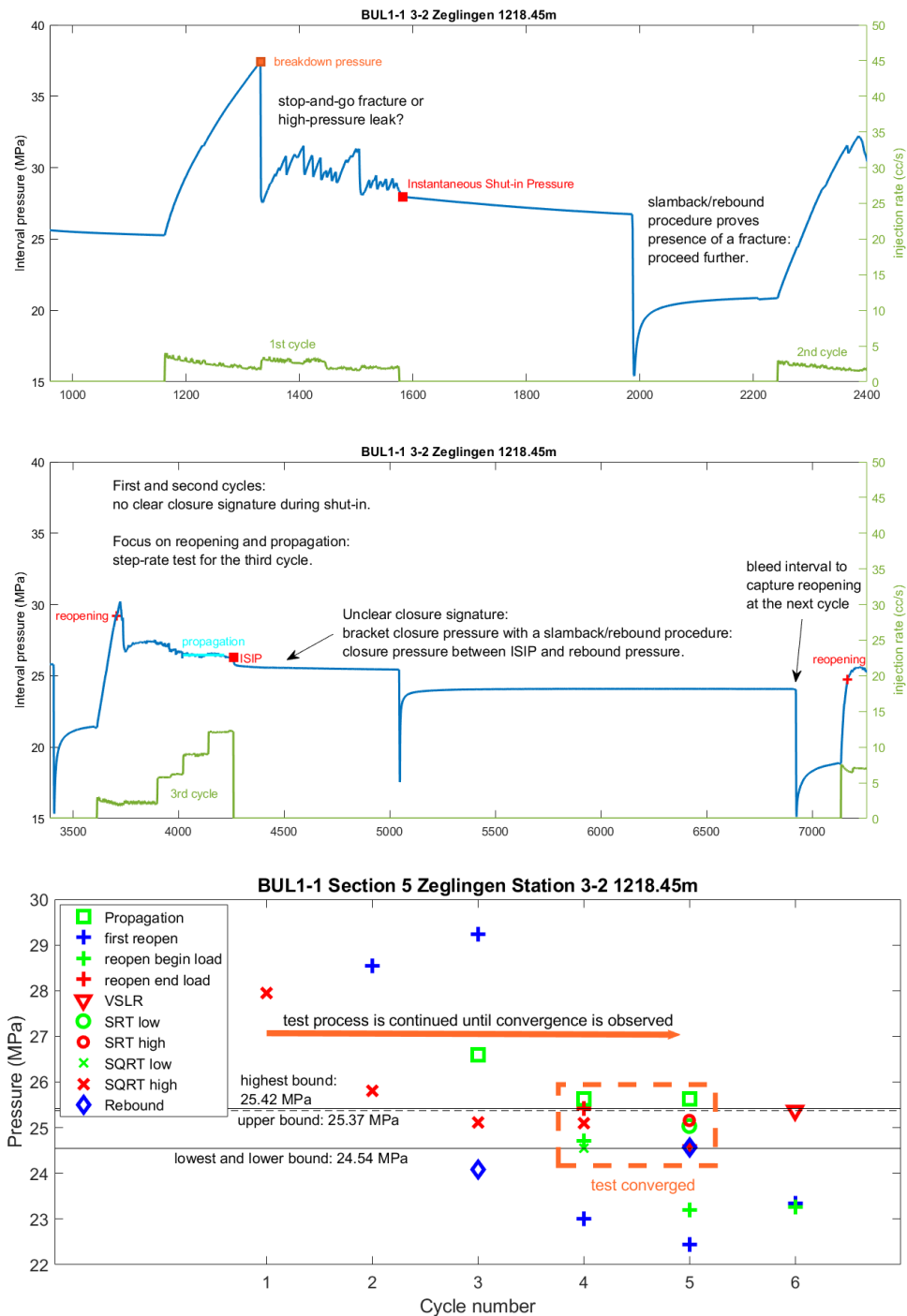


Fig. 3-1: Example of a microhydraulic fracturing (MHF) test

Test example from the BUL1-1 borehole performed at a centre depth of 1,218.45 m in the Zeglingen Formation. The first two top panels present the pressure in the interval (left axis) and the injected flow rate (right axis) as a function of test time (in seconds). The top panel shows the first cycle as well as the beginning of the second one. The intermediate panel shows the third and fourth cycle. The bottom panel shows the reconciliation plot for the entire test, displaying closure stress estimates for each consecutive cycle. VSLR stands for very slow reopening, SRT stands for step-rate test, SQRT stands for square-root of shut-in time, all of which being means to estimate the closure stress.

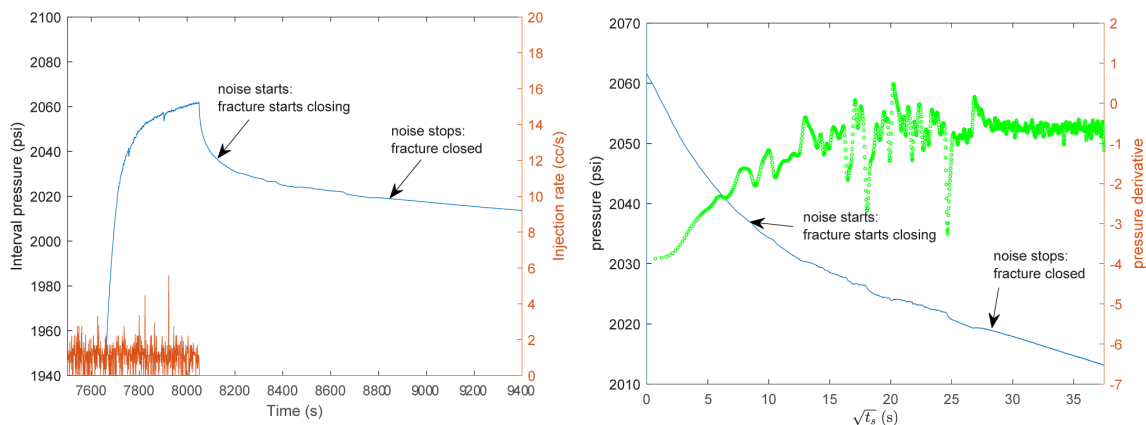


Fig. 3-2: Example of a shut-in cycle demonstrating that fracture closure is not instantaneous but is an extended process

Shut-in example from the STA3-1 borehole performed at a centre depth of 644.8 m in the Wildegge Formation (5th cycle). The left panel shows the pressure in the interval (blue line) and the injection rate (orange line) as a function of time. The right panel shows the interval pressure (blue line) and the pressure derivative (green line) as a function of the square root of the time since shut-in. As the fracture starts to close on asperities, noise starts to develop, visible both on straight time and the square root of shut-in time. When the fracture is fully closed, noise also stops. The closure process took more than 10 minutes for a range of about 20 psi (0.14 MPa).

Because of the physics of hydraulic fracturing, the closure stress cannot be estimated exactly, but a range can be determined by combining the various closure pressure estimates and their variation as the fracture grows. For the TBO campaign, it was decided for each test to determine two different ranges for the closure stress: a wide range (bounded by a “lowest” and a “highest” value) and inside which the true closure stress value should lie, and a narrow range (extending from a “lower” to an “upper” bound) that is the most likely range for the closure stress. Note that these four bounds are not necessarily all different: for the test presented in Fig. 3-1, the lowest and the lower bounds are similar, whereas the upper and the highest bounds are different.

To further illustrate that closure stress should be defined as a range and not as a single value, a clear example of a fracture closing over a time and pressure range during a shut-in/falloff is presented in Fig. 3-2. Not only is there no single method that provides an exact value of closure stress, but even from a single method for estimating closure pressure, no single value can always be determined.

The interpretation process used here incorporates the interpretation of fracture rebounds and flowbacks (forced closure), as recently described by de Lesquen & Armand (2023). As will be further detailed in Section 3.1.3 through examples, closure stress estimates resulting from rebounds and flowbacks were fully integrated with the other closure pressure estimates – as it should be when multiple high-quality stress estimates can be derived from a test.

All pressure records are presented in Dossier VI for each borehole (see Tab. 1-1) and will not be presented here. Dossier VI also include initial ranges for the closure stress. Tests have been further interpreted to obtain the wide and narrow ranges reported here.

Once closure stress ranges have been determined, the next step is to assign – or not – that closure stress range to a principal stress magnitude, which will be described in Section 3.1.2. Once this step is completed, a model of the interaction of a fracture with a borehole is used to determine, when possible, ranges of the S_{Hmax} magnitude using the results of the SR tests. This is described in Section 3.2.

3.1.2 Closure stress assignment to principal stress magnitudes

Once ranges for the closure stress have been determined, the next step consists of assigning the closure stress to a principal stress orientation – or not. For tests of a pre-existing fracture misaligned with a principal stress orientation, also known as HTPF (hydraulic tests of pre-existing fractures; Haimson & Cornet 2003), such an assignment cannot be performed as the stress normal to the fracture is a combination of all principal stresses. For other tests, during which a new fracture was created, three possibilities are considered: either the hydraulic fracture ultimately senses the minimum horizontal stress (S_{hmin}), the vertical stress (S_v), or it most likely senses the minimum horizontal stress, although there is some persistent doubt about this. For the last case, the closure stress range is assigned to a separate category labelled S_{hmin} ?

A combination of the behaviour of the convergence on the reconciliation plot, the comparison between pre- and post-MHF images (Fig. 3-3) and the absolute gradient of the closure stress with respect to true vertical depth are considered to perform the assignment.

The closure stress is assigned to S_v when:

- Its value is close to that of the integrated density, **and**
- There are only small variations from one cycle to the next, especially for reopening (there is no effect of the stress concentration around the borehole to move away from), **and**
- No new vertical fractures can be seen on the post-MHF imaging, or a stimulated bed boundary can be seen.

The closure stress is assigned to S_{hmin} or S_{hmin} ? when:

- Its value is different from that of the integrated density, **or**
- There is a clear trend as the size of the fracture grows, especially for reopening, indicative of the effect of the stress concentration around the borehole.

The following is considered to refine the assignment:

- If the post-MHF image shows two subvertical conductive fractures, 180 degrees apart, like the example presented in Fig. 2-3, and the reconciliation plot has shown full convergence of the closure stress estimates, the closure stress is then assigned to S_{hmin} .
- If the post-MHF image shows two subvertical conductive fractures, 180 degrees apart, like the example presented in Fig. 2-3, and the reconciliation plot does not exhibit convergence of the closure stress estimates, the closure stress is then assigned to S_{hmin} ?, which can be a lower or an upper bound of S_{hmin} (depending on the trend of the reconciliation plot).
- If the post-MHF image does not present such a feature – e.g. it exhibits a new inclined fracture, or more than two subvertical fractures, and the reconciliation plot clearly demonstrates that the stress estimates have been decreasing and stabilising, the closure stress is assigned to S_{hmin} (the fracture may have initiated at an angle from the preferred far-field fracture plane, but has turned to sense it mostly).

- If the post-MHF image does not present such a feature and the reconciliation plot leaves open the possibility that the fracture may still reorient, the closure stress is assigned to S_{hmin} ?, which is then an upper bound for S_{hmin} .

Comparing the closure stress ranges as well as the reconciliation plots of MHF tests that were performed close to each other and in the same facies also brings clarity to the closure stress assignment, as both tests should yield a similar stress gradient if a principal stress has been measured.

Even if a test did not yield an estimate of S_{hmin} , bounds can be put on the value of S_{hmin} :

- If an MHF test yielded an estimate for S_v , then S_{hmin} is larger than S_v at that depth: the test demonstrates that it was easier to propagate a horizontal fracture than a vertical fracture, which, in the presence of sleeve fracturing prior to hydraulic fracturing, implies that $S_v < S_{hmin}$.
- If an MHF test yielded an estimate for S_{hmin} ?, observation of both pre- and post-MHF imaging as well as the trends of the reconciliation plot allow determination of whether it is a lower or an upper bound of S_{hmin} (see above).

Remarks on the trace of MHF induced fractures on resistivity images

Let us note that, even if the minimum principal stress is horizontal and the borehole vertical, fracture initiation and propagation is a complex 3-dimensional process that may not result into a vertical fracture trace at the borehole wall. The geometry of pre-existing defects in the formation, as well as the possibility of combining shear and tension for initiating a fracture, will for example lead to a slanted fracture at the borehole wall.

It is worth noting that a microhydraulic fracture that initiated perpendicular to a principal stress direction (e.g. perpendicular to S_{hmin}) will not sense any shear on its plane as it propagates, and therefore will not reorient even if S_{hmin} is not the minimum principal stress. The fracture will not reorient perpendicularly to the minimum stress, unless a heterogeneity in the formation disturbs this metastable process. Clear laboratory examples can be found in Weijers (1995). This behaviour is what enables MHF tests to estimate the magnitude of S_{hmin} if the fracture is initiated perpendicular to S_{hmin} , even in cases where the minimum stress is vertical.

Finally, because of the contrast between the vertical scale (of the order of 2 metres) and the unwrapped horizontal scale (of the order of $\frac{1}{2}$ a metre) of the resistivity images, fractures with a few degrees off the vertical will appear slanted on the image. A fracture with a 5-degree deviation from the vertical was considered here to be vertical. As an example, the fracture in Fig. 3-3 clearly exhibits some curvature but has a dip of 85° .

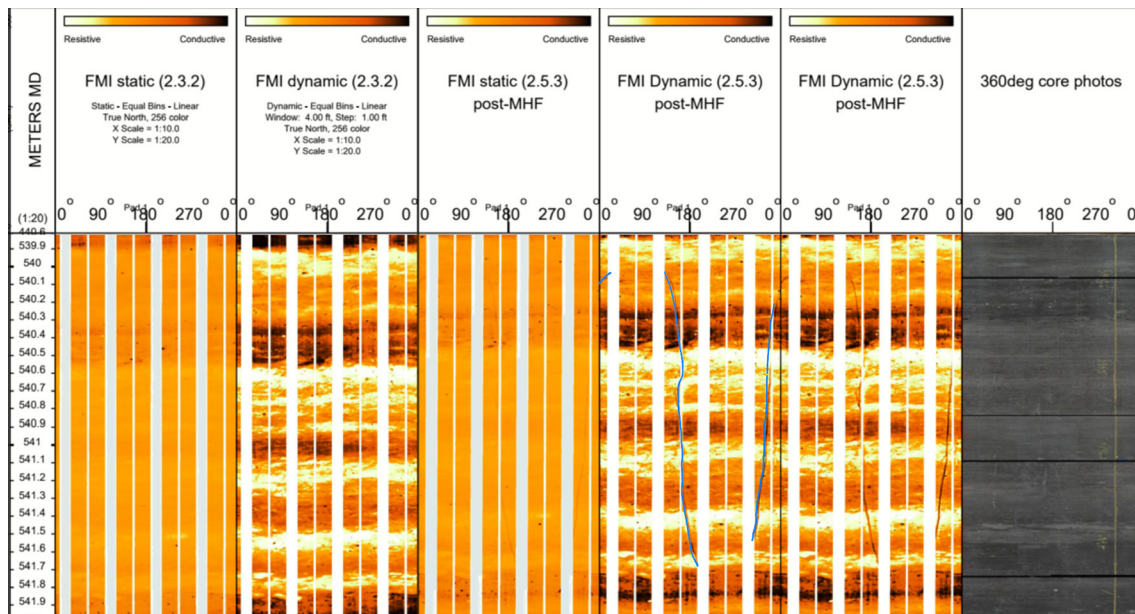


Fig. 3-3: Example of pre- and post-MHF imaging

Test example from the STA3-1 borehole performed at a centre depth of 541 m in the Schwarzbach Formation. All images are circumferentially unwrapped with true north as the reference. The tracks present, from left to right, the measured depth from the top of the borehole, the static resistivity image of the borehole prior to MHF, the dynamically normalised resistivity image prior to MHF, the static resistivity image after MHF, the dynamic resistivity image after MHF with the trace of the created fracture highlighted in blue, the same dynamic resistivity image without any highlight, and the core photograph. A new near-vertical bi-wing fracture can be identified on the dynamic post-MHF image. Note that the core photograph is shown in core depth and would need shifting down approx. 15 cm to align with FMI log depth.

3.1.3 Re-evaluation of the Benken MHF tests in the Opalinus Clay

An earlier stress measurement campaign was performed in the Benken borehole with a different toolstring and test protocol, and a first analysis was reported in Nagra (2001). Even though the equipment used was different (packers must be inflated to maximum pressure from the beginning of the test, fluid is injected from the surface), the same interpretation protocol as that used to interpret the tests of the TBO campaign was applied to reinterpret the two tests that were performed in the Opalinus Clay at a centre depth of 629 and 632 m.

The reconciliation plot for the test carried out at 632 m is presented in Fig. 3-4. Convergence is observed for the last three cycles, although the band between low and high estimates of the closure stress does not shrink.

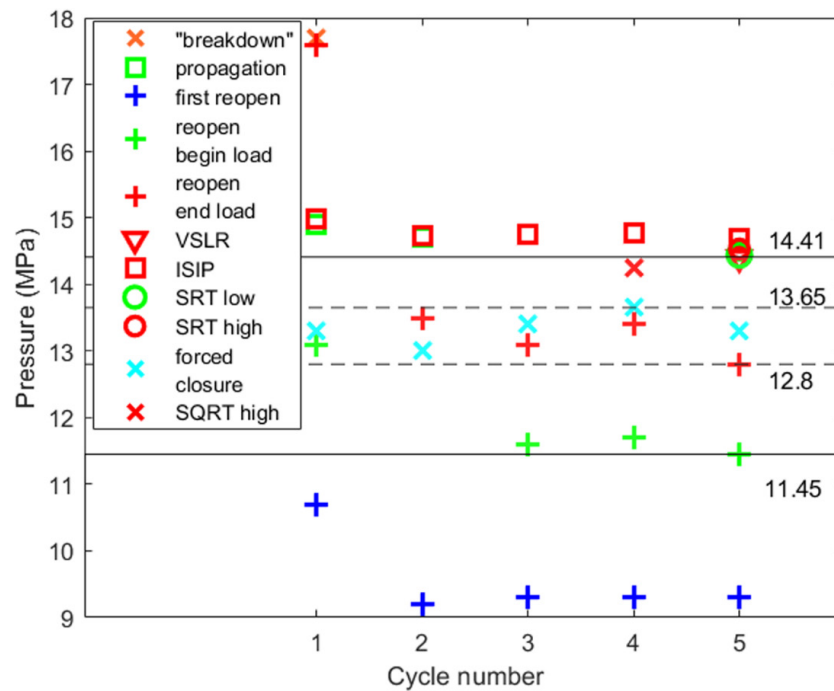


Fig. 3-4: Example reconciliation plot for a Benken MHF test

Performed in the Opalinus Clay at a centre depth of 632 m. Closure stress estimates are plotted as a function of cycle number. The narrow range for S_{hmin} magnitude is indicated by dashed black lines while the wide range is indicated by solid black lines. VSLR stands for very slow reopening, ISIP for instantaneous shut-in pressure, SRT for step-rate test and SQRT for square-root of shut-in time – all of which being estimates of the closure stress.

On the use of forced closure

Of particular interest are the flowback tests performed in the Benken borehole through a choke at the surface, enabling the measurement of flow from the fracture during flowback. It is thus possible to analyse these flowback tests as forced closure tests using the method proposed by Raaen & Brudy (2001) and Raaen et al. (2001) – highlighted in a recent paper by de Lesquen & Armand (2023). A specialised plot of the square root of the differential pressure across the choke versus flowback volume was used, and an example is presented in Fig. 3-5. For those tests, closure pressure estimates from these flowback tests were typically of a better quality than other closure pressure estimates because of the location of the pump at the surface. Consequently, they were given a high weighting for the estimation of the narrow range of S_{hmin} magnitude during the reinterpretation process. Nevertheless, these estimates were fully integrated into the reconciliation plot and treated as any other good quality estimate of the closure stress.

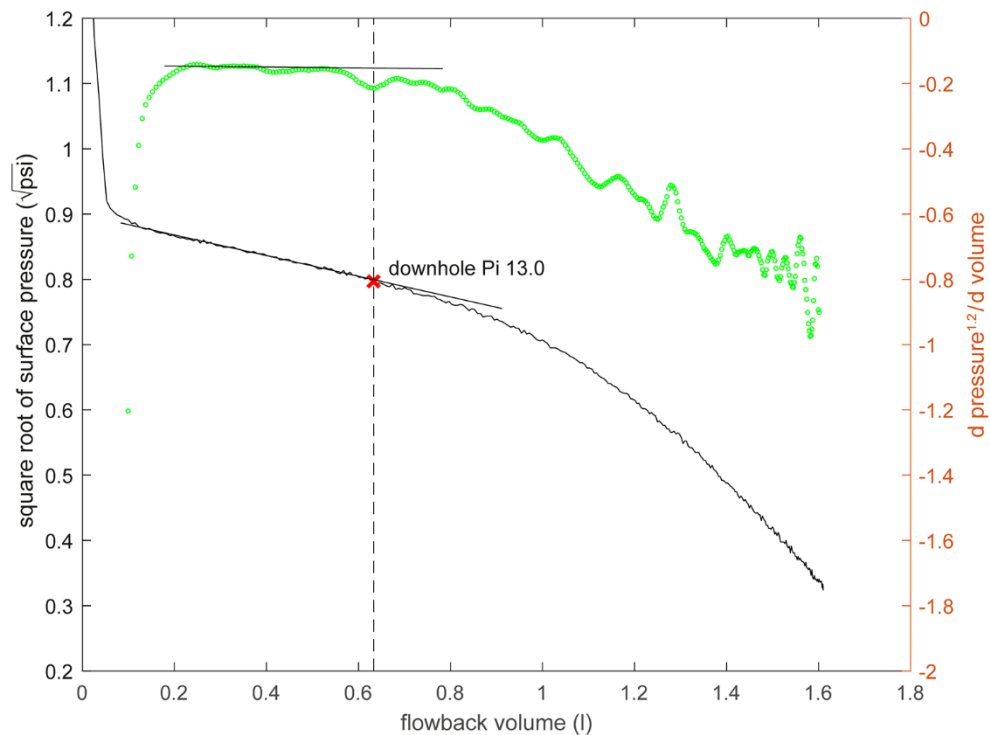


Fig. 3-5: Forced closure analysis of one MHF test cycle in the Benken borehole

Example from cycle 2 of the MHF test performed in Benken in the Opalinus Clay at a centre depth of 632 m (2nd cycle). The square root of the surface pressure (black line – left axis, also equal to the pressure across the choke) is plotted as a function of the flowback volume. The derivative of the square root of the pressure versus the flowback volume is also plotted on the same graph (green line). The point of first significant departure of the black curve from a linear behaviour is taken as the closure pressure and indicated with a red cross. The corresponding downhole interval pressure P_i is also reported.

Note that forced closure tests were also regularly performed during the TBO campaign with the use of a downhole choke, with varying degrees of success as the quality of the tests depends on the flowback rate, which could not be adjusted with the toolstring used during the TBO campaign. Although the flowback volume could not be measured, tests with a sufficiently low flowback rate can also be interpreted through a specialised plot of the square root of the differential pressure across the choke versus time, and an excellent example is presented in Fig. 3-6.

It is worth noting, however, that forced closure is only one estimate of the closure stress obtained from an open fracture to a closed fracture (see Section 0), which needs to be compared with all other estimates. The reconciliation plot for the test used to illustrate a forced closure test in Fig. 3-6 is presented in Fig. 3-7. Observing the behaviour from one cycle to the next illustrates that even good quality forced closure estimates cannot be taken in isolation to determine the closure stress. Furthermore, the zoom on the last cycle shows that, in this case, the forced closure estimate is a lower bound for the closure stress.

In other words, the TBO data demonstrate that forced closure cannot be construed as the lead method for reliably estimating closure stress even in close to impermeable formations. It is a positive addition to other estimation methods and needs to be integrated with all other estimates acquired during a test.

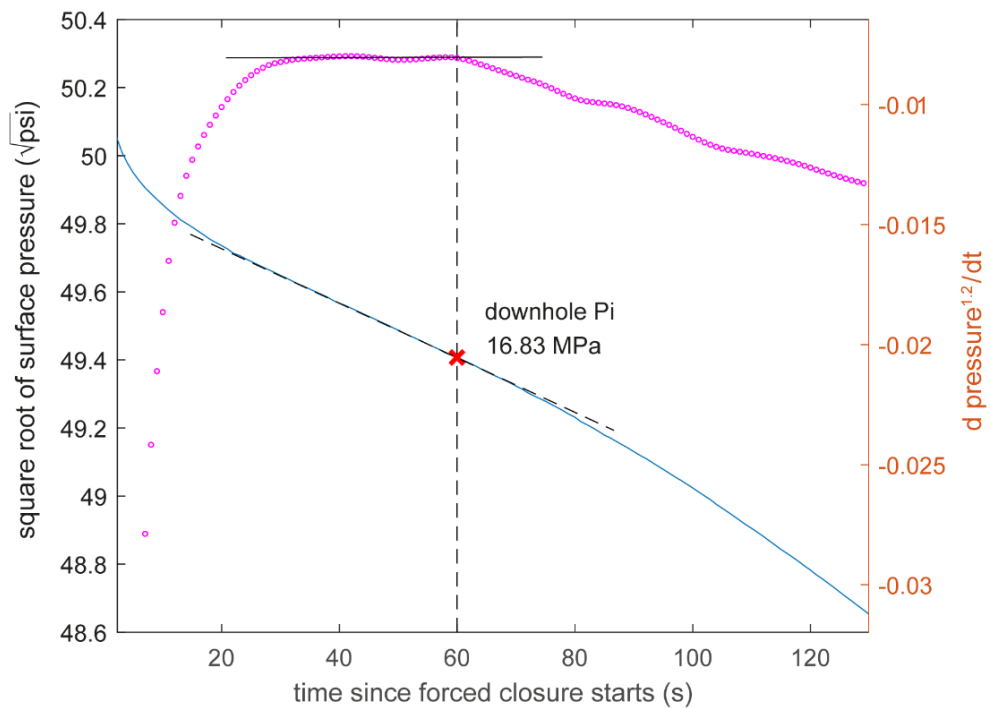


Fig. 3-6: Forced closure example analysis of one MHF test cycle from the TBO campaign

Example from cycle 5 of the MHF test performed in STA3-1 in the Klettgau Formation at a centre depth of 933.7 m (5th cycle). The square root of the differential pressure across the choke (blue line – left axis) is plotted as a function of the flowback time. The derivative of the square root of the pressure versus the flowback time is also plotted on the same graph (purple line). The point of first significant departure of the blue curve from a linear behaviour is taken as the closure pressure and indicated with a red cross. The corresponding downhole interval pressure P_i is also reported.

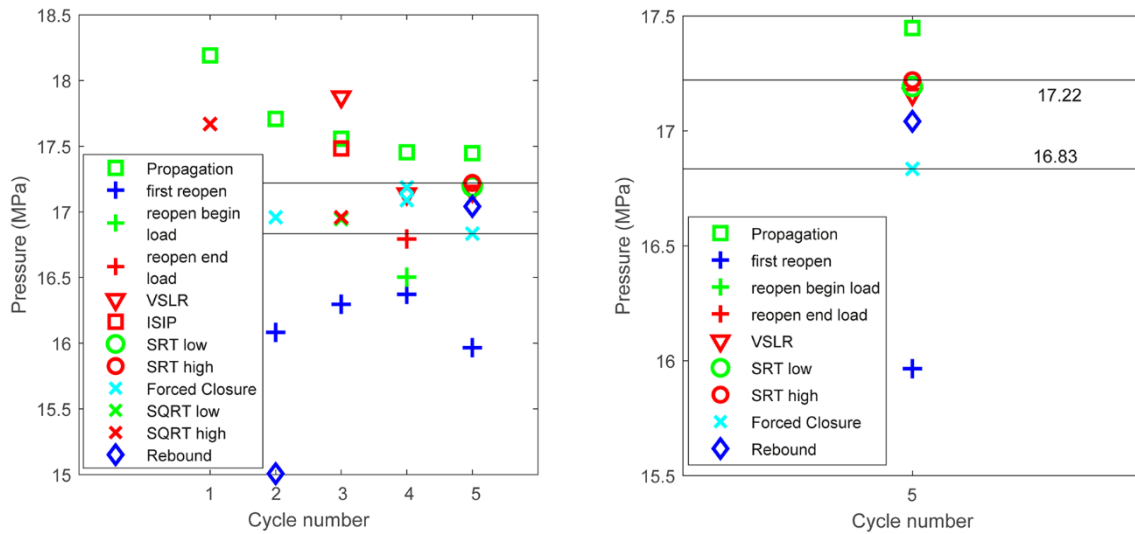


Fig. 3-7: Reconciliation plot for the MHF test in the Klettgau Formation at a centre depth of 933.7 m in the STA3-1 borehole

The complete reconciliation plot is presented in the left panel. It is worth noting that the forced closure estimates (cyan crosses) do fluctuate from cycle to cycle. A high and a low estimate were determined for the 4th cycle. A zoom on the 5th cycle is presented in the right panel. Compared with all other estimates, the forced closure estimate clearly provides a lower bound for the closure stress.

3.2 Sleeve reopening (SR) to estimate S_{Hmax} magnitudes

Once a large bi-wing hydraulic fracture has been created to estimate the magnitude of S_{hmin} , the S_{Hmax} magnitude can be estimated by an SR test (Wileveau et al. 2007). During such a test, a packer is placed in front of the created fracture and pressure is gradually increased until the previously created fracture is reopened.

Because the pressure is applied via the packer membrane, no fluid is injected into the fracture. The pressure at which the fracture reopens senses the concentration of stresses at the borehole wall. When the fracture reopens, the stiffness of the borehole/fracture system changes (the system becomes less stiff as soon as the fracture starts to reopen). Such a change in stiffness can be detected on a plot of packer pressure versus injected volume. Fig. 3-8 provides an example from an SR test in the Opalinus Clay in the MAR1-1 borehole where both the pressure inside the packer and the pressure derivative are plotted as a function of the volume injected in the packer.

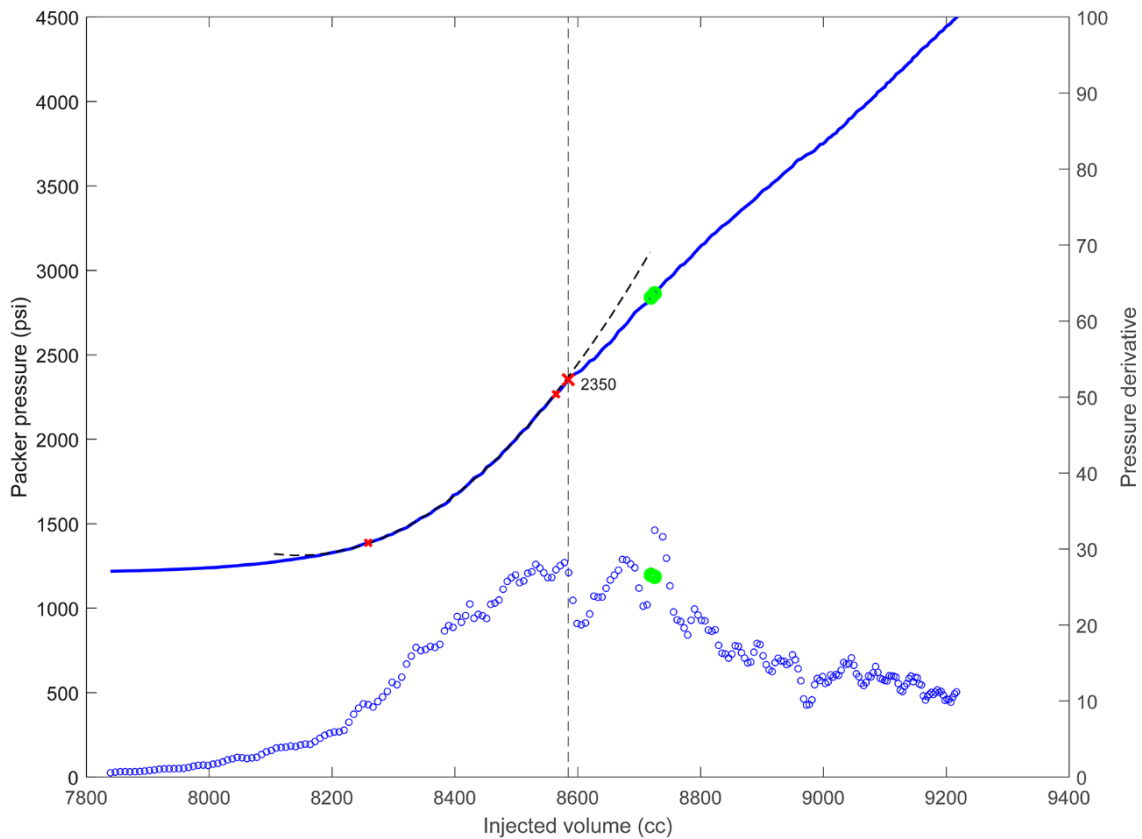


Fig. 3-8: Example of a Sleeve Reopening (SR) test

Test performed after the MHF test in the MAR1-1 borehole at a centre depth of 662 m in the Opalinus Clay. The absolute pressure in the packer (solid blue curve, left axis) is plotted against volume injected in the packer system. The blue circles display the derivative of pressure versus injected volume (right axis). The two small red crosses indicate the segment of data used to compute a parabolic fit that is plotted as a dashed black line. The point of first departure from that fit also corresponds to a break in the derivative indicated by a vertical black dashed line. The pressure at that point, indicated by a large red cross, corresponds to the pressure at which the fracture created by the MHF is reopened. The green dots correspond to the point where the pump switches direction, which sometimes leads to a strong signal on the pressure behaviour: they are plotted to discriminate against false positives.

Because of the packer construction, the pressure versus volume behaviour without a fracture can be locally fitted by a parabola. Such a parabolic fit is plotted as a dashed black line in Fig. 3-8. Opening of the fracture creates a clear softening departure from this behaviour, which can be seen both as a departure of the pressure from the parabolic fit, and as a break on the pressure derivative (both reported in Fig. 3-8). Those indicate the packer pressure at which the fracture reopens, or sleeve reopening pressure (2,350 psi – 16.2 MPa for the example test in Fig. 3-8).

Quality control checks ensure that the softening behaviour can be solely attributed to the reopening of a fracture and not, for example, to artifacts coming from the piston pump used to inflate the packer or from the packer itself.

Once the sleeve reopening pressure P_{SR} has been selected, the test can be interpreted with the help of a plane strain model of a reopening fracture extending from a borehole (Atkinson & Thiercelin 1995). If the fracture extension into the formation is large enough (larger than 10 times the borehole radius, which will be the case after a full MHF test), the borehole pressure at which the fracture starts to reopen (P_{SR}) recovers the stress concentration at the borehole wall (Kirsch 1898), with an added effect of the fluid pressure in the fracture P_f :

$$P_{SR} = 3S_{hmin} - S_{Hmax} - P_f.$$

Because of the difference between the test situation and the model hypotheses, a series of corrections are applied to the sleeve reopening pressure P_{SR} . First, the effect of the membrane stiffness (also known as ballooning) is corrected for. Second, as the model assumes a plane strain situation, the sleeve reopening pressure estimated from the test is reduced by a geometric factor that considers the packer length / packer diameter ratio, to compensate for the fact that the packer length is not infinite and the situation thus not fully plane strain (Elkhoury et al. 2021).

A check of the validity of the model is also performed by checking on post-MHF images that the fracture tested by the MHF test is close to vertical and that the two wings are close to 180 degrees apart. Tests where the created fracture did not satisfy these criteria were removed.

The range of S_{hmin} magnitude considered for this computation is the narrow range determined from the MHF test analysis. That range was carefully determined with that particular use in mind to represent the most likely range of S_{hmin} magnitude. The value of P_{SR} is estimated from the SR test after the corrections mentioned above. The value of the pressure in the fracture at the time of the sleeve reopening test P_f is, however, unknown, but can be bracketed. Because the formations encountered in the TBO campaign are of low permeability, the lower bound for P_f is the hydrostatic pressure of the drilling mud in the borehole, whereas an upper bound can be extrapolated from the shut-in behaviour of the last MHF cycle. Applying the equation above for a range of P_f and S_{hmin} values results in a single range for the S_{Hmax} magnitudes.

For the example presented in Fig. 3-8, the range considered for the S_{hmin} magnitude is [12.93:13.43] MPa. The fluid pressure in the fracture was bracketed between [8.3:10.96] MPa. The range of the horizontal stress ratio S_{Hmax}/S_{hmin} as a function of S_{hmin} and P_f is presented in Fig. 3-9. For this particular example, the horizontal stress ratio ranges from 1 to 1.076.

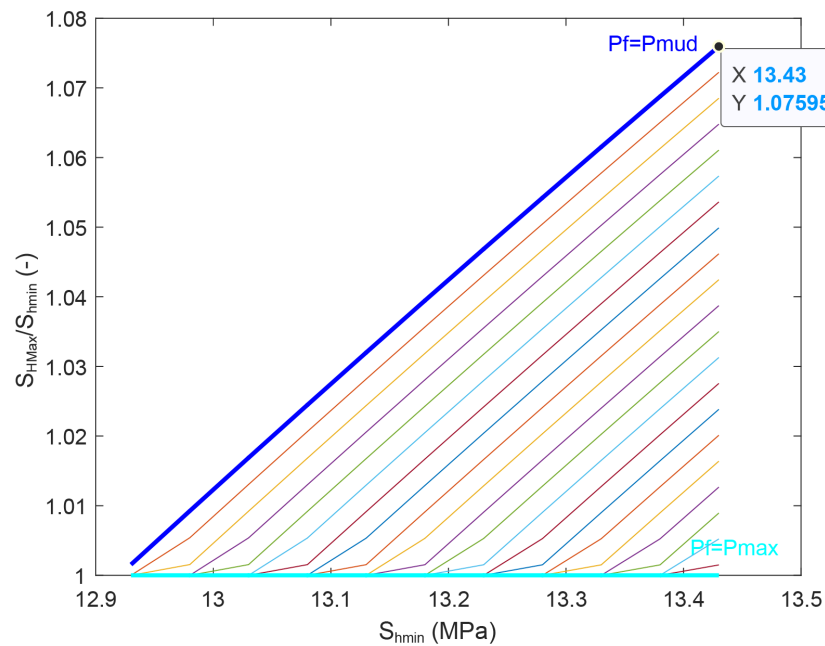


Fig. 3-9: Ratio of horizontal stresses determined from an SR test as a function of the range of the S_{Hmin} magnitude

SR performed after the MHF test in the MAR1-1 borehole at a centre depth of 662 m in the Opalinus Clay. The cyan line corresponds to the assumption that the pressure in the fracture during the test is equal to the maximum of the selected range, whereas the blue line corresponds to the assumption that the pressure in the fracture is equal to the borehole static mud pressure.

The details of the reopening pressure picked for each interpreted sleeve reopening test, as well as the range of fluid pressure in the fracture at the time of the test, are reported in App. D.

3.3 Determination of S_v

In some cases, even with the creation of a vertical pre-existing defect along the borehole wall, the MHF test will propagate a sub-horizontal fracture, usually by delaminating a bed boundary. Such tests usually result in a pressure record that indicates a radial-like fracture, exhibits quick convergence between cycles and results in a narrow closure stress range, all because of the absence of a stress concentration around the borehole acting on the fracture surface: regardless of the extent of the fracture, the stress acting normal to the fracture surface is the same.

On some occasions, the post-MHF imaging does show the presence of an enhanced horizontal feature. Such an example is presented in Fig. 3-10 for the MHF test carried out in the BOZ2-1 borehole at a centre depth of 417.8 m in the Passwang Formation.

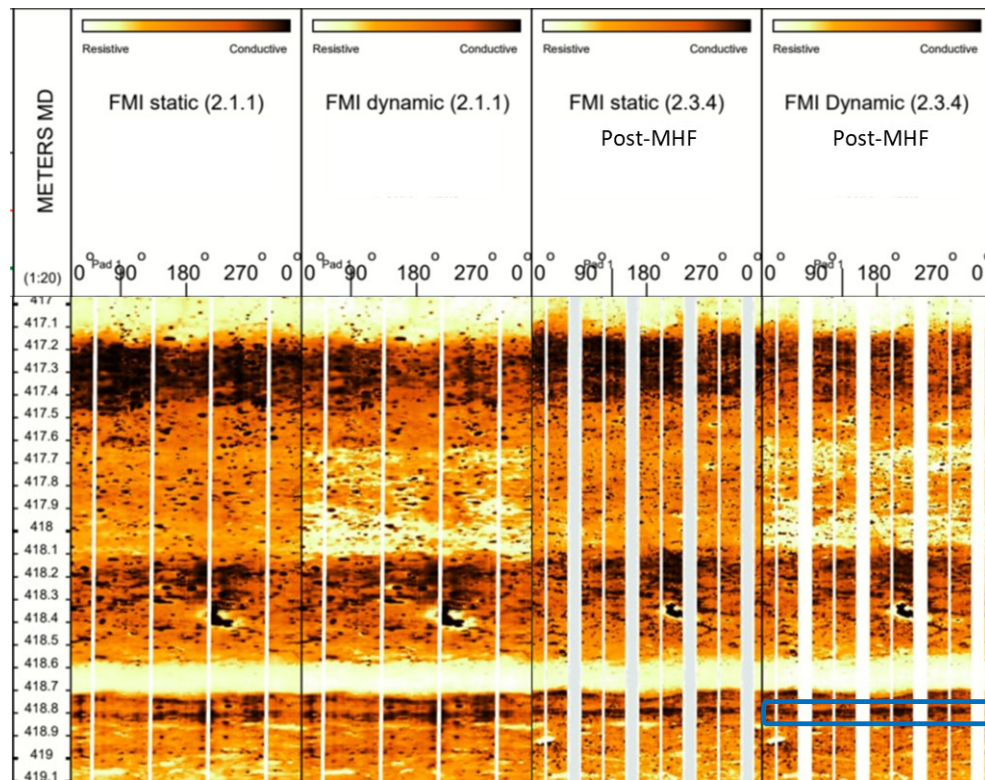


Fig. 3-10: Comparison of pre- and post-MHF imaging for the test performed at a centre depth of 417.8 m in the BOZ2-1 borehole

All images are circumferentially unwrapped with true north as the reference. The tracks present, from left to right, the measured depth from the top of the borehole, the static resistivity image of the borehole prior to MHF, the dynamically normalised resistivity image prior to MHF, the static resistivity image after MHF, the dynamic resistivity image after MHF. A horizontal enhanced feature can be seen on both post-MHF images and is highlighted by a blue box.

In the absence of any significant structural effect (such as the existence of stiff arches that might take some of the weight off), S_v is close to the weight of the overburden at that point - as calculated by integrating the density of the formation up to the surface. The range of closure stress estimated from such tests should thus encompass that value of the overburden. An example is presented in Fig. 3-11, comparing the closure stress ranges for the two MHF tests performed within 10 m in the Passwang Formation in the BOZ2-1 borehole. The computed overburden from integration of density clearly passes through the narrow range of closure stress for these two tests, validating that S_v was indeed measured by those MHF tests.

Finally, because of the protocol that was used to perform these series of MHF tests, i.e. the creation of vertical initial defects through sleeve fracturing prior to MHF tests, the measurement of the magnitude of S_v by an MHF test at a particular location indicates that the magnitude of S_{hmin} is at least equal to or larger than S_v .

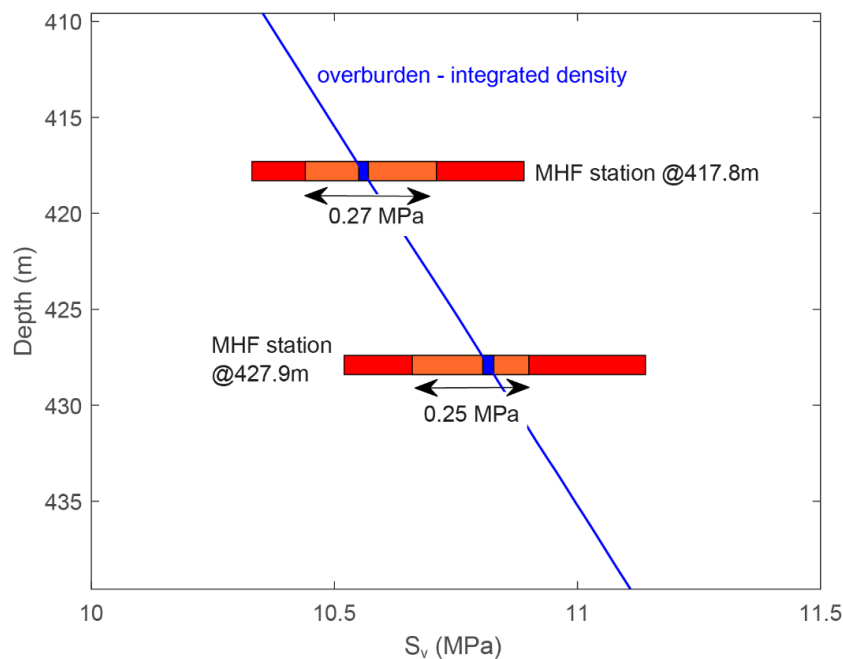


Fig. 3-11: Comparison between the overburden stress magnitude computed from the integration of density logs for the BOZ2-1 borehole with MHF measurements

Orange bars span the narrow range determined for the closure stress, whereas red bars span the wide range determined for the closure stress. The blue squares indicate the value of the integrated density at the depth of the MHF test.

3.4 Complementary stress estimates

3.4.1 Hydrofrac (HF) test

During the campaign of hydrological tests, a procedure similar to a minifrac test was performed in borehole BAC1-1B by pumping water from the surface into an interval isolated by a straddle-packer arrangement. Pressure in the interval was measured with a downhole gauge.

The length of the interval is much larger than that for MHF tests (12 m instead of 1 m), but the injection rate is only about twice that used for MHF tests (1 to 2 L/min instead of around 0.5 L/min).

Four cycles of injection / falloff / bleedoff were performed. A plot of the raw data versus time is presented in Fig. 3-12.

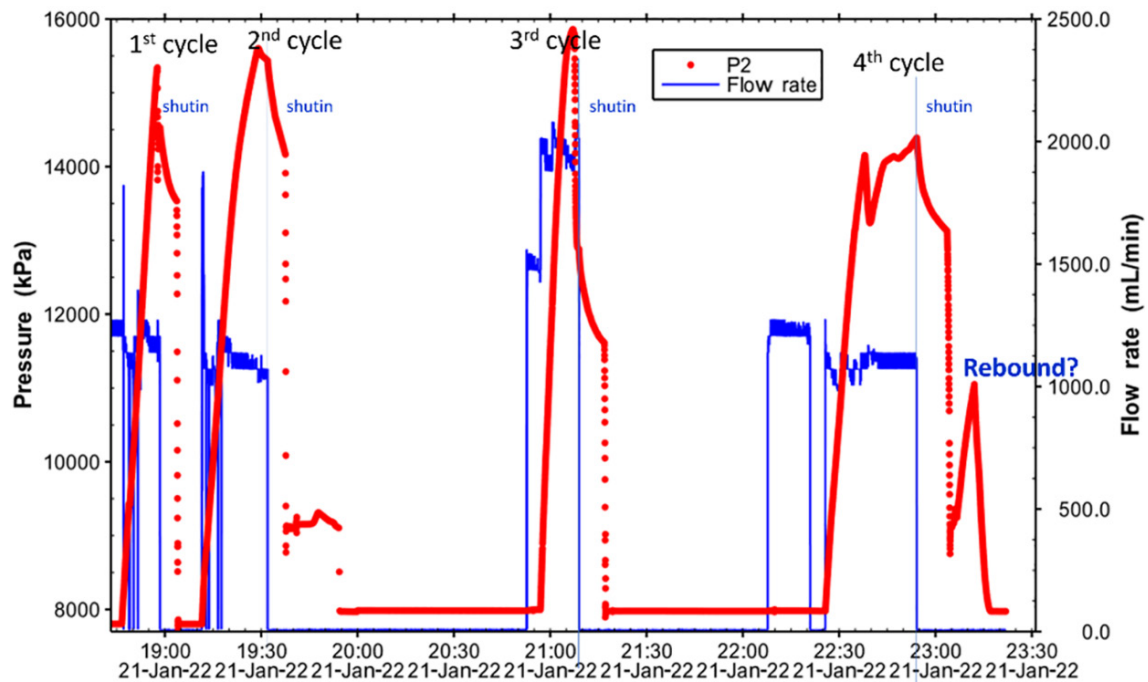


Fig. 3-12: Plot of hydrofrac test BDO4a raw data, performed in the BAC1-1B borehole

The test was performed at a centre depth of 804.5 m and spanned the «Murchinsonae-Oolith Formation» and the Opalinus Clay. The pressure in the interval is plotted in red (left axis) whereas the injection flow rate is plotted in blue (right axis).

A rebound after bleedoff is likely after the fourth cycle, confirming that a fracture was indeed created. The post-test images indicate that a new bi-wing slightly inclined fracture was created at the borehole wall, extending from 798.5 m to 800.5 m in the «Murchinsonae-Oolith Formation». Furthermore, the behaviour of the fourth cycle, with a breakdown-like type of initiation, is congruent with the presence of an inclined fracture at the borehole wall.

Each cycle can be analysed by applying the same technique as for an MHF test. The result of this analysis is reported as a reconciliation plot in Fig. 3-13. It is likely that the fracture did not close during the falloffs of the first two cycles, hence no closure estimate was reported for these cycles. No convergence between subsequent cycles was achieved (stress indicators for the fourth cycle are all larger than those for the third cycle).

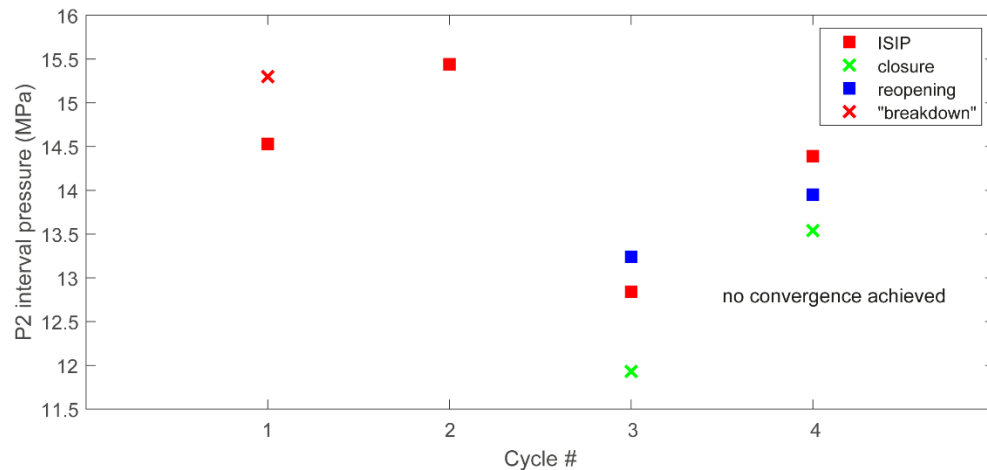


Fig. 3-13: Reconciliation plot for the hydrofrac test performed in the BAC1-1B borehole

Closure stress estimates are plotted as a function of cycle number. No convergence of these indicators was achieved so that no estimate for the closure stress was determined. ISIP stands for instantaneous shut-in pressure. Example from section 2B, 797 – 812 m.

A range for closure stress of [13.54:14.95] MPa could be determined from the last cycle (that extending furthest into the formation and thus most likely to represent the far-field stress), with the closure pressure as the lowest bound and the ISIP as the highest bound. However, because of that lack of convergence, it cannot be assigned for certain to a far-field stress value.

The corresponding closure stress gradient range of [16.9:18.7] MPa/km is comparable to, although much wider than, the S_{hmin} gradient range of [17.45:18.28] MPa/km estimated from the MHF test performed across the boundary between the «Murchinsonae-Oolith Formation» and the Wedelsandstein Formation in STA2-1 at a centre depth of 787.05 m.

The hydrofrac test results are thus congruent with MHF results.

3.4.2 Gas threshold pressure tests (GTPT)

A series of GTPT tests were performed in the TBO boreholes in the Opalinus Clay (Nagra 2024a). During such tests, an interval containing an inclined pre-existing natural discontinuity is isolated with a straddle-packer arrangement and gas is injected into the interval until localisation of the flow is observed. An example of the raw pressure record of such a test is presented in Fig. 3-14, where two injection cycles showing localised flow (as in a fracture) were performed (labelled GRi2 and GRi3), each followed by a shut-in cycle (labelled GRiS2 and GRiS3). Because the viscosity of gas is very low, the pressure immediately after injection is stopped (ISIP, instantaneous shut-in pressure) is a likely estimate of the closure stress acting on the discontinuity in which the gas is mostly flowing.

There are two competing phenomena that influence the estimation of stress magnitudes from GTPT tests. The first is that it is likely that the gas percolates into the pre-existing inclined feature, for which closure stress is a combination of all three principal stresses and contains a vertical component. Thus, the closure stress magnitude is larger than that of the minimum principal stress (MHF tests indicated that S_{hmin} is the minimum stress at those depths, and the magnitude of S_v is thus higher than that of S_{hmin}). The behaviour during the shut-in phase could only be driven by the minimum principal stress if there was a population of small vertical discontinuities normal to the minimum principal stress through which gas would preferably leak into the formation. However, such discontinuities have not been observed in the Opalinus Clay.

The second is that, because of the very low viscosity of the injected fluid and the nature of the pre-existing discontinuity, flow can localise by partially opening the discontinuity, thus creating a hydraulic aperture, at a pressure much lower than that required to fully separate the fracture walls, and therefore at a pressure that is lower than the stress acting normal to that discontinuity. Normal stress can still be transmitted via local asperities of the discontinuity, resulting in ISIP values that are smaller than the closure stress. Note that this effect, although well reported in the literature (Tsang & Witherspoon 1981, Barton et al. 1985), remains extremely difficult to quantify. It is, however, akin to laboratory studies on the self-sealing capability of the Opalinus Clay that show that a minimum effective closure stress of 2 – 3 MPa is required for robust sealing to take place (Nagra 2024c). Translated into stress estimation parlance, the closure stress estimated from a GTPT test could be 2 – 3 MPa lower than the actual closure stress.

For both reasons, the ISIP values from the GTPT tests that are used as a proxy for the fracture closure pressure might not be reliable estimates of the S_{hmin} magnitudes in the Opalinus Clay. Nevertheless, these will be discussed in Section 3.7 (subsection 3.7.3), where stress magnitudes in the Opalinus Clay Formation are detailed.

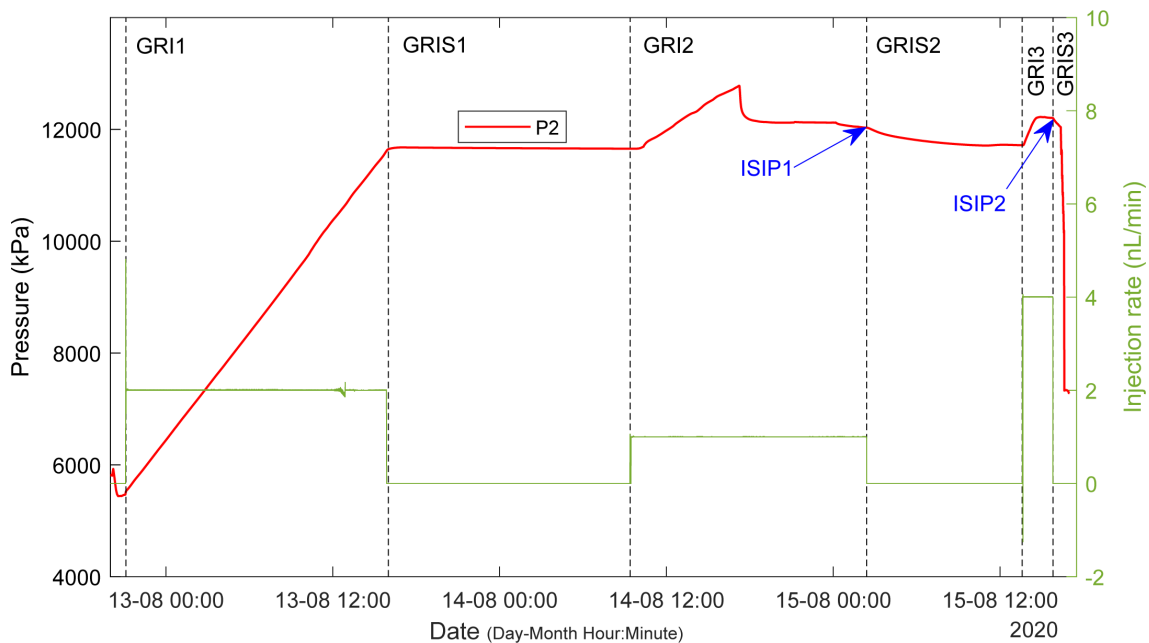


Fig. 3-14: Pressure record of a GTPT test performed in the Opalinus Clay in the BOZ1-1 borehole (BOZ1-1-OPA4)

The pressure in the interval P2 is plotted versus time in red (left axis). The gas injection rate is also plotted versus time (green, right axis). The pressure at the end of injection periods 2 and 3, ISIP1 and ISIP2, are highlighted with blue arrows. Adapted from Nagra (2024a).

3.5 Test statistics

The first goal of the test programme was to provide a description of the state of stress in the Opalinus Clay and in the neighbouring layers (directly above and below). The second goal was to estimate the in-situ stress field along the entire lithological column, from the Malm formations to the basement. The final goal was to develop an understanding of the mechanisms driving the state of stress and stress differences between layers.

To fulfil these goals, open-hole MHF and SR tests were performed in the 8 vertical TBO boreholes with a wireline-conveyed formation tester (SLB's Modular Dynamic Formation Tester – MDT). 139 successful MHF stations were performed, insofar as a fracture was hydraulically extended into the formation, from which estimates for the closure stress could be determined. Estimates of the magnitude of S_{hmin} , S_v and S_{Hmax} were then derived through further interpretation (see Section 3.6). Note that the term “station” corresponds to a particular depth at which one or several MHF tests were performed, all of which were considered together for interpretation of the state of stress at that depth.

Experience quickly showed that the difference in mechanical stiffness was a key factor to the magnitude of S_{hmin} , as there are large contrasts in mechanical stiffness both between formations (e.g. «Felsenkalk» + «Massenkalk» or Villigen Formation are stiffer than the Schinznach Formation or the Opalinus Clay) and within formations (e.g. Bänkerjoch and Zeglingen Formations, with evaporite series mixed with more clay-rich facies). An effort was thus made to sample not only all formations – with a stronger focus on Dogger and Lias formations – but also sample the variability in formation stiffness.

The two end points of the lithological column of interest, the «Felsenkalk» + «Massenkalk» mostly consisting of massive limestone, and the basement (Permo-Carboniferous), were also tested to possibly provide an understanding of their effects on the overall state of stress.

In order to best adapt the location of test points to achieve optimum coverage and sampling both within each borehole, at each siting region and across the three siting regions, while keeping the number of tests under control, an iterative selection process for the depth of the MHF tests was devised, spanning the planning phase (with a priori information), the wellsite planning phase (depending on borehole conditions and open-hole data) and the adjustment of the test procedure in real time. For more details, the reader is referred to (Desroches et al. 2021, Desroches et al. 2023). Operational constraints such as borehole shape, presence of fractures in the interval, and homogeneity of the tested interval were incorporated to determine the location of MHF tests that would maximise the outcome of obtaining a successful test.

Tab. 3-1 presents the number of successful tests per formation grouped by siting region. Note that the number of S_{hmin} and S_{Hmax} magnitude estimates are less than the number of successful stations, the difference coming from tests that measured the overburden, tests of pre-existing natural fractures and some poorer-quality stations that are not worth considering because of the wealth of good MHF tests.

Note that the lithological column at the JO siting region is much shallower than at the other siting regions. In particular, the «Felsenkalk» + «Massenkalk» and the Schwarzbach Formation are not exposed there.

Tab. 3-1: Number of successful tests per formation and per siting region from the TBO campaign

Note the different formation and member names in the Dogger for JO and NL/ZNO siting regions. Two stations in the Opalinus Clay from a former campaign performed in the Benken borehole have also been reinterpreted. N/A: Not applicable.

Group	Formation (JO)	JO	NL	ZNO	Formation (NL/ZNO)
Cenozoic					
Malm	«Felsenkalke» + «Massenkalk»	N/A	5	3	«Felsenkalke» + «Massenkalk»
	Schwarzbach	N/A	5	3	Schwarzbach
	Villigen	-	1	3	Villigen
	Wildeggen	6	3	2	Wildeggen
Dogger	Ifenthal	1	-	-	Wutach / Variansm.
			3	N/A	«Herrenwis Unit»
	Klingnau	-	2	2	«Park.-Württ.-Sch.»
	Hauptrogenstein	5			
	Passwang	3	-	-	«Humphriesiololith»
			2	2	Wedelsandstein
			-	-	«Murch.-Oolith»
	Opalinus Clay	9	8	10 (+2) ¹	Opalinus Clay
Lias	Staffelegg	3	4	2	Staffelegg
Keuper	Klettgau	2	5	2	Klettgau
	Bänkerjoch	2	9	3	Bänkerjoch
Muschelkalk	Schinznach	3	2	2	Schinznach
	Zeglingen	2	5	-	Zeglingen
	Kaiseraugst	1	1	-	Kaiseraugst
Buntsandstein	Dinkelberg	1	2	1	Dinkelberg
Rotliegend (Permo-Carboniferous)	Weitenau	-	9	-	Weitenau
	TOTAL	38	66	35	139

¹ On top of the 10 MHF tests performed in the Opalinus Clay in the ZNO boreholes, another 2 MHF tests previously performed in the Benken borehole were re-interpreted.

There is complete coverage of all main units, especially the Opalinus Clay and the bounding formations, as well as formations that the potential access to a repository will traverse.

The coverage for the NL siting region is more detailed, especially for the upper (Malm) and lower (Keuper and further down to and including the basement) parts of the lithological column. Understanding from measurements at NL is likely transferable to the other siting regions through geo-mechanical-numerical modelling.

Throughout the test selection process, the tension between selecting stations in the same formation / facies for certainty and testing different formations to increase coverage was always present, with a focus on multiple points in the Opalinus Clay but typically favouring increased coverage for other formations. Sampling of the variability between different borehole locations, i.e. testing the same formation / facies combination at different siting regions, was also carefully considered as the testing programme unfolded.

A detailed table with per borehole statistics of tests per formation and per mechanical facies can be found in App. B (in digital format). It shows the variation / evolution of the number of planned tests (at the planning and wellsite phase), the number of successful tests and the number of estimates of S_{hmin} magnitude interpreted from those tests. More stations need to be planned than the desired number of S_{hmin} magnitude estimates, as there is no a priori guarantee first that there will be a suitable test location in the desired formation / facies, and second that a particular test location will yield an interpretable test. Note that both the selection process and the test protocol significantly improved throughout the TBO campaign, increasing the testing success rates. Tests of particular importance for the anchoring of the in-situ stress field are highlighted in green. The absence of tests in formation / facies is also highlighted, with a colour-coding indicating the consequences for the completeness of the coverage.

Tab. 3-1 also highlights borehole sections where no test was possible, either because drilling stopped before reaching the basement, because of bad hole conditions or because of the tool becoming stuck. These are particularly noticeable for JO (no tests from Keuper down to basement in borehole BOZ2-1) and ZNO (no tests from Keuper down to basement for borehole MAR1-1). These results highlight the requirement for at least two boreholes per siting region – and the advantage of having even more (as for NL), as later boreholes can be used to acquire missing data points (as was the case for BAC1-1: important data were acquired to strongly improve / complete the coverage – as highlighted in green).

As a final note, it should be emphasised that having an estimate of the magnitude of S_{hmin} in each and every formation / facies is not a requirement for providing a reliable description of the overall state of stress over the entire lithological column – nor has it ever been a goal of the TBO programme. Good quality stress estimates coupled with good descriptions of the mechanical properties and the 3D structure are the key deliverable that then allows prediction of the state of stress throughout the siting regions via geomechanical-numerical modelling.

3.6 Stress magnitude data from individual MHF and SR tests

The number of successful stations vs. that of attempted stations, as well as the number of resulting estimates for S_{hmin} , S_V and S_{Hmax} magnitudes are presented for each borehole in Tab. 3-2.

Tab. 3-2: Number of estimates of S_{hmin} , S_V and S_{Hmax} magnitudes per TBO borehole

$S_{hmin}?$ indicates tests for which the result of the test cannot be assigned to S_{hmin} with certainty.
 $S_{Hmax}?$ indicates tests that result from $S_{hmin}?$ tests and thus cannot be assigned to S_{Hmax} with certainty. See also App. B for a more detailed test overview.

Siting region	Borehole	Attempted stations	Successful stations	S_{hmin}	$S_{hmin}?$	S_V	S_{Hmax}	$S_{Hmax}?$
NL	BAC1-1	13	12	11	1	1	5	0
JO	BOZ1-1	31	26	21	0	1	13	0
JO	BOZ2-1	18	12	9	0	2	6	0
NL	BUL1-1	19	13	9	0	0	9	0
ZNO	MAR1-1	13	13	11	2	0	6	1
NL	STA2-1	22	19	19	0	0	6	0
NL	STA3-1	22	22	22	0	0	11	0
ZNO	TRU1-1	28	22	19	2	0	9	0
Total		166	139	121	5	4	65	1

In App. B (digitally attached Excel files, one per siting region), the data for each individual station deemed to be successful are presented for each borehole: station depth (centre of the test interval), formation tested, interpreted closure stress bounds (lowest bound and highest bound defining the wide range, lower bound and upper bound defining the narrow range), and stress assignment of the closure stress (poor quality, S_{hmin} , $S_{hmin}?$, S_V , HTPF). The width of the narrow range, i.e. the difference between the upper and the lower bound of the closure stress, is also presented as it provides an estimate of the quality of the station (the narrower the band, the better the quality): less than 0.5 MPa is considered an excellent station, whereas greater than 1.5 MPa is considered a mediocre station.

In the cases where the closure stress was deemed representative of S_{hmin} , comments on the post-MHF imaging comparison with the pre-MHF imaging are also presented to explain why some SR tests were not interpreted, namely when the trace of the created fracture at the borehole wall is not subvertical, bi-wing and 180 degrees apart. If all conditions for SR interpretation are met (geometry of the fracture at the borehole wall and detection of a definite sleeve reopening signal), a range for S_{Hmax} (bounded by minimum and maximum likely values) is also presented, with the corresponding ratios of S_{Hmax} / S_{hmin} compared to S_{hmin} . It is worth noting that, because the conditions for interpretation of SR tests are more restrictive than those for the interpretation of MHF tests, there are less S_{Hmax} values than S_{hmin} values overall.

The closure stress ranges determined from the re-interpretation of the Benken tests were assigned to S_{hmin} and added to the TBO series of stress estimates for the ZNO siting region.

Variations of S_{hmin}

In Fig. 3-15, the gradients of the wide range of S_{hmin} magnitude are presented per formation and per siting region on a single figure, so that a comparison can be made even if the depth of the formation varies in different boreholes and siting regions. The name of the formation is shown on the right-hand side of the figure, and the stress ranges are colour-coded per siting region. There is no absolute depth reference in the figure: the gradient ranges are presented with increasing distance from the top of the formation.

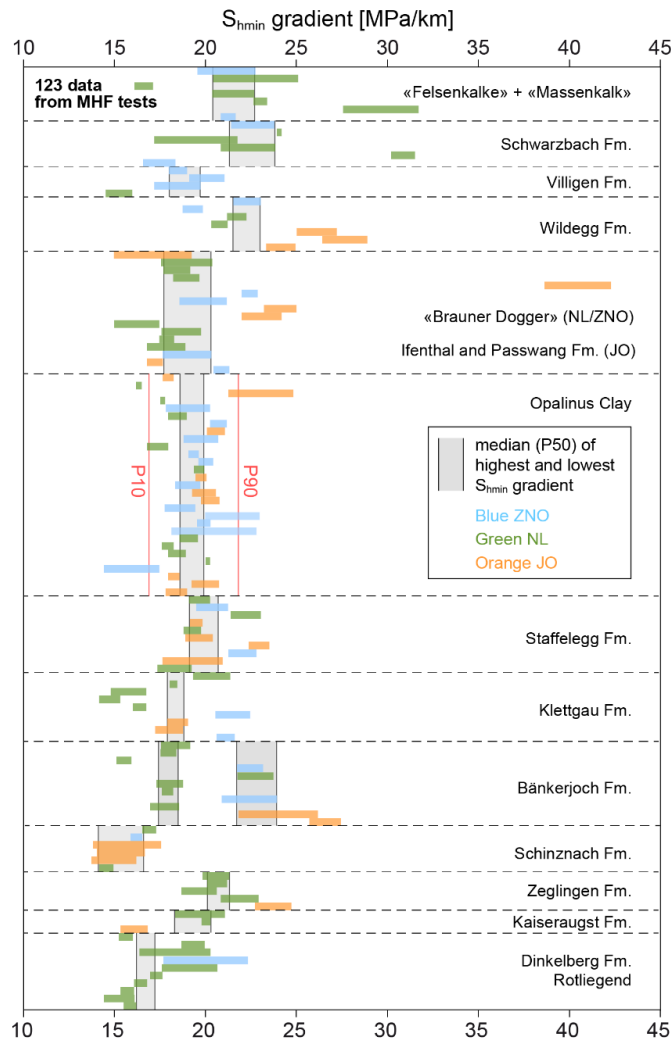


Fig. 3-15: Overview of S_{hmin} gradients for each lithology

Note that the vertical scale is not a depth scale, but only the succession of stratigraphic units with depth. «Brauner Dogger» groups all Dogger formations in NL & ZNO apart from Opalinus Clay. Within each formation the data are ordered by their distance from the top of the formation. Horizontal bars show the range of S_{hmin} gradients computed from the wide range of the S_{hmin} magnitudes; bounds of the vertical grey bars show the median (P50) of the lowest and highest bound (wide range) of the S_{hmin} gradients for each lithology. For the Opalinus Clay, the P10 of the lowest bound and the P90 of the highest bound of the mean S_{hmin} gradients are plotted as red vertical lines (see Section 3.7.1 for further details). Note that, for the Bänkerjoch Formation, two lowest and highest bounds of the S_{hmin} gradient were estimated. This is to take into consideration the bimodal nature of the data because of the alternating bands of stiff and weaker layers.

For the Schinznach Formation, S_{hmin} gradients appear to be quite homogeneous within and across siting regions. For other formations there is stronger variability, but it appears that this variability is mostly independent of the siting region.

Investigations in the Bänkerjoch Formation showed that variations of S_{hmin} gradients are highly correlated with the amount of anhydrite in the tested interval, and therefore the stiffness of the tested formation (the higher the anhydrite content, the greater the stiffness and the higher the S_{hmin} gradient).

This is in agreement with the prediction of horizontal stress in an infinite stack of porous horizontal layers with different elastic properties, submitted to gravity loading and horizontal strain along the orientation of S_{hmin} and S_{Hmax} , respectively ϵ_h and ϵ_H (Thiercelin & Plumb 1994):

$$S_{\text{hmin}} - \alpha P_p = \frac{\nu}{1-\nu} (S_v - \alpha P_p) + \frac{E}{1-\nu^2} \epsilon_h + \frac{\nu E}{1-\nu^2} \epsilon_H,$$

where α is Biot's poroelastic constant, P_p is the pore pressure, S_v is the vertical stress, E is the local Young's modulus of the formation and ν is the Poisson's ratio of the formation, all being functions of depth. This equation can be complexified at will to consider more complex rheology descriptions of the rock formations, but its simplest form is presented here to show the link between horizontal stress and formation stiffness: provided there is some compressive strain along the formations, the stiffer the formation (higher E), the larger is the magnitude of S_{hmin} .

Strong variations in the Malm can also be attributed to variations in stiffness associated with the local facies, with limestone sections being stiffer and claystone sections being softer. A graphical illustration of the process is presented in Fig. 3-16.

The case of the massive limestone in the «Felsenkalke» + «Massenkalk» appears to be different, as there is no clear local stiffness variation, whereas strong variations of S_{hmin} gradients are still present. Because the formation bears many discontinuities, it is proposed that the large-scale stiffness of the formation – which likely controls the state of stress and is likely affected by the density of these discontinuities over a large volume – is different from the local scale stiffness.

Finally, one JO point acquired in the Upper Dogger clearly stands out from all others, exhibiting the highest stress gradient of all (around 40 MPa/km). This station was shallow, in an area with strong topographic effects, both phenomena being known to yield high stress gradients. This point should thus not be seen as representative of the stress behaviour further down.

Because of its importance, variations within the Opalinus Clay will be detailed in Section 3.7, for both the minimum and the maximum horizontal stress estimates.

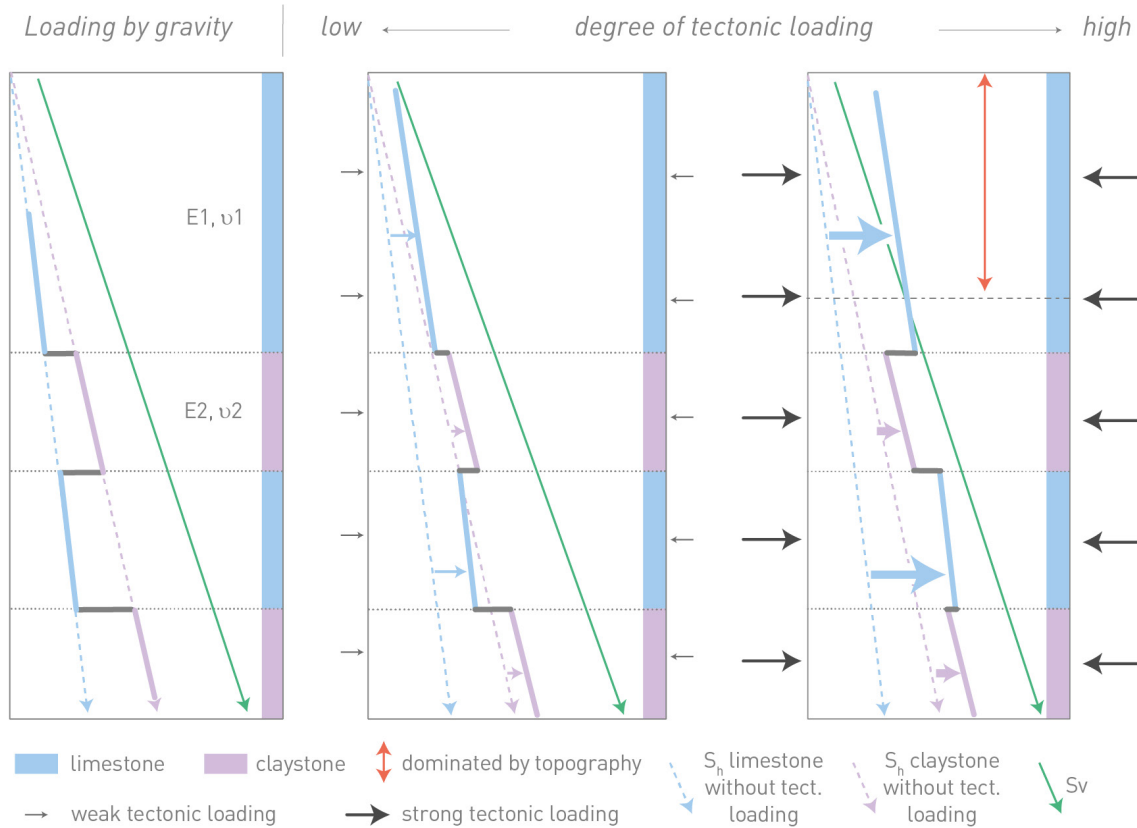


Fig. 3-16: Cartoon of the effect of tectonic loading on a limestone / claystone stratigraphic column on the magnitude of S_{hmin}

In the absence of tectonic loading, gravity loading only results in higher S_{hmin} magnitudes in the claystone than in the limestone because of higher Poisson's ratio ($\nu_2 > \nu_1$, left panel). Tectonic loading increases S_{hmin} preferentially in the limestone because of the higher Young's modulus ($E_1 > E_2$, middle panel). As tectonic loading increases (right panel), limestone close to the surface can exhibit S_{hmin} magnitudes that are higher than those of S_v .

Variations of S_{Hmax}

Stiffness also appears to be controlling the variation of S_{Hmax} magnitudes. In particular, larger S_{Hmax} gradients tend to correspond to stations with larger S_{hmin} gradients and vice versa.

To better visualise this effect, the ratio of horizontal stress magnitudes S_{Hmax}/S_{hmin} is presented as a function of the S_{hmin} gradient in Fig. 3-17 for all stations across all siting regions with an estimate of the S_{Hmax} magnitude. A global trend, regardless of siting region, is highlighted by a dashed black line and shows that a higher stress ratio (and thus a higher S_{Hmax} gradient) is associated with higher S_{hmin} gradients. There is a single outlier close to the top of BOZ2-1, which is already an outlier with respect to the magnitude of S_{hmin} as it has the highest S_{hmin} gradient of the entire TBO campaign. It is thus not entirely surprising that this point falls outside the general trend.

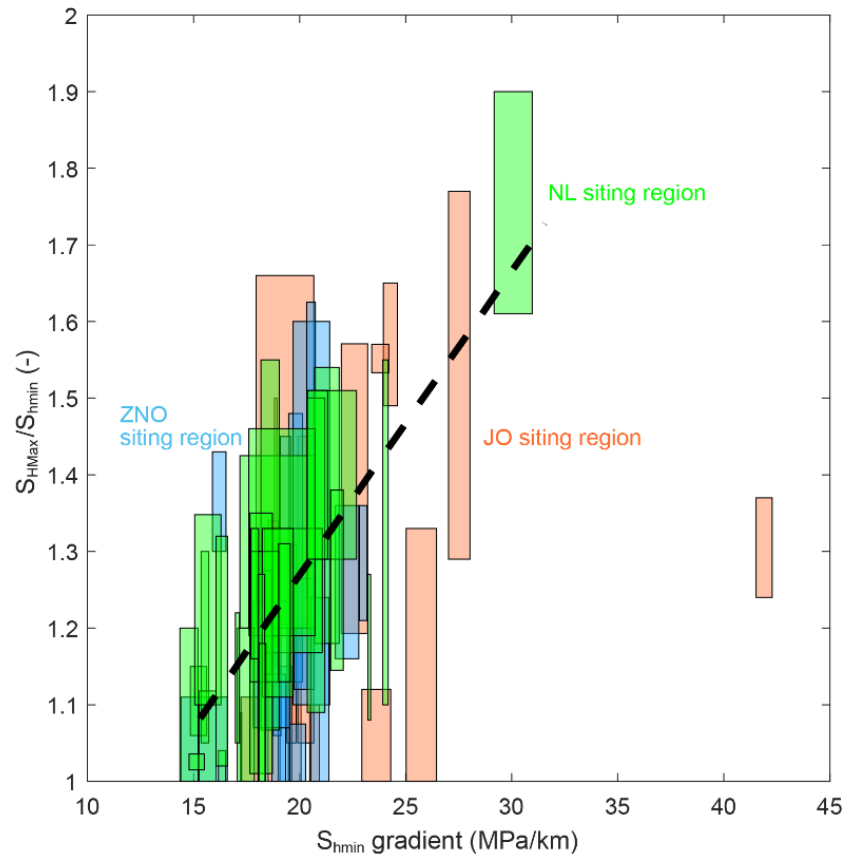


Fig. 3-17: Range of horizontal stress ratio versus range of S_{Hmin} gradients for all siting regions

The black dashed line indicates a rough correlation between the S_{Hmin} gradient and the horizontal stress ratio.

3.7 Stress magnitudes in the Opalinus Clay

3.7.1 Minimum horizontal stress S_{Hmin}

29 ranges for S_{Hmin} magnitude could be determined in the Opalinus Clay across all three siting regions. Both the narrow and the wide ranges are plotted against depth in Fig. 3-18. Additionally, the pore pressure corresponding to a freshwater column starting from the surface, as well as an average overburden stress across the siting regions in the Opalinus Clay, are also displayed. All estimates of S_{Hmin} magnitude across all siting regions are between the pore pressure and overburden stress limit.

Furthermore, to highlight that these estimates of S_{Hmin} magnitudes follow a common trend regardless of depth and siting region, the gradients of S_{Hmin} have been plotted against depth in Fig. 3-19. Four bounds were computed from the distribution of the wide S_{Hmin} magnitude range. The median of the gradient of the lowest and the highest bounds are plotted as a thin dashed black line (both in Fig. 3-18 and Fig. 3-19). The 10% probability value of the distribution (P10) of the lowest bound of the S_{Hmin} gradient for all Opalinus Clay tests is plotted as a thin black continuous line on both figures. It corresponds to the lowest value below which an estimate of S_{Hmin} magnitude would be considered as an outlier. The 90% probability value of the distribution (P90) of the highest bound of the S_{Hmin} gradient for all Opalinus Clay tests is also plotted as a thin black

continuous line on both figures. It corresponds to a maximum value above which an estimate of the magnitude of S_{hmin} would be considered an outlier. The complete cumulative probability distribution of the lowest and highest S_{hmin} gradients is presented in App. E, and the four bounds are indicated in Fig. E-1.

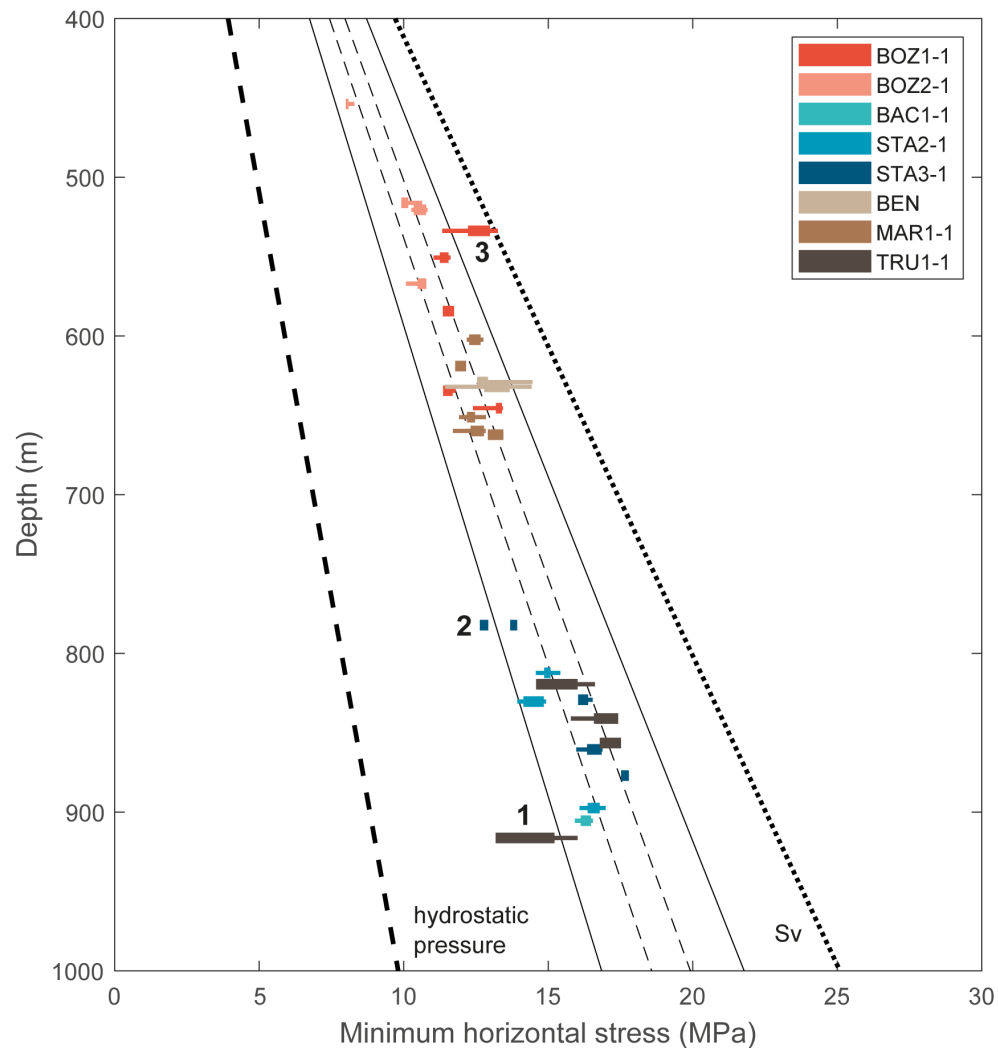


Fig. 3-18: Ranges of S_{hmin} magnitudes in the Opalinus Clay for all TBO boreholes and the Benken borehole as a function of depth

The narrow ranges for the magnitude of S_{hmin} are plotted as thick horizontal bars. The wide S_{hmin} magnitude ranges are plotted as thin horizontal lines – they do not appear when there is no difference between the wide range and the narrow range. Note that no MHF test was performed in the Opalinus Clay in the BUL1-1 borehole, so that it is not reported in this figure. The hydrostatic pressure corresponding to a freshwater column going all the way to the surface is plotted as a thick long-dashed black line. The average overburden stress across the Opalinus Clay is plotted as a thick short-dashed black line. The median of the distributions of the gradients of the lowest and highest S_{hmin} bounds (bounds that determine the wide S_{hmin} range) are plotted as thin black dashed lines. The P10 of the lowest bound and the P90 of the highest bound are plotted as thin black continuous lines. Data falling outside the P10 and P90 S_{hmin} gradients, labelled from 1 to 3, are considered outliers and are discussed further below.

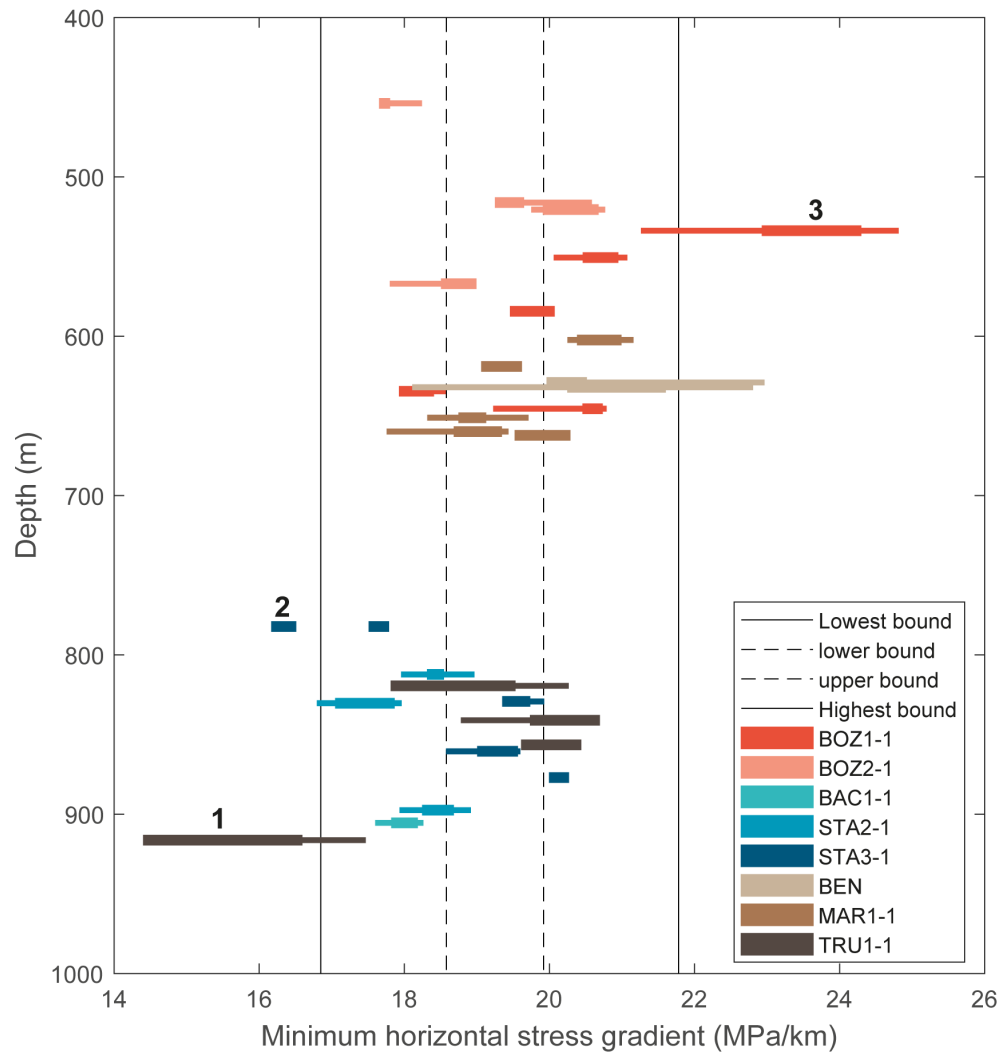


Fig. 3-19: Ranges for the S_{hmin} gradient in the Opalinus Clay for all TBO boreholes and the Benken borehole as a function of depth

The narrow S_{hmin} gradient ranges are plotted as thick horizontal bars. The wide S_{hmin} gradient ranges are plotted as a thin horizontal line – they do not appear when there is no difference between the wide range and the narrow range. Note that no MHF test was performed in the Opalinus Clay in the BUL1-1 borehole, so that it is not reported in this figure. The median of the distributions of the lowest and highest S_{hmin} bounds (bounds that determine the wide S_{hmin} range) are plotted as thin black dashed lines. The P10 of the lowest bound and the P90 of the highest bound are plotted as thin black continuous lines. Data falling outside the P10 and P90 S_{hmin} gradients, labelled from 1 to 3, are considered outliers and are discussed further below.

Three MHF points are outliers, insofar as the narrow range of S_{hmin} magnitude is outside the P10 – P90 range. They are labelled “1” to “3” on Fig. 3-18 and Fig. 3-19. Apart from these three points, which will be considered in detail further below, there is no clear distinction between siting regions or depth with respect to the S_{hmin} magnitude in the Opalinus Clay. In other words, there is a strong consistency in the S_{hmin} magnitudes in the Opalinus Clay regardless of depth or siting region.

Outlier in the TRU1-1 borehole

The bottommost MHF point in the TRU1-1 borehole (outlier “1”) shows a significantly lower value of S_{hmin} magnitude compared to all other points tested in the Opalinus Clay.

As mentioned earlier, the stiffness of the formation strongly controls the horizontal stress magnitudes – as a reaction to tectonic strain. As a proxy for the stiffness, the dynamic Young’s modulus computed from sonic and density logs is plotted as a function of depth for the Opalinus Clay in the TRU1-1 borehole (Fig. 3-20). This dynamic Young’s modulus is positively correlated to the formation stiffness that drives the formation state of stress, even if the logs do not sample the formation at the appropriate scale, frequency and strain for stress prediction. High and low values of dynamic Young’s modulus will correspond, respectively, to high and low values of the formation stiffness driving the state of stress.

The location of each MHF test interval is also presented as light red bars in Fig. 3-20. The bottommost point, outlier 1, is located on a trough, or negative peak, in the log of dynamic Young’s modulus, i.e. a small layer with different mechanical properties compared to the rest of the formation. The Young’s modulus value there is the lowest of the entire formation and is also significantly lower than the rest of the formation.

The low stiffness of this small bed of the Opalinus Clay is congruent with the lower S_{hmin} magnitude measured at that point. The softer bed, about 4 m thick, is shielded by the stiffer neighbouring formation. This will be further explored through 3D numerical modelling in Section 4.5.

Also note that this small layer of low Young’s modulus close to the bottom of the Opalinus Clay has also been observed in the other borehole of ZNO as well as in all boreholes of the NL but is not clearly visible in the boreholes of the JO siting region. It is likely that, whenever it is present and always close to the bottom of the formation, the minimum horizontal stress borne by that small portion of the formation is lower than in the rest of the formation.

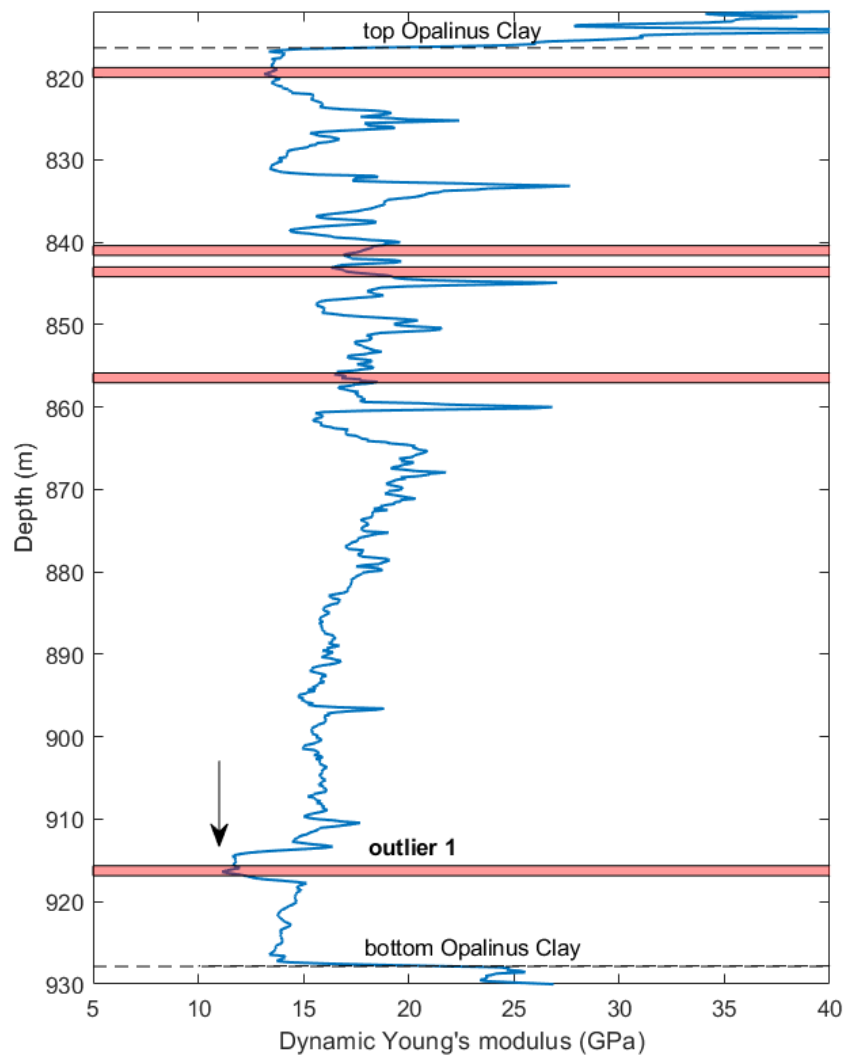


Fig. 3-20: Dynamic Young's modulus computed from sonic and density logs as a function of depth across the Opalinus Clay in borehole TRU1-1

The depth interval for each MHF test is highlighted by a red bar. The value of the dynamic Young's modulus across the bottommost interval ("outlier 1") is significantly lower than that for every other test interval and corresponds to the lowest value for the entire Opalinus Clay.

Outlier in the STA3-1 borehole

The topmost MHF point in the STA3-1 borehole clearly sampled two different layers bearing two different closure stresses, hence two S_{hmin} points located at the same depth. One of them (outlier "2") is an outlier on the low side.

A similar explanation to that for the previous outlier can be provided, although acting at a different scale, namely at the vertical scale of the interval tested during an MHF test (in the order of 1 m). Pre- and post-MHF resistivity images are plotted in Fig. 3-21 for that station. In the Opalinus Clay, resistivity contrasts are a proxy for formation stiffness: a conductive bed is clay-rich and less stiff than a resistive bed that is calcite-rich. The post-MHF images show that the created fracture spans a soft bed in the middle of the interval, as well as two stiffer beds above and below. These stiffer beds bear a higher stress and shield the softer bed from the tectonic strain.

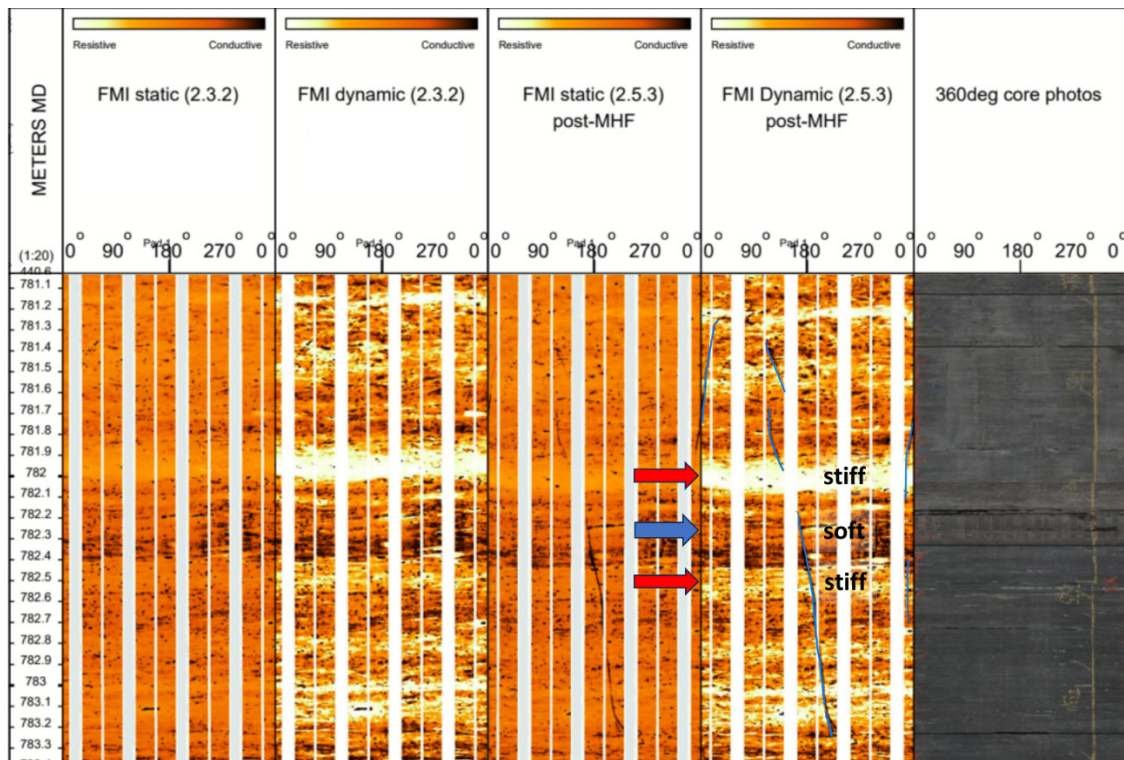


Fig. 3-21: Comparison of pre- and post-MHF imaging

These are presented for the test performed at a centre depth of 782.2 m in borehole STA3-1 and identified as point 2 in Fig. 3-18 and Fig. 3-19. All images are circumferentially unwrapped with true north as the reference. The tracks present, from left to right, the measured depth from the top of the borehole, the static resistivity image of the borehole prior to MHF, the dynamically normalised resistivity image prior to MHF, the static resistivity image after MHF, the dynamic resistivity image after MHF with the trace of the created fracture highlighted in blue, the same dynamic resistivity image without any highlight, and the core photograph (not depth-matched). A new near-vertical bi-wing fracture (dip $\geq 84^\circ$) can be seen on the post-MHF images, spanning a softer core in the centre of the tested interval (as indicated by a more conductive clay-rich rendering) sandwiched between stiffer layers (as indicated by a more resistive limestone-rich rendering). The softer and stiffer layers are highlighted by blue and red arrows, respectively.

The data here show that, at a localised scale of less than 0.5 m, stiffness contrasts in the formation can lead to lower stress in the softer layer and higher stress in the stiffer layers. In other words, local variations of formation stiffness will translate into local variations of S_{hmin} magnitudes.

Outlier in the BOZ1-1 borehole

The minimum horizontal stress magnitude measured at the topmost MHF point in the BOZ1-1 borehole (outlier “3”) is much larger than that for any other point in the Opalinus Clay, insofar as it is closest to the overburden stress.

Similarly to Fig. 3-22, the dynamic Young’s modulus computed from logs in the BOZ1-1 borehole is plotted for the Opalinus Clay. The top 34 m of the Opalinus Clay (530 to 564 m) have been classified as a “Subunit with silty calcareous beds”, with more and more limestone-rich beds closer to the top of the formation leading to much stiffer beds close to the top.

The location of each MHF test interval is also presented as light red bars in Fig. 3-22. The interval sampled by the topmost MHF test is clearly located in the limestone-rich facies in a much stiffer part of the formation, explaining a much larger gradient of S_{hmin} compared to the rest of the formation.

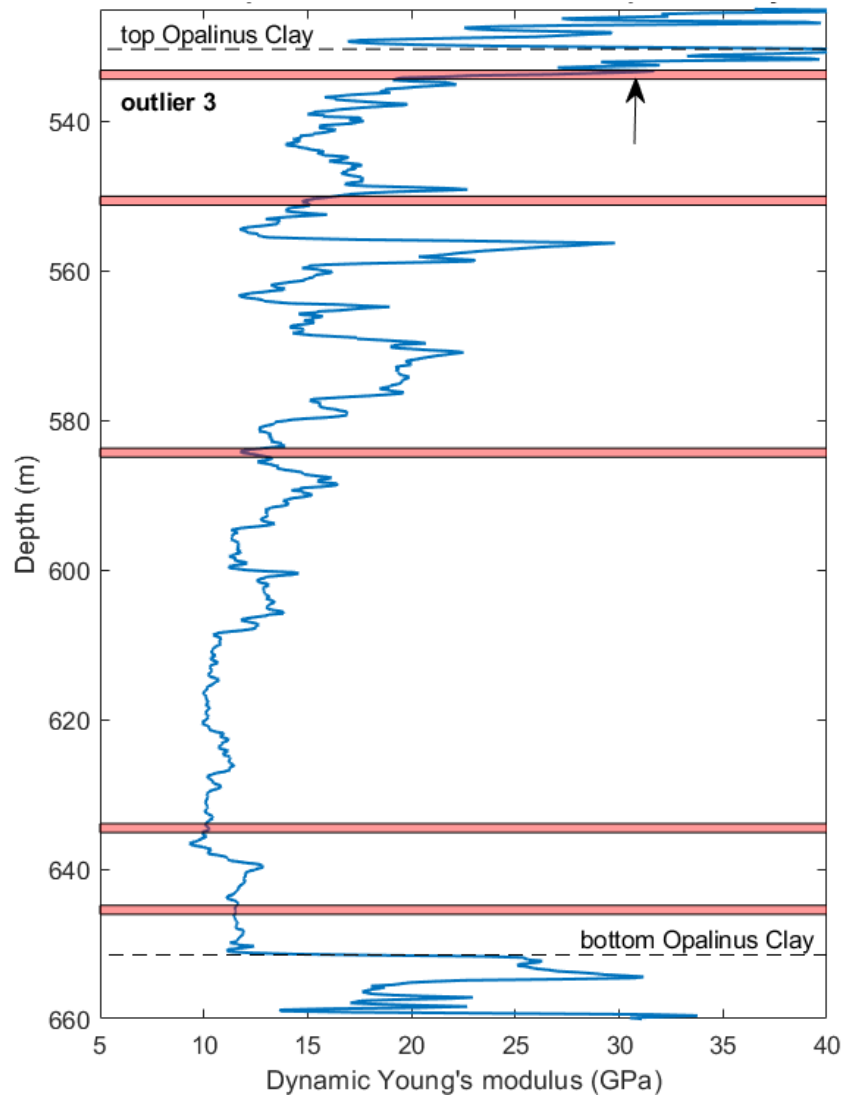


Fig. 3-22: Dynamic Young's modulus computed from sonic and density logs as a function of depth across the Opalinus Clay in borehole BOZ1-1

The depth interval for each MHF test is highlighted by a red bar. The value of the dynamic Young's modulus across the bottommost interval ("outlier 3") is significantly higher than that for every other test interval and corresponds to the highest value for the entire Opalinus Clay.

3.7.2 Maximum horizontal stress S_{Hmax}

In Fig. 3-23, the ranges for S_{Hmax} magnitudes are added to the S_{hmin} profile presented in Fig. 3-18. Similarly to S_{hmin} magnitude ranges, the distribution of S_{Hmax} magnitude ranges does not exhibit different trends depending on depth or siting region. The same outliers (identified as “1” to “3” on Fig. 3-23) can be found for S_{Hmax} as those highlighted for S_{hmin} : softer layers tend to bear lower horizontal stresses (both S_{hmin} and S_{Hmax}), whereas stiffer layers tend to bear higher horizontal stresses (both S_{hmin} and S_{Hmax}).

A fourth outlier (“4” on Fig. 3-23) could be identified for a test in the BOZ2-1 borehole. A closer examination shows that it really stems from the fact that the pressure in the fracture at the time of the SR test (see Section 3.2 for more details) bears a very large uncertainty, resulting into a very wide range for the magnitude of S_{Hmax} for that test. Instead of classifying it as poor – or eliminating it completely, it was decided to keep it, to acknowledge the fact that the quality of data can be uneven.

As in the case of the S_{hmin} magnitudes, four bounds can also be computed for S_{Hmax} magnitudes from the cumulative distribution of the minimum and maximum bounds of all tests. These bounds are illustrated in App. E (Fig. E-2).

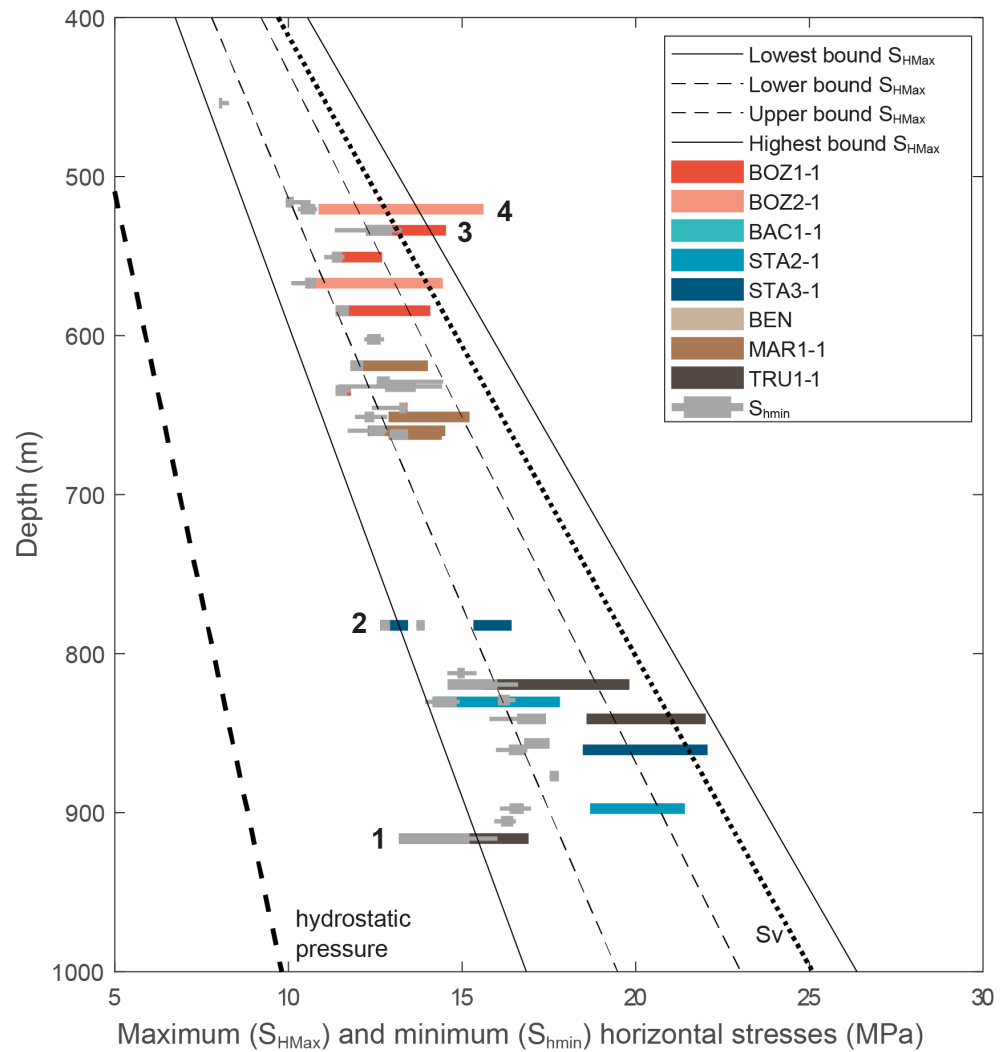


Fig. 3-23: Ranges for magnitudes of S_{hmin} and S_{hmax} in the Opalinus Clay for all TBO boreholes and the Benken borehole as a function of depth

The magnitude ranges for S_{hmax} are plotted as thick horizontal bars, colour-coded per borehole. The narrow and the wide magnitude ranges for S_{hmin} are plotted as thick and thin grey horizontal bars, respectively. The hydrostatic pressure corresponding to a freshwater column going all the way to the surface is plotted as a thick long-dashed black line. The average overburden stress across the Opalinus Clay is plotted as a thick short-dashed black line. The median of the distributions of the gradients of the lowest and highest S_{hmax} bounds (bounds that determine the wide S_{hmax} range) are plotted as thin black dashed lines. The P10 of the lowest bound and the P90 of the highest bound are plotted as thin black continuous lines. Data falling outside the P10 and P90 S_{hmax} gradients, labelled from 1 to 4, are considered outliers.

3.7.3 Comparison with GTPT data

The values of the interval pressure in GTPT tests immediately after gas injection has stopped (instantaneous shut-in pressure, ISIP), for portions of the test during which flow has localised and exhibits fracture-like flow, are plotted in Fig. 3-24 overlaying the S_{hmin} magnitude ranges from MHF tests. Note that the GTPT test in STA2-1 was not reported here, as it is not completely reliable.

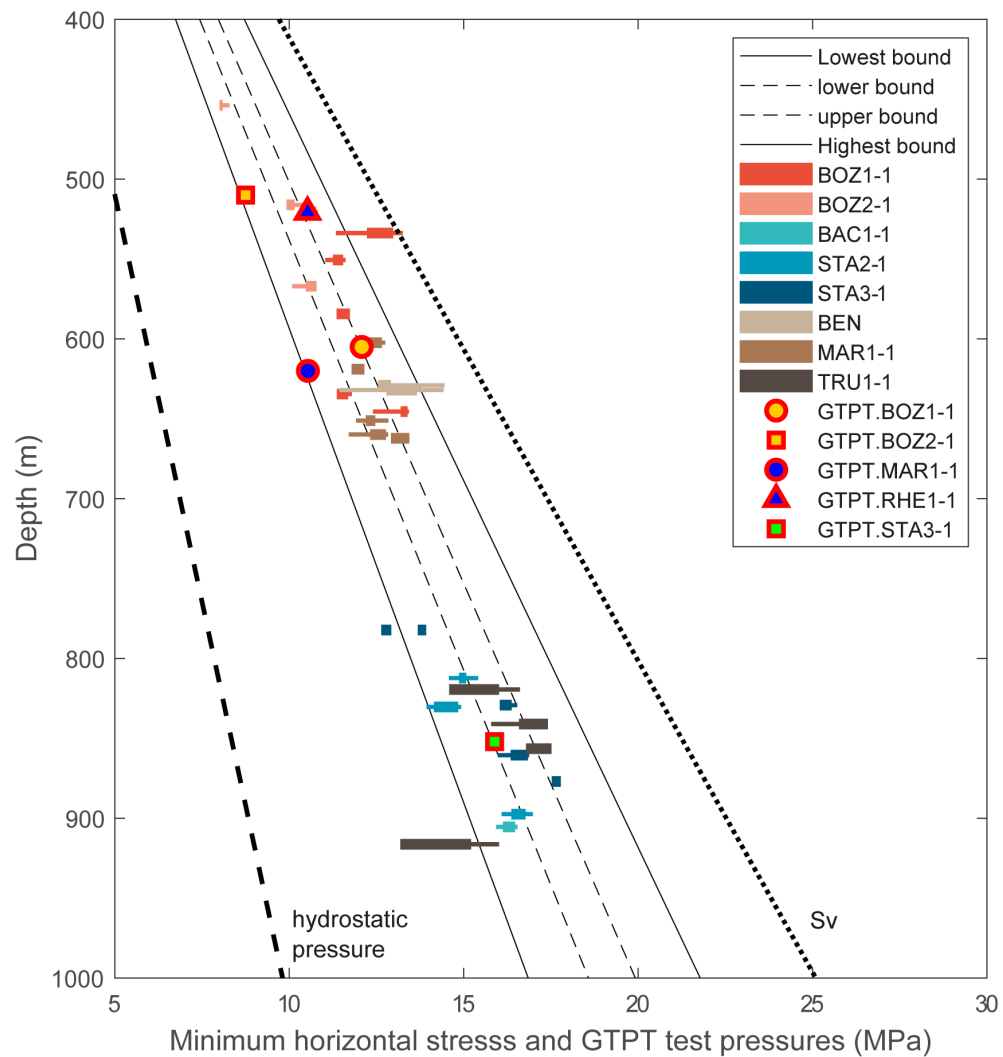


Fig. 3-24: Overlay of instantaneous shut-in pressure of the last injection cycle for GTPT tests with S_{hmin} magnitude ranges in the Opalinus Clay for all boreholes

The GTPT tests are plotted as symbols with a red border. The median of the distributions of the gradients of the lowest and highest S_{hmin} bounds (bounds that determine the wide S_{hmin} range) are plotted as thin black dashed lines. The P10 of the lowest bound and the P90 of the highest bound are plotted as thin black continuous lines.

All points are located within the wider range for the magnitude of S_{hmin} , and closer to the lower part of the range, which is in contradiction with the fact that, for each test, an inclined pre-existing feature has likely been tested: these points should lie closer to the overburden stress than they actually are.

Further information can be obtained from the G-plot analysis (Jung et al. 2016) for each test. Indeed, fracture closure from a fully opened fracture can be detected by a clear increase in fracture stiffness sometime after shut-in. Apart from the test in BOZ1-1, all shut-in cycles for GTPT tests showed no such feature, indicating that the fracture started closing from an already partially closed state (Nagra 2024a). In other words, apart from the GTPT test in BOZ1-1, all other tests are congruent with a fracture that is not fully open at the end of injecting. As mentioned in Section 3.4 for such cases, the pressure allowing flow localisation along the discontinuity is less than the stress normal to that discontinuity. Therefore, the ISIP for all GTPT tests apart from that in BOZ1-1 would correspond to a lower bound to the closure stress acting on the tested discontinuity and should not be taken as an estimate of the magnitude of S_{hmin} .

As for the test in the BOZ1-1 borehole, the ISIPs are likely to represent the stress acting normal to the tested discontinuity. However, the fact that the ISIP for the second cycle is larger than that of the first cycle shows that the test is still sensing the stress concentration around the borehole and that the second ISIP is likely still a lower bound for the closure stress. Similarly, the result cannot be taken as an estimate of the magnitude of S_{hmin} , only a lower bound for it.

3.7.4 Summarising stress magnitudes in Opalinus Clay

As discussed in Section 3.7.1 and illustrated in Fig. 3-18, the S_{hmin} magnitudes follow a common depth trend (gradient) which can be bracketed by four bounds. These four bounds are shown in Fig. E-1 and Fig. E-2 and are listed in Tab. 3-3.

Examples of stress values in the depth range between 400 and 1,000 m are provided in Chapter 5 (Tab. 5-1).

Tab. 3-3: Gradients of horizontal stress magnitudes in Opalinus Clay

For the estimation of the stress magnitude gradients with depth, the wide ranges of the S_{hmin} and S_{Hmax} magnitudes, respectively, are used. The median (P50) corresponds to the vertical dashed red lines in Fig. E-1 and Fig. E-2, respectively. The P10 and P90 values of the lowest and highest bound for S_{hmin} and S_{Hmax} gradient correspond to the continuous red lines in Fig. E-1 and Fig. E-2, respectively.

Minimum horizontal stress gradient S_{hmin} [MPa/km]				Maximum horizontal stress gradient S_{Hmax} [MPa/km]			
Lowest bound P10	Lowest bound P50	Highest bound P50	Highest bound P90	Lowest bound P10	Lowest bound P50	Highest bound P50	Highest bound P90
16.85	18.58	19.92	21.78	16.85	19.48	23.03	26.37

4 3D stress model of the siting regions

The key purpose of the 3D geomechanical-numerical models – referred to as “stress models” in the following – is to predict the stress tensor in a larger rock volume beyond the stress data taken along the borehole trajectories of the TBO campaign. The new stress magnitude data from the MHF/SR tests, as well as rock-mechanical properties from core testing and petrophysical logging, allow a robust calibration of the three site-specific stress models. Besides the stress prediction in a larger volume, the stress models also allow the effects of mechanical layering, topography and of major fault zones on the local in-situ stress field to be explored.

4.1 Modelling workflow and assumptions

Geomechanical modelling can follow two different conceptual approaches. The first investigates the geodynamic processes that control the evolution of the in-situ stress field on geological time-scales (Burov & Toussaint 2007, Kaus et al. 2009). The second aims at achieving a continuous description of the contemporary 3D in-situ stress field in the model volume for geotechnical applications (Lecampion & Lei 2010, Hergert et al. 2015). The first approach would need initial assumptions (structure, properties) going backwards in time and tests which processes such as plate tectonics, erosion, sedimentation, compaction and faulting would result in the structure and in-situ stress field that is observed today. Such a model could be used to quantify the evolution of faults and their slip rates, but the uncertainties of the model parameters that control the driving processes and the initial conditions are too large to result in the geological structure and in-situ stress field that is observed today.

For the site selection process for a deep geological repository, the key objective is to have reliable 3D in-situ stress field predictions in the siting regions due to the variability of today’s structure and rock properties. Thus, the stress model approach that is used here focuses on the best possible in-situ stress field prediction based on the given data of the imaged structure, rock properties and stress magnitude data from the TBO campaign.

Two basic model assumptions are made. First, it is assumed that transient and anthropogenic processes can be ignored, and that linear elasticity is appropriate in the rock volume beyond the model faults where plastic deformation is allowed. Second, only the contributions from gravitational volume forces and tectonic stresses (surface forces) are considered. Ignoring acceleration, the equilibrium of these two forces must be solved (Fig. 4-1). Using the assumed elasto-plastic stress-strain relation, this results in a time-independent partial differential equation of 2nd order with displacement u as the field variable. With given rock density and elastic properties as well as fault friction, the model assumptions reduce the problem of finding appropriate lateral displacement boundary conditions that result in a best fit with respect to the stress magnitude data from the TBO campaign. These displacements are to some extent arbitrary and integrate the tectonic loading history of the rock volume.

The technical model workflow is shown in Fig. 4-1 where the colour-coded boxes indicate the four major stages. The first stage (white boxes) is the construction of the 3D model geometry including faults, model stratigraphy and topography. The second stage (grey boxes) comprises the two-step procedure for applying the forces. The first defines the initial stress that is in equilibrium with the gravitational volume forces. The second step determines lateral displacement boundary conditions that result in a best fit with respect to the stress magnitude data. The third stage is the model calibration (orange boxes) and the fourth the analysis of the model results (blue box). Technical details of this procedure can be found in Hergert et al. (2015) and Heidbach et al. (2014).

For the construction and discretisation of the 3D model geometry SKUA-GOCAD v18 and HyperMesh v2021, respectively, were used. For the numerical solution of the resulting partial differential equation, the Finite Element Method (FEM) is applied using the implicit solver of the FEM software Abaqus v2021. For the analysis and visualisation of the model results, Tecplot 360 EX v2021 R1 extended with the library GeoStress v2.0 from Heidbach et al. (2020) was used.

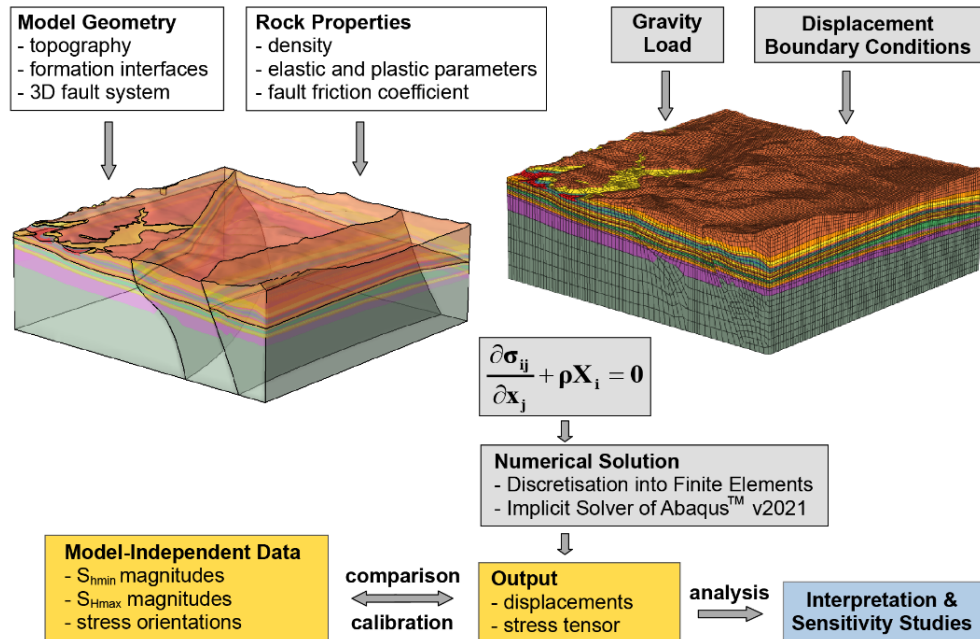


Fig. 4-1: General workflow of 3D geomechanical-numerical modelling

White boxes: Assembly of 3D model geometry, rock and fault properties. Left figure: 3D view of an arbitrary model structure. Grey boxes: Gravitational load, displacement boundary conditions and numerical solution. Right figure: Discretised model volume. The partial differential equations of the equilibrium of forces are solved using the Finite Element Method (σ_{ij} stress tensor, x_j Cartesian coordinates, ρ density, and X_i body forces). Orange boxes: Model is calibrated with stress magnitude data. Blue box: Interpretation and analysis of model results as well as sensitivity studies of the model parameters.

The following sections describe the construction of the model geometry and implementation of the faults (Section 4.2), model stratigraphy and discretisation of the model volume (Section 4.3), assignment of rock properties (Section 4.4), calibration procedure and key results of the best fit model (Section 4.5). Section 4.6 presents the results of sensitivity studies that investigate the effect of faults, topography, and the reef facies in the NL siting region on the stress field. Finally, Section 4.7 discusses limitations and uncertainties of the stress models.

4.2 Model boundaries and fault implementation

The areas of the stress models are rectangular and rotated counterclockwise in the horizontal plane from the north direction by 10° for the siting region ZNO, 14° for the siting region NL, and 15° for the siting region JO. This results in model boundaries that are parallel and perpendicular to the observed S_{Hmax} orientation (Tab. 2-2). The lower boundaries, i.e. the bottom of the model geometry, is at 2,000 m below sea level. Fig. 4-2, Fig. 4-3 and Fig. 4-4 show the lateral extent of the model boundaries and the faults that are implemented in the model. The spatial extent of the faults and their dip can be seen in the N-S and W-E cross-sections through the model stratigraphy explained in Section 4.3.

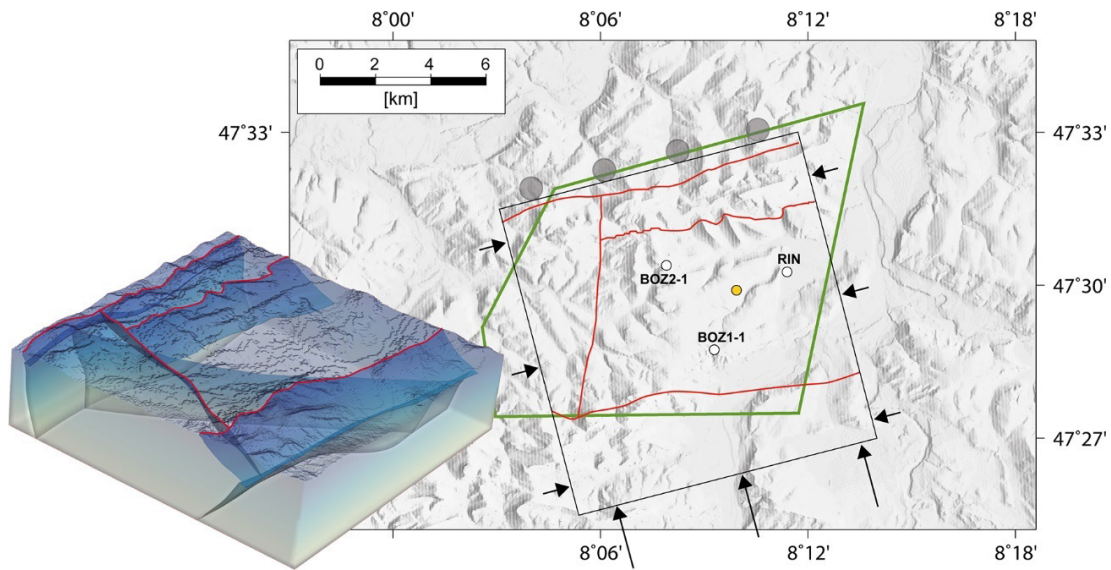


Fig. 4-2: Map view of model boundaries and implemented faults for JO siting region

Model boundaries (11.2 km W-E, 11.5 km N-S, black box) compared with the area covered by the geological model from 3D seismic (green polygon). White circles indicate borehole locations. The orange circle indicates the position of an arbitrary vertical trajectory into the high-level waste section of the current repository project for license application. Grey circles at the northern boundary denote that displacements are constrained perpendicular to that model boundary; arrows indicate displacement boundary conditions. Red lines show the surface trace of modelled faults.

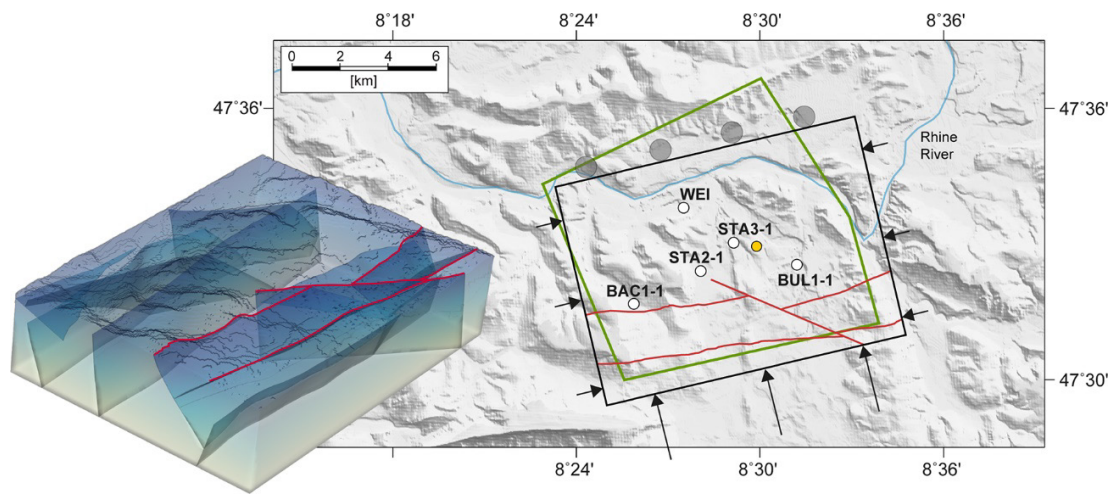


Fig. 4-3: Map view of model boundaries and implemented faults for NL siting region

Model boundaries (12.9 km W-E, 9.4 km N-S, black box) compared with the area covered by the geological model from 3D seismic (green polygon). White circles indicate borehole locations. The orange circle indicates the position of an arbitrary vertical trajectory into the high-level waste section of the current repository project for license application. Grey circles at the northern boundary denote that displacements are constrained perpendicular to that model boundary; arrows indicate displacement boundary conditions. Red lines show the surface trace of modelled faults.

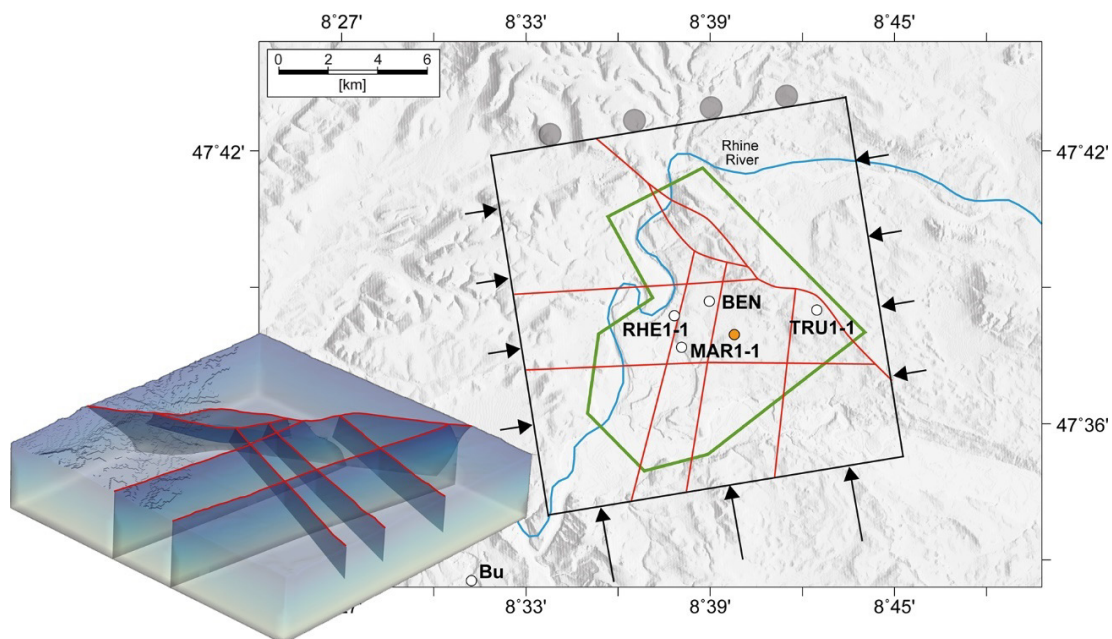


Fig. 4-4: Map view of model boundaries and implemented faults for ZNO siting region

Model boundaries (14.7 km WE, 14.8 km NS, black box) in comparison with the area covered by the geological model from 3D seismic (green polygon). White circles indicate borehole locations. The orange circle indicates the position of an arbitrary vertical trajectory into the high-level waste section of the current repository project for license application.. Grey circles at the northern boundary denote that displacements are constrained perpendicular to that model boundary; arrows indicate displacement boundary conditions. Red lines show the surface trace of modelled faults

To extract the internal model geometry, i.e. stratigraphy and faults, the geological models that are based on the 3D seismic interpretations are used. Since the lateral extent of the stress models is greater than the 3D seismic perimeter, geological information at the regional scale was used for interpolation between the 3D seismic and the model boundaries.

The delivered geological models also provide many short fault surface segments based on the analysis and interpretation of the 3D seismics (Fig. 4-5). From these segments, larger faults were simplified and implemented in the model as so-called contact surfaces (see Section 4.3). Along these surfaces Mohr-Coulomb frictional sliding is allowed. It is assumed that the faults have zero cohesion and a static friction coefficient of $\mu = 0.6$. Due to the numerical resolution limit, the fault segments must be generalised into larger faults. Small segments as interpreted from the seismics in the order of a few hundred metres would generate substantial numerical artefacts at the fault tips as they cannot slip properly due to their size compared to the model resolution (Section 4.3).

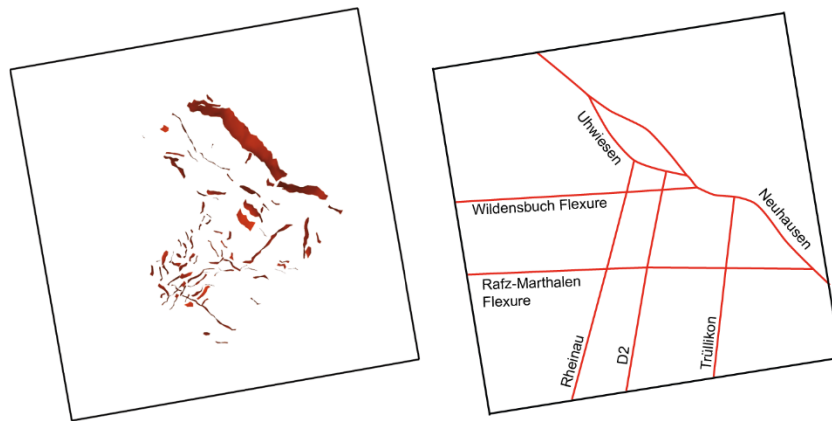


Fig. 4-5: Generalisation of small fault segments into major faults in the ZNO model

The 3D seismic interpretation initially available for model building contained a large amount of small fault segments (left figure). These segments were highly simplified and integrated into a first order fault system that can be implemented as contact surfaces in the model where fault friction is assigned and relative displacement is allowed.

The three guiding arguments for the fault segment generalisation were:

1. Whenever reasonable and technically possible, avoid fault tips that end within the model volume. These result in numerical artefacts as they generate stress concentrations at the tips.
2. Avoid sharp kinks within a fault surface description using the finite element faces. This prevents stress concentrations around the kinks, which are numerical artefacts rather than real in-situ stress field features.
3. Implement only faults that are reasonable in a greater structural context and that potentially generate displacement where shear stresses are reduced or where a vertical offset of formations is observed.

Following these arguments, the model geometries include seven faults in the stress models for JO and ZNO and six faults in the stress model for NL. Note that some faults are not visible in Fig. 4-2, Fig. 4-3 and Fig. 4-4 as they exist only in deeper structures and have no surface trace (see cross-sections in Fig. 4-7). In summary, given the model resolution and modelling objective, the implemented faults in the models are highly simplified and differ substantially from the detailed seismic interpretation.

4.3 Model stratigraphy and discretisation into finite elements

Given that an analytical solution of the partial differential equation that describes the equilibrium of forces in the model volume cannot be found, a numerical method must be used to provide a solution at discrete points. For complex geological structures where the field parameters depend on the rock property distribution, the Finite Element Method (FEM) is advantageous. The FEM allows the use of unstructured meshes where the discrete points follow the structure. Furthermore, areas of less variability of the field parameters can be discretised with low resolution, whereas areas where the field parameters are expected to change over a shorter distance (e.g. from one sediment layer to the next) a higher resolution can be assigned. Thin sedimentary layers can be discretised efficiently using hexahedral elements with high aspect ratios of 1:10 of the vertical to lateral distance between the discrete nodes of the finite element mesh.

However, very thin layers with thicknesses <10 m cannot be resolved in the given model volumes to find a reasonable balance between computer power and efficiency of the simulations. Note that to represent a geomechanical layer in a numerically reasonable way, a minimum of three finite elements in the vertical are needed. With a limit of approximately 100 m in the horizontal direction, thin layers of <10 m would result in aspect ratios of >1:30 which can result in numerical convergence issues or buckling effects. Using the implicit solver of Abaqus in a model with more than two million linear hexahedral elements, the lateral model resolution is in the order of 100 m in the horizontal and 5 to 20 m in the vertical.

Tab. 4-1 shows an overview of the rock formations in the three siting regions and the formations that were implemented in the stress models. In the JO model, the «Felsenkalke» + «Massenkalk» as well as the Schwarzbach Formation were not found in the boreholes and thus these are not implemented in the model. Furthermore, in the JO model the Ifenthal and Klingau Formations as well as the Hauptrogenstein had to be combined into one layer due to their small thickness (labelled as I-UpperDogger).

In the NL and ZNO siting regions, the Ifenthal, Klingau, Hauptrogenstein and Passwang formations were not found in the relevant TBO boreholes and thus are not implemented in the respective model. The «Felsenkalke» + «Massenkalk» as well as the Schwarzbach Formation exist in the of ZNO and NL siting regions, but in ZNO this layer is too thin to be represented in the model and it has been combined with the Villigen Formation.

Furthermore, the «Herrenwis Unit» only exists partly in the southeastern part of the model area NL. This so-called reef facies has been mapped laterally and is also reflected within the NL model layer I-Upper Dogger. The volume is labelled here as K-Upper Dogger to account for the different rock properties and to investigate the potential effect on the stresses with a sensitivity study (see Section 4.6.3).

Tab. 4-1: Stratigraphy of the stress models of the three siting regions

Models contain fewer formations than listed in column two since some do not exist in all siting regions (indicated as white fields). Furthermore, formations that are very thin (10 – 20 m), cannot be resolved within the numerical resolution limit. They were then combined with the layer below or above that has similar rock stiffness. Details for the three siting regions can be found in App. F where the rock properties and the combination of thin layers are presented.

Age	Formation	Model JO	Model NL	Model ZNO
Quaternary	Quaternary sediments	A-Quartär	A-Quartär	A-Quartär
Paleogene Neogene	Obere Süßwassermolasse	B-OSM	B-OSM	B-OSM
	Obere Meeresmolasse	C-OMM	C-OMM	C-OMM
	Untere Süßwassermolasse	D-USM	D-USM	D-USM
Malm	«Felsenkalke» + «Massenkalk»		E-MalmFels	E-MalmFels
	Schwarzbach		F-MalmSchw	F-MalmSchwVi
	Villigen	G-MalmVilligen	G-MalmVilligen	
	Wildegg	H-MalmWildegg	H-MalmWildegg	H-MalmWildegg
Dogger	Ifenthal	I-UpperDogger		
	Klingnau			
	Hauptrogenstein			
	Passwang	L-Passwang		
	Wutach / Variansmergel		I-UpperDogger K-UpperDogger *	I-UpperDogger
	«Herrenwis Unit»			
	«Park.-Württ.-Sch.»		L-MidDogger	L-MidDogger
	«Humphriesiolith»			
	Wedelsandstein			
	«Murch.-Oolith»			
	Opalinus Clay	M-Opalin	M-Opalin	M-Opalin
Lias	Staffelegg	N-Lias	N-Lias	N-Lias
Keuper	Klettgau	O-MidKeuper	O-MidKeuper	O-MidKeuper
	Bänkerjoch	P-Gipskeuper	P-Gipskeuper	P-Gipskeuper
Muschelkalk	Schinznach	R-UppMuka	R-UppMuka	R-UppMuka
	Zeglingen	S-MidMuka	S-MidMuka	S-MidMuka
	Kaiseraugst	T-LowMuka	T-LowMuka	T-LowMuka
Buntsandstein	Dinkelberg	U-BssRotKris	U-BssRotKris	U-BssRotKris
Rotliegend	Weitenau			
Pre-Mezozoic	Kristallin			

* In the southeastern part of the NL siting region, the Upper Dogger has a reef facies («Herrenwis Unit»). Thus, the Upper Dogger layer in the NL model is also separated laterally in order to test the potential effect of the stiffer reef facies (see Section 4.6).

To allow numerically for relative displacement at the faults, so-called contact elements are used for their implementation. A contact is defined by opposing surfaces that are defined by a set of element faces (Fig. 4-6). The nodes of the contact elements are not connected to each other, and they are only allowed to displace parallel to the surfaces that define the contact (fault).

The nodes are displaced when the given fault strength according to the Mohr-Coulomb failure criterion is reached. Thus, when the ratio of shear stress τ to normal stress σ_n both resolved on the fault is larger than the static friction coefficient μ , the fault is displaced until an equilibrium of forces is reached again. For all models it is assumed that the faults have no cohesion and a static friction coefficient of $\mu = 0.6$. The effect of other static friction coefficients on the in-situ stress field is tested with sensitivity studies (see Section 4.6.1).

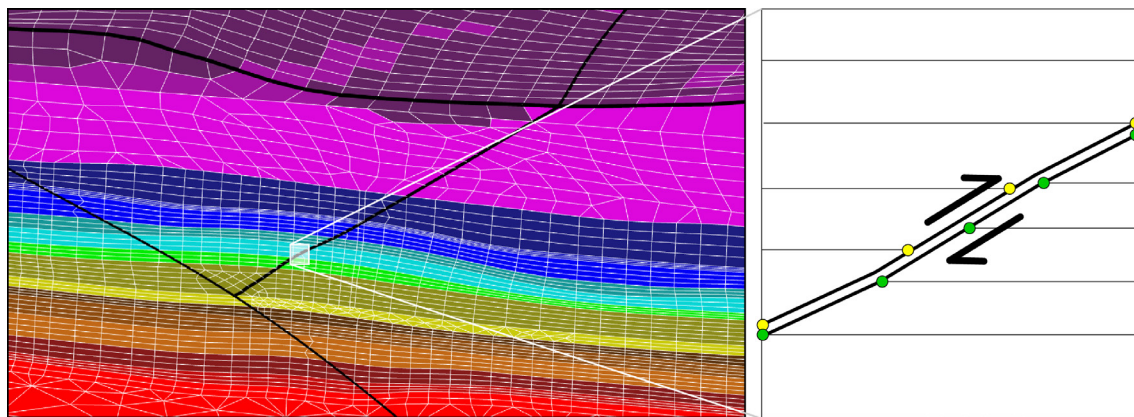


Fig. 4-6: Finite element mesh and contact elements for fault representation

Left figure shows colour-coded lithological units that are implemented in the model and their discretisation into finite elements. Thick black lines show faults where relative displacement is allowed with so-called contact elements. Zoom on the right shows a 2D sketch of the contact elements that represent a fault. A contact consists of two surfaces (lines) each defined by a set of element faces (lines). The nodes of the element faces (lines) that define the contact are not connected to each other, but they can move parallel to the face (line) to release shear stresses when the fault strength according to the Mohr-Coulomb failure criterion is reached.

Fig. 4-7 shows N-S and W-E cross-sections at the locations of the TBO campaign boreholes through the formations that are implemented in the three stress models of the three siting regions. The cross-sections are not exaggerated in the vertical and show the challenge of implementing numerically a succession of relatively thin sediment layers with respect to the lateral extent of the stress models. Black lines in Fig. 4-7 show the fault locations that are implemented with contact elements to allow for relative displacement and to represent the vertical offset of sediment layers, which is clearly seen at the Neuhausen Fault in the model for ZNO. This offset results in a potential horizontal contrast in rock stiffness which may influence the horizontal stress tensor components.

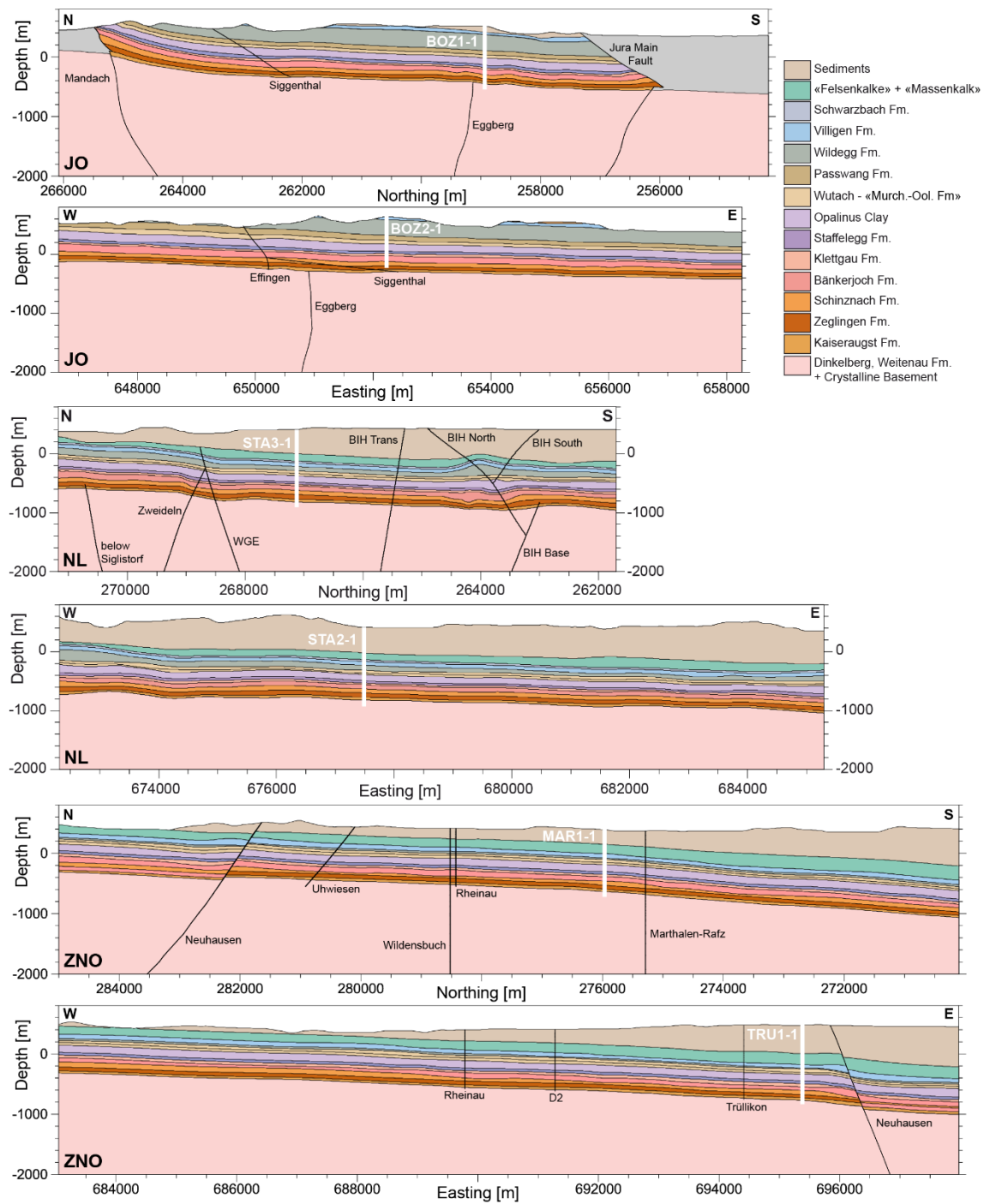


Fig. 4-7: Cross-sections through stress model stratigraphy of siting regions JO, NL and ZNO

Cross-sections cut through selected boreholes that are indicated with white vertical bars. The lithology is according to the model layers stated in Tab. 4-1. Note that in the N-S cross-section in JO north of the Mandach Fault and south of the Jura Main Thrust Fault formation borders are shown due to the higher internal deformation and the resolution limit of this figure.

4.4 Implementation of rock mechanical properties

For each siting region, the distribution of elastic properties has been determined for each formation using core testing results and the analysis of petrophysical logs (Nagra 2024b). The combination of these data resulted in a cumulative density function of individual rock properties for each formation. Fig. 4-8 shows the results for the static Young's modulus E for each siting region along the borehole trajectories of BOZ1-1, STA2-1 and TRU1-1. The probability distribution expressed with the P05 – P95 range (light grey areas), the P25 – P75 range (dark grey areas), and the median (P50) values are indicated with black lines. Tab. 4-2 presents the P50 values for the Poisson's ratio and the static Young's modulus for all layers in each siting region. Furthermore, rock density taken from the density log is given as well. Further details on the rock properties and their probability distributions are presented in App. F for each siting region.

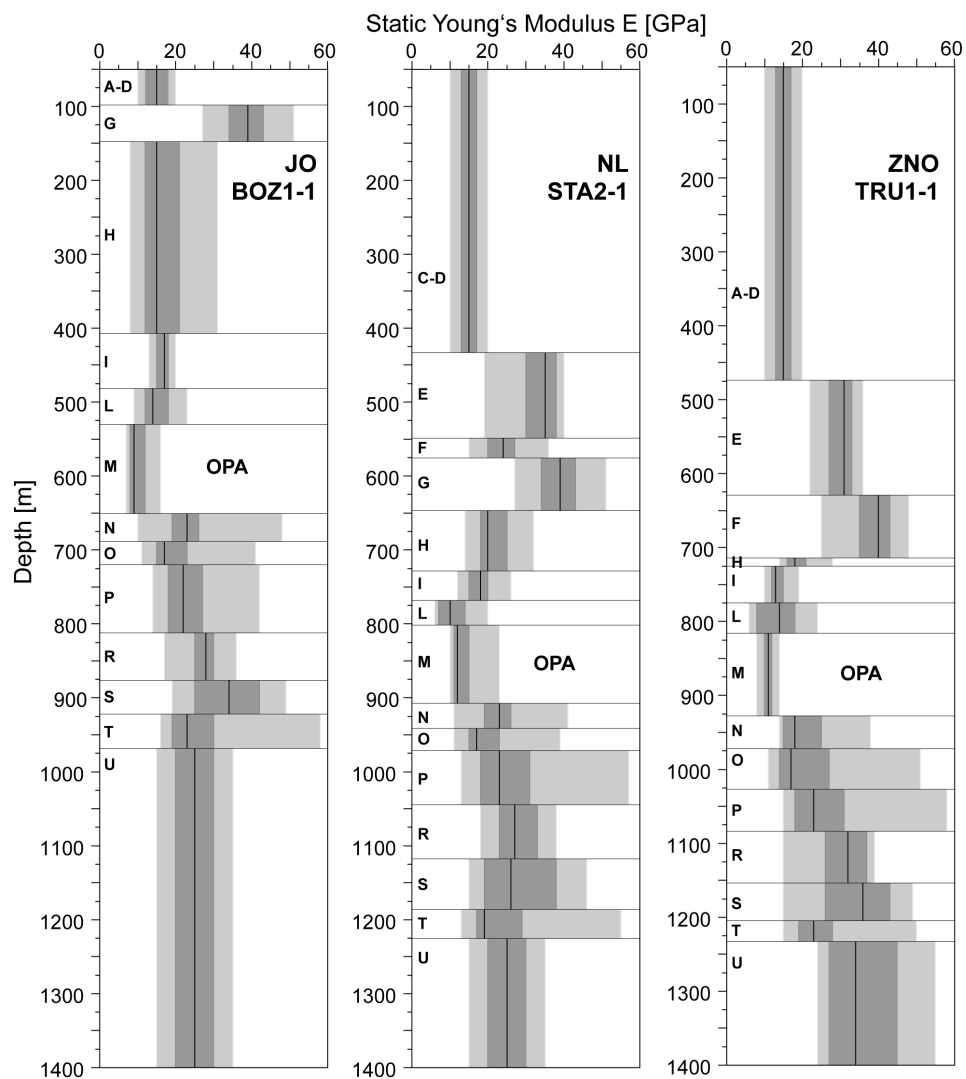


Fig. 4-8: Variability of rock stiffness along borehole profiles from the three siting regions

Dark lines are the P50 median value of rock stiffness. Dark grey areas denote the P25 – P75 probability range and light grey areas the P05 – P95 probability range. Bold capital letters denote the formations that are implemented in the model as explained in Tab. 4-1.

Tab. 4-2: Rock mechanical P50 values in the three siting regions

White fields indicate that formations do not exist in the respective siting region. Formations from Upper and Middle Dogger (Ifenthal to “Murchisonae-Oolith”) occur differently in the three siting regions and are summarised individually. Details are given in App. F.

Formation		Model unit names	JO			NL			ZNO		
			v [-]	E [GPa]	r [kg/m³]	v [-]	E [GPa]	r [kg/m³]	v [-]	E [GPa]	r [kg/m³]
Quaternary sediments		A-Quartär	0.30	15	2,350	0.30	15	2,350	0.30	15	2,350
Obere Süsswassermolasse		B-OSM	0.30	15	2,350	0.30	15	2,350	0.30	15	2,350
Obere Meeresmolasse		C-OMM	0.30	15	2,350	0.30	15	2,350	0.30	15	2,350
Untere Süsswassermolasse		D-USM	0.30	15	2,350	0.30	15	2,350	0.30	15	2,350
«Felsenkalke» + «Massenkalk»		E-MalmFels				0.19	35	2,686	0.18	31	2,685
Schwarzbach		F-MalmSchwarz				0.25	24	2,656	0.20	40	2,685
Villigen		G-MalmVill	0.21	39	2,685	0.21	39	2,685			
Wildeggen Fm. (with Effingen Mb.)		H-MalmWildeg	0.27	15	2,610	0.25	20	2,625	0.26	18	2,610
JO: Ifenthal, Klingnau Haupt- rogen- stein	NL / ZNO: Wutach / Varians- mergel «Park.- Württ.- Sch.»	I-UppDogger	0.20	17	2,600	0.24	18	2,680	0.32	13	2,530
«Herrenwis Unit»		K-UppDogger				0.26	19	2,676			
JO: Passwang	NL / ZNO: "Humphr. oolith", Wedel- sandstein, «Murch.- Oolith»	L-MidDogger L-Passwang	0.20	14	2,570	0.29	10	2,306	0.28	14	2,540
Opalinus Clay		M-Opalin	0.38	9	2,520	0.35	12	2,544	0.37	11	2,520
Staffelegg		N-Lias	0.25	23	2,550	0.24	23	2,573	0.26	18	2,540
Klettgau		O-Mid-Keuper	0.22	17	2,540	0.23	17	2,544	0.23	17	2,570
Bänkerjoch		P-Gipskeuper	0.22	22	2,720	0.20	23	2,625	0.22	23	2,700
Schinznach		R-UppMuka	0.23	28	2,650	0.23	27	2,683	0.24	32	2,710
Zeglingen		S-MidMuka	0.18	34	2,800	0.20	26	2,800	0.19	36	2,840
Kaiseraugst		T-LowMuka	0.28	23	2,640	0.27	19	2,664	0.30	23	2,620
Dinkelberg & Weitenau		U-RotBssKris	0.23	25	2,540	0.23	25	2,479	0.27	34	2,540
Kristallin											

For the upper units of the Neogene where no logs and cores were available (model units A to D), standard values from the literature were used. Also note that at ZNO stiffer values for the basement were taken. The P50 values are the ones taken in stress models for an initial best fit with respect to the stress magnitudes.

4.5 Model calibration and best fit model results

The contemporary stress state is the result of various processes acting over geological times. It is mainly a combination of gravitational volume forces and their changes over time due to erosion and sedimentation as well as lateral surface forces from plate tectonic processes. However, a model that aims at describing the 3D in-situ stress field in the contemporary structure cannot reproduce these processes. Technically these processes are integrated in two consecutive modelling steps that are explained in the following two paragraphs.

In the first step gravity is applied. The vertical stress S_V is controlled by rock density and the horizontal stress magnitudes by the Poisson's ratio ν . To avoid the horizontal stresses being much lower than the vertical stress, the gravity step $\nu = 0.42$ is used for the weaker clay-rich formations of the Dogger and $\nu = 0.36$ for all other formations. Sensitivity tests for the choice of the initial Poisson's ratio during the gravity steps showed that using approximately 20% higher values compared to other formations resulted in a better overall fit of the stress magnitude data. This resulting higher Poisson's ratio for the clay-rich layers can be related to overconsolidation effects (Hergert et al. 2015). To compensate for the vertical displacements due to compaction in the gravity step, we use the resulting equilibrated stress state as an initial stress in an undeformed model geometry in the second model step. The residual vertical displacements are then in the order of a few centimetres only.

In the second step, the estimated P50 Poisson's ratios for each formation as stated in Tab. 4-2 are used and the lateral displacement boundary conditions that result in the least mean deviation compared to the stress magnitude data from the TBO campaign are estimated. The two unknowns are the displacements in the x- and y-directions. The best fit lateral displacements at the model boundaries are estimated in a semi-automatic way using the tool FAST Calibration v2.0 from Ziegler (2021, Ziegler & Heidbach) and Ziegler & Heidbach (2021). Details on the procedure are given in App. G. The best fit lateral boundary conditions given in pairs of E-W extension and N-S shortening are 0.74/3.22 m for JO, ZNO 0.82/4.1 m and NL 0.42/2.74 m for the P50 elastic rock properties values given in Tab. 4-2.

Fig. 4-9 shows as an example the result of the best fit stress model for ZNO as a continuous stress-depth plot along the borehole trajectory of TRU1-1 compared with the stress magnitude ranges of S_{Hmin} and S_{Hmax} displayed as red and blue horizontal bars, respectively. The fit in Fig. 4-9 is in general agreement with the stress magnitude data, but e.g. in the Klettgau and Bänkerjoch Formations the stress model underestimates the S_{Hmin} magnitudes. The explanation for the deviations is that the stress models use the P50 value for the stiffness for all formations, but the MHF tests sample on a metre scale where the stiffness can deviate substantially locally from the P50 value (Fig. 4-8). To test whether this is the key driver of the deviation between model and stress magnitude data, the sonic log information is used to estimate for each MHF station the most likely stiffness value from the distribution shown in Fig. 4-8. The dashed lines in Fig. 4-9 show the model result of the adapted stiffness values for each layer and it is obvious that the fit improves significantly.

These results show that the key control of the in-situ stress field is the rock stiffness. As a consequence, the stress magnitude data also follow in each formation a distribution as shown in Fig. 3-15. The same argument is valid for the remaining outlier at the MHF station at 916 m TVD in the Opalinus Clay. This station is located at a minimum of the dynamic Young's modulus of the entire formation (see Fig. 3-20) and it is presumably lower than the estimated P05 value of

8 GPa for the stiffness (Fig. 4-8). A very low stiffness of this small bed of the Opalinus Clay is congruent with the lower S_{hmin} magnitude measured at that point. A model was therefore generated with a weak lens with $E = 3$ GPa to account for this exceptional low stiffness at this MHF station. Fig. 4-10 shows the effect of the weak lens (dashed lines) in comparison to the P50 best fit model results (continuous lines).

The consequence of the stiffness control on the variability of the horizontal stress magnitudes is that their prediction beyond the measurements along the boreholes must be a distribution and not a single value. This is addressed in Chapter 5 where the stress models are used to predict the distribution of the stress field beyond the boreholes with a bandwidth that covers the P05 to P95 probability distribution.

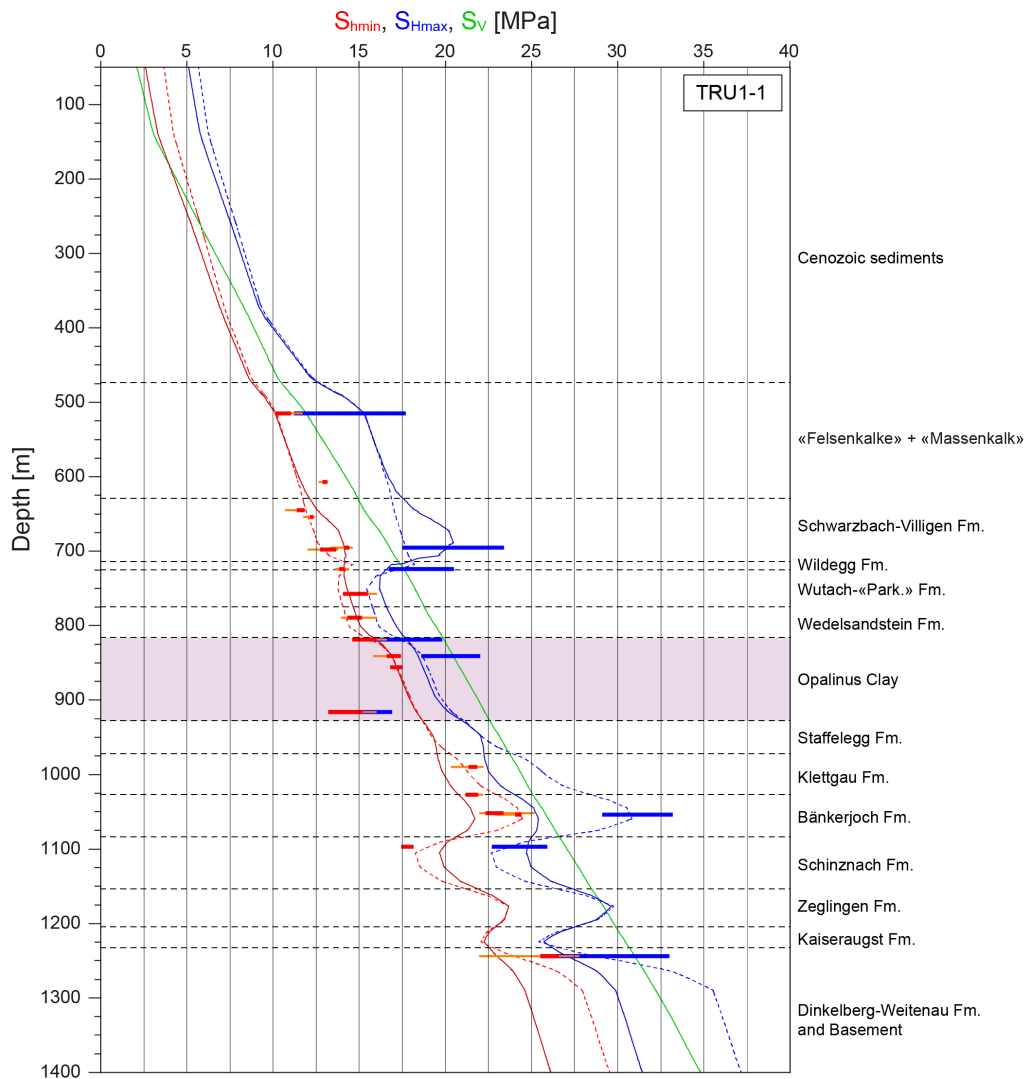


Fig. 4-9: Model results along the borehole TRU1-1 trajectory – Part I

Continuous lines are the stress components derived from best fit model results using the P50 values of the rock stiffness. Dashed lines are the results using instead individual stiffness values from the P05 – P95 rock stiffness distribution. The assignment depends on the stiffness values at each MHF station which is estimated using the sonic logs and appropriate empirical relations.

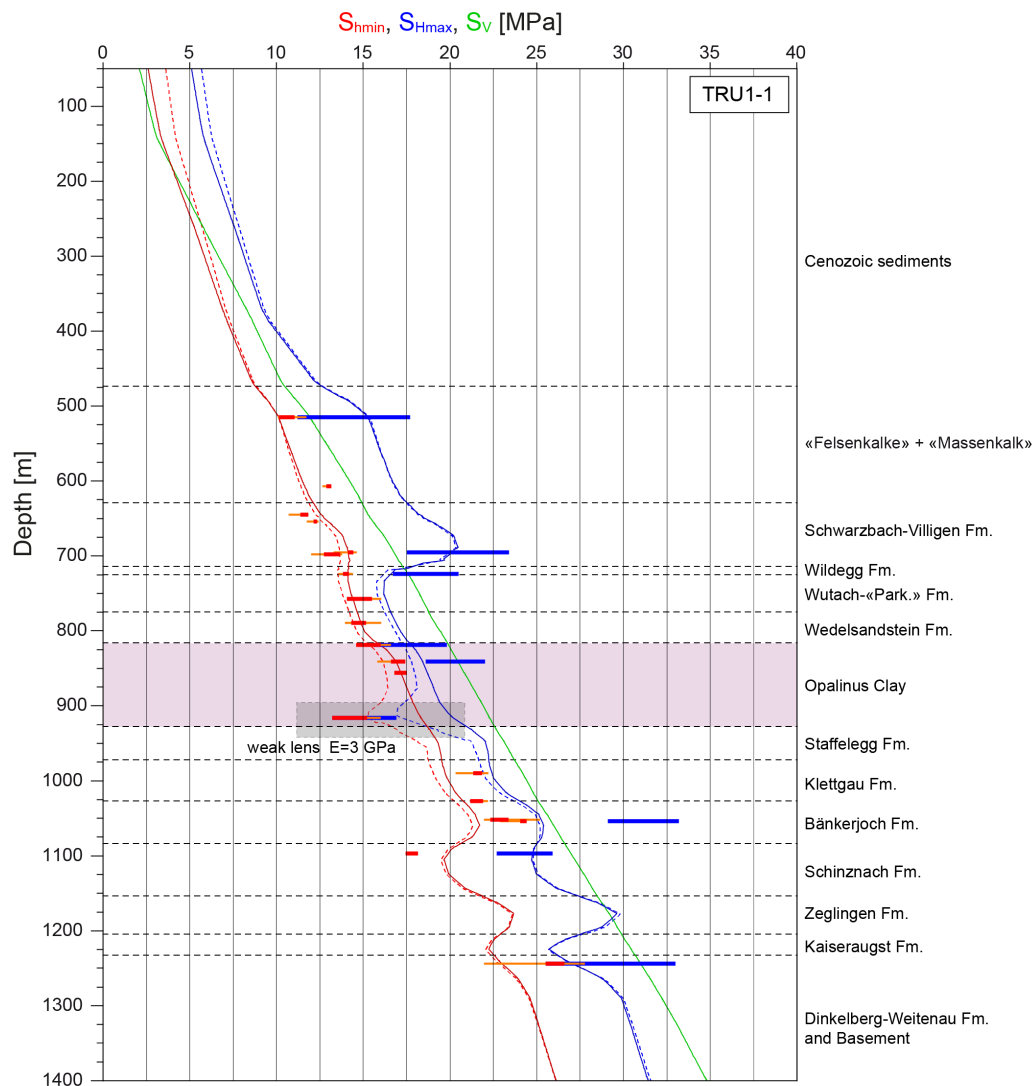


Fig. 4-10: Model results along the borehole TRU1-1 trajectory – Part II

Continuous lines are the stress components derived from the best fit results using the P50 values of the rock stiffness. Dashed lines are the results from a model that has a weak lens implemented in the surroundings of the MHF station at 916 m TVD in the Opalinus Clay with $E = 3$ GPa.

To compare the best fit model results for the three siting regions, the differential stress $S_1 - S_3$ is used and displayed with contour lines on the mean layer of the Opalinus Clay as well as on E-W and N-S cross-sections crossing the locations of individual boreholes in the siting regions. Fig. 4-11 shows the results for the JO siting region, Fig. 4-12 for the NO siting region and Fig. 4-13 for the ZNO siting region. All three figures have the same colour-coding for the displayed differential stress. The three main results from these three stress models are: First, and not surprising, is that stress magnitudes are depth-dependent. Second, the stiff layers exhibit higher differential stress and shield the weaker layer of the clay-rich formation and third, the key results are the same for all three models.

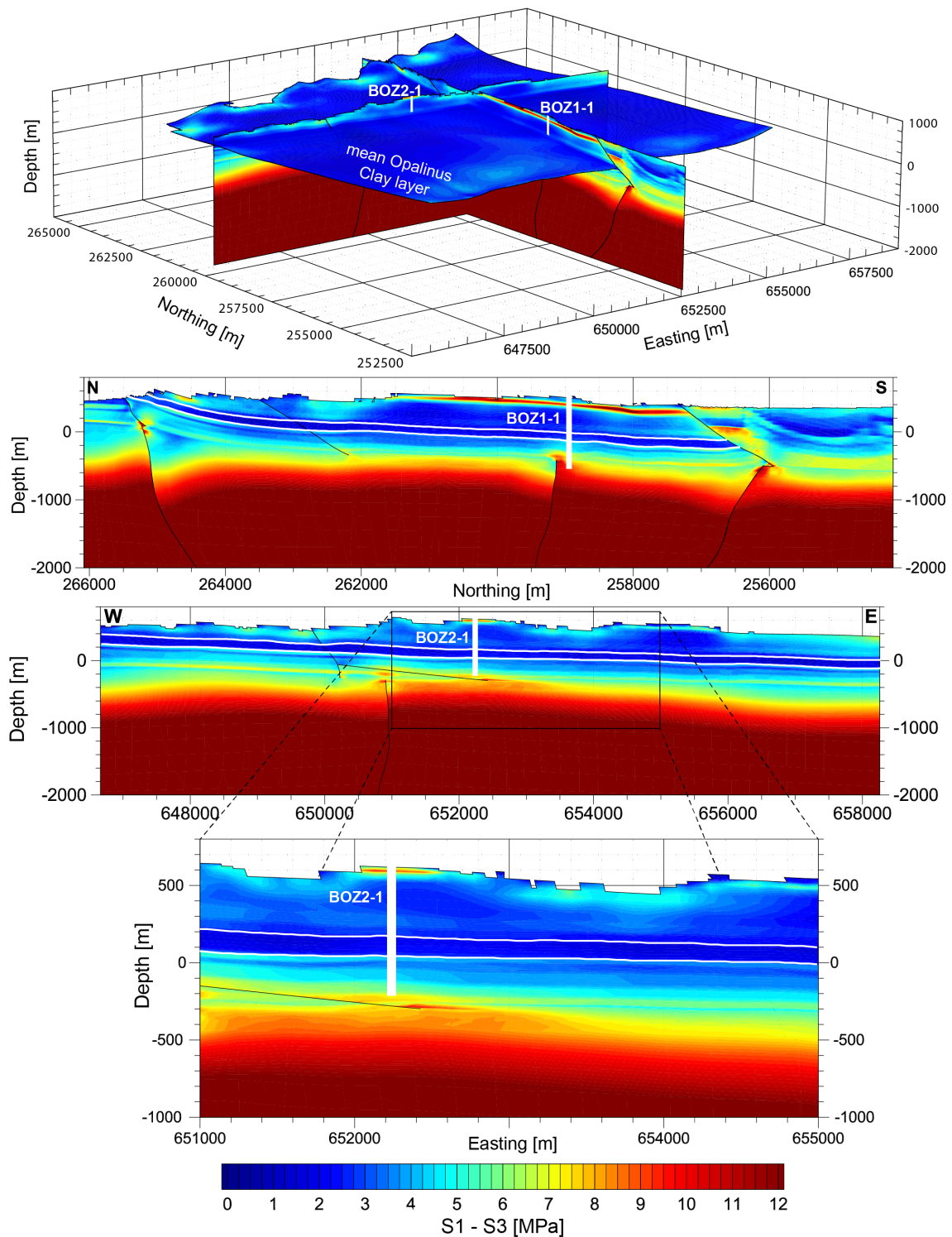


Fig. 4-11: Differential stress from best fit stress model JO using P50 values

Top: Mean Opalinus Clay layer dips towards the south-east. Cross-sections show the mechanical stratification. Layers with higher stiffness (Malm, Muschelkalk) show higher differential stress compared to clay-rich layers. Top and bottom of the Opalinus Clay are indicated with horizontal white lines. Vertical white bars show borehole trajectories.

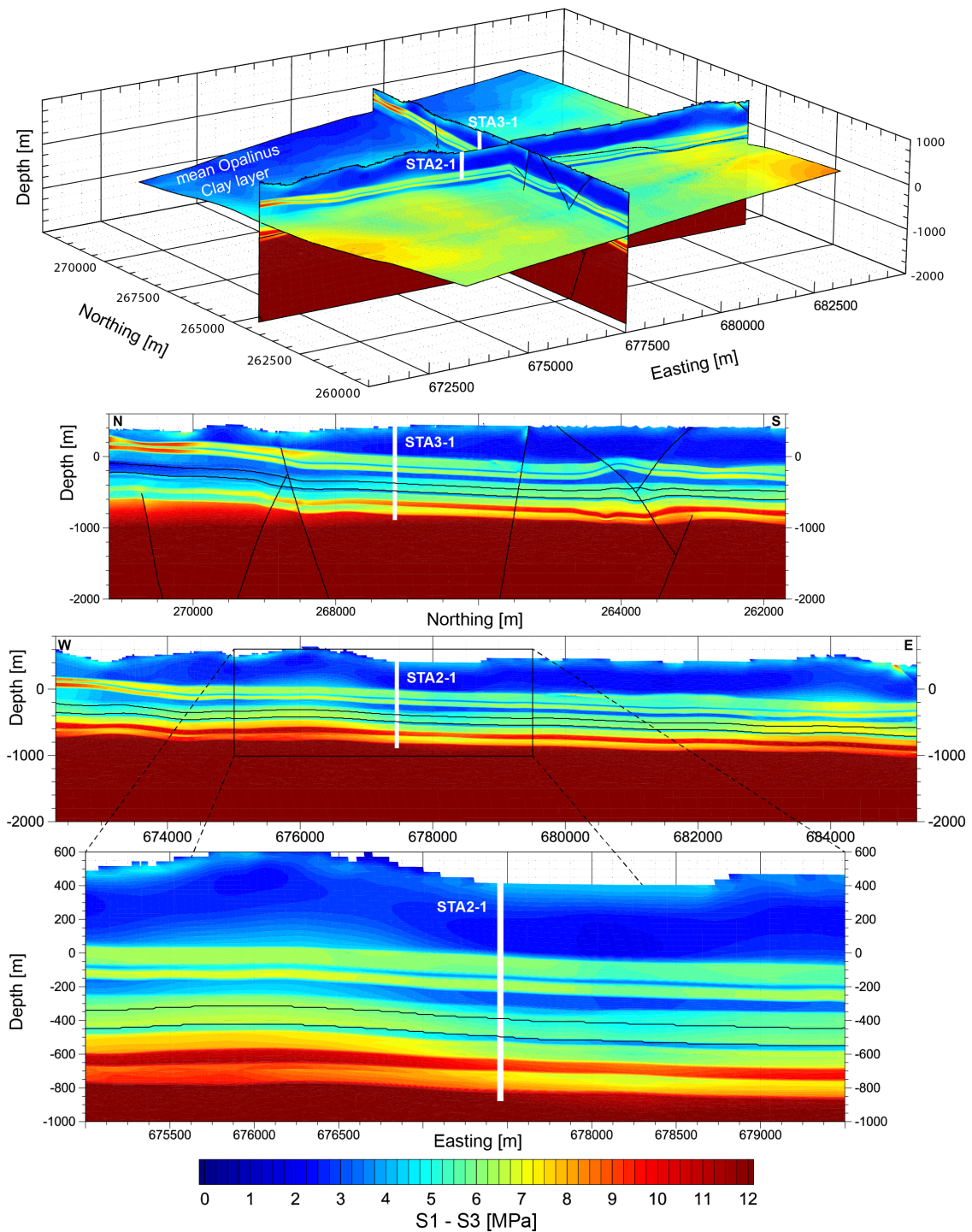


Fig. 4-12: Differential stress from best fit stress model NL using P50 values

Top: Mean Opalinus Clay layer dips towards south-east. Cross-sections show the mechanical stratification. Layers with higher stiffness (Malm, Muschelkalk) show higher differential stress compared to clay-rich layers. Top and bottom of the Opalinus Clay are indicated with horizontal white lines. Vertical white bars show the borehole trajectories.

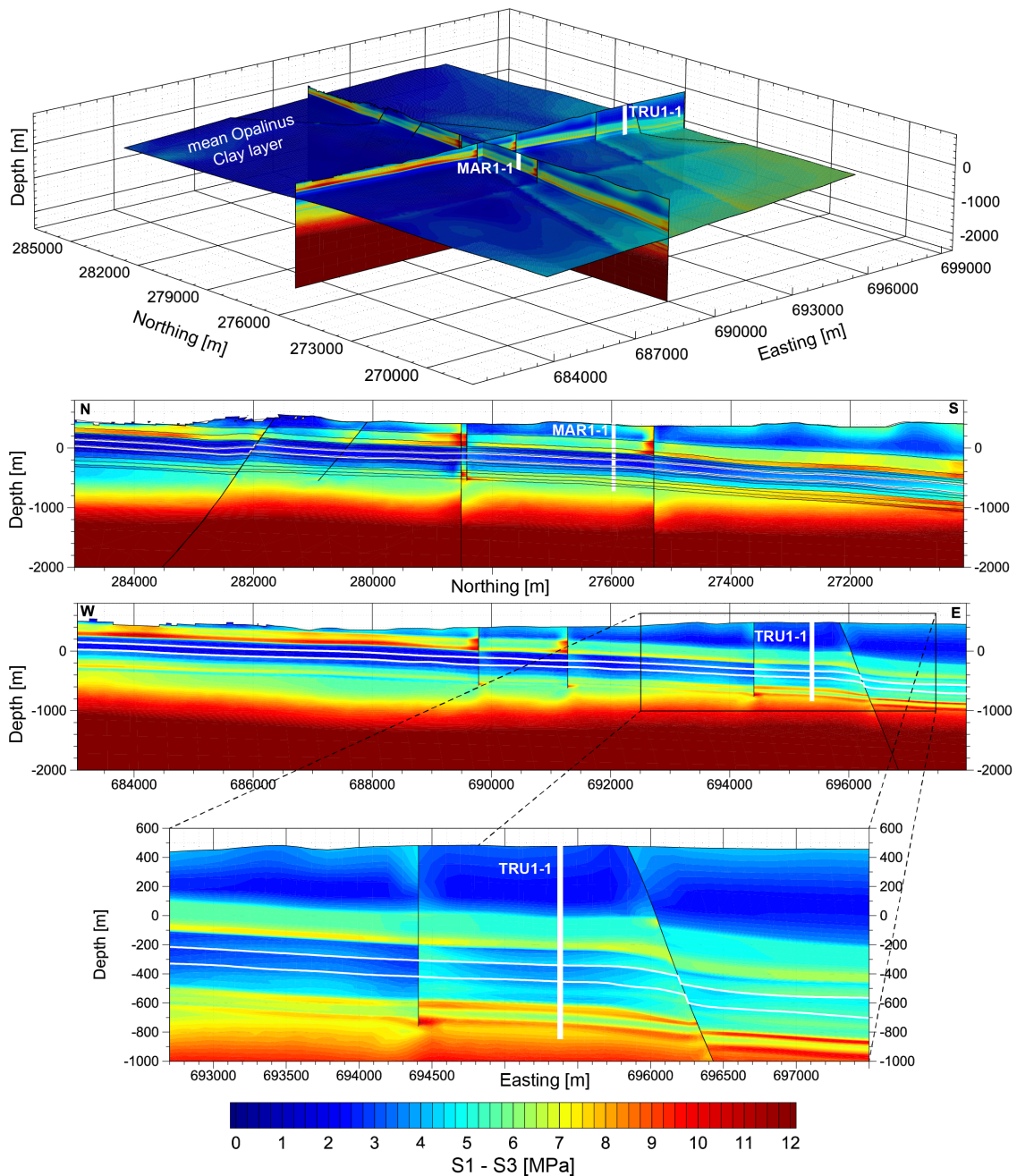


Fig. 4-13: Differential stress from best fit stress model ZNO using P50 values

Top: Mean Opalinus Clay layer dips towards south-east. Cross-sections show the mechanical stratification. Layers with higher stiffness (Malm, Muschelkalk) show higher differential stress compared to clay-rich layers. Top and bottom of the Opalinus Clay are indicated with horizontal white lines. Vertical white bars show the borehole trajectories.

4.6 Effect of faults, topography and reef facies on stress model results

4.6.1 Effect of faults

To investigate the effect of faults on the stress tensor components the P50 model results were compared with a model where faults are excluded. The exclusion is technically implemented either by deleting the contact surfaces or by increasing the static coefficient of friction to $\mu = 50$, both leading to zero relative displacement at the faults. Fig. 4-14 shows the result of this sensitivity study (dashed lines) for the ZNO siting region along a SW-NE profile at 300 m below sea level compared with the P50 model results (continuous lines). Black vertical lines in Fig. 4-14 show the locations where the faults of the ZNO stress model cut the profile. In the rock volume between faults, the stress magnitudes of S_{Hmax} and S_{Hmin} show very little differences between the models, except for the area between the Rafz – Marthalen Flexure and the Rheinau Fault where differences are visible, but still <1 MPa. However, here the profile runs at high angle close to the fault which may explain this feature. In general, only in the near-field of the faults at distances of a couple of hundred metres can differences be observed between the two model results, but these are generally small (<1 MPa) compared to the uncertainties of the stress magnitude data.

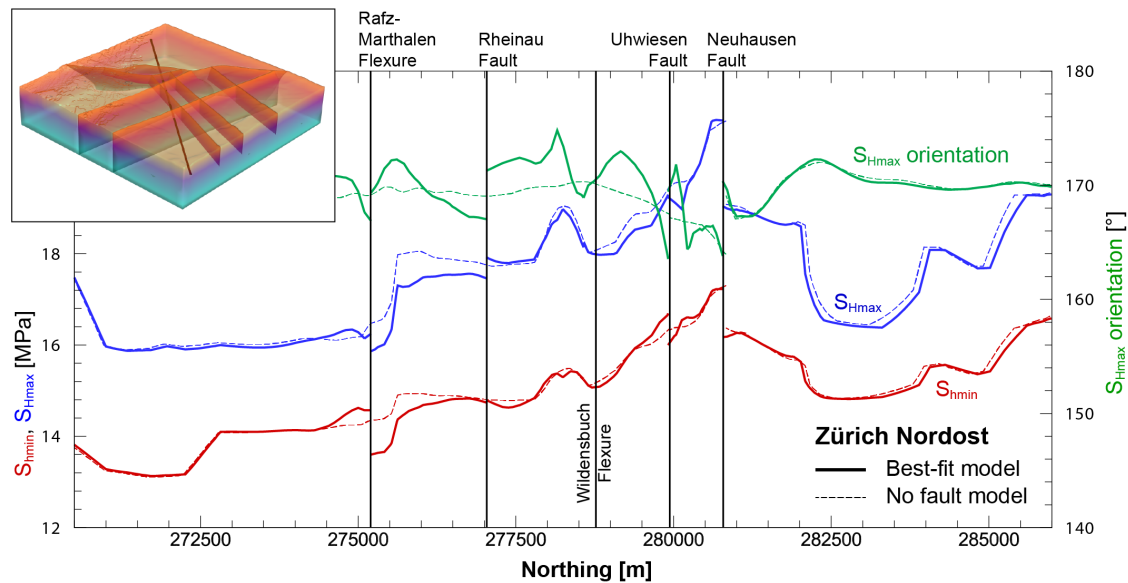


Fig. 4-14: Effect of faults on stress magnitudes and stress orientation in ZNO

Stress magnitudes and S_{Hmax} orientation are shown along a horizontal profile from SW to NE at 300 m depth below sea level. The inlay figure shows the location of the profile as a black line; colours are arbitrary. Vertical black lines denote cross-points of the modelled faults with the horizontal profile.

Furthermore, the effect of faults is also small compared to the expected variability of stress due to the variability of rock stiffness. Note the remaining offset stress magnitudes where the profile crosses the Neuhausen Fault in the model with no fault displacement. This reveals that stress changes are not necessarily controlled by fault displacement but are imposed by lateral stiffness and density contrasts due to the vertical offset of formations. Also, long-term models that allow for more fault displacement would not change these observations. Fault slip does not constantly lower shear stresses along faults, but it is a continuous build-up and release of stress and strain in

the seismic cycle (Heidbach & Ben-Avraham 2007). In this sense displacement along faults keeps the rock volume within the faults strong as it releases stress and strain imposed by plate tectonics (Townend & Zoback 2000).

To summarise, the effect of faults on the stress tensor components is small compared to other sources that control stress magnitude changes. These changes are localised within a few hundred metres around the fault. As a result, the changes in the S_{Hmax} orientation are small as well ($<5^\circ$). Such small rotations cannot be resolved due to the resolution limit of any stress indicator which, even with high quality image logs, is not better than 10° in the best case. Only on the metre scale can a rotation of S_{Hmax} be detected locally as shown in Fig. 2-4 where the borehole TRU1-1 cuts a fault. These findings agree with the results of a recent comprehensive study of Reiter et al. (2024) who showed using a generic 3D geomechanical-numerical model that any changes in stress tensor components are indeed localised and probably only resolvable in the fault core and damage zone around the fault at a couple of hundred metres.

4.6.2 Effect of topography

The effect of topography can be visualised with a comparison of S_v and the Regime Stress Ratio (RSR) value. The RSR is a continuous variable used to describe the tectonic stress regime. It is calculated after the formula given in Simpson (1997) and is basically a combination of the Andersonian stress regime index n (Anderson 1905, 1951):

$$RSR = (n + 0.5) + (-1)^n(R - 0.5)$$

where $R = (S_2 - S_3)/(S_1 - S_3)$ where S_1 , S_2 , and S_3 are the three principal stresses (see Fig. 1-1) and $n = 0$ for normal faulting, $n = 1$ for strike-slip and $n = 2$ for thrust faulting. The RSR variable ranges from radial extension (RSR = 0) over normal faulting stress regime (RSR = 0.5), strike-slip stress regime (RSR = 1.5) and thrust faulting stress regime (RSR = 2.5) to constriction (RSR = 3), including the transitional stress regimes of transtension (RSR = 1) and transpression (RSR = 2).

Fig. 4-15 shows as an example a zoom into the E-W cross-section through STA2-1 of the best fit stress model results for NL. It is the same zoom as presented in the lower part of Fig. 4-12, but with different values displayed. S_v is horizontally variable due to the almost 200 m increase of topography within 1,200 m west of the STA2-1 borehole. Due to the relatively small variability of density between the different formations, S_v approximately follows the topography. The RSR variable, however, depends also on the horizontal stress magnitudes which are largely controlled by the stiffness of the individual formations. This results in laterally variable RSR values within formations that are closer to the surface and that have high stiffness. Therefore, in the «Felsenkalke» + «Massenkalk» layer the stress regime below the high topography west of STA2-1 is strike-slip due to higher values for S_v and transpressional east of the the location of STA2-1 where the topography is lower.

This effect vanishes with greater depth as the relative contribution of the additional vertical stress due to topography decreases with depth. In the Formations below the Opalinus Clay, the effect of the topography is small in S_v and no longer visible in the RSR variable which is laterally almost constant with values around 0.5 indicating a normal faulting stress regime.

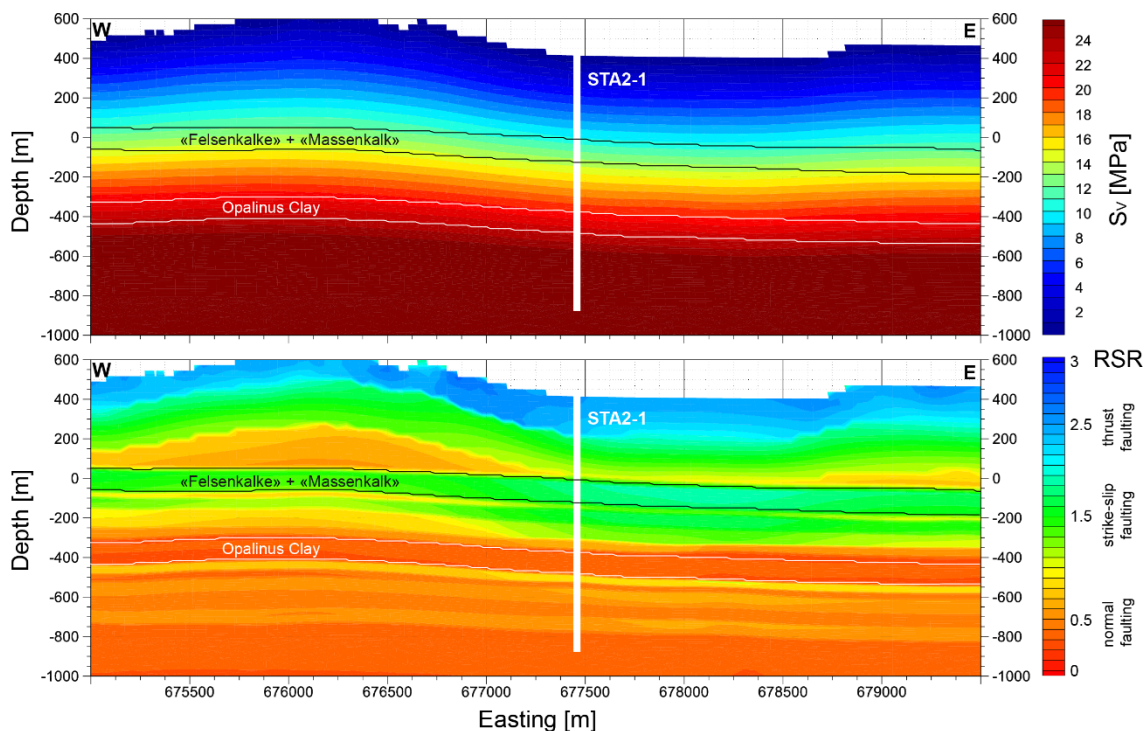


Fig. 4-15: Effect of topography on stress magnitudes along a cross-section through STA2-1

Upper figure shows the vertical stress magnitude S_v , lower figure the Regime Stress Ratio RSR. The RSR is a continuous scale for the tectonic stress regime with $RSR = 0.5$ for a normal faulting stress regime, $RSR = 1.5$ for a strike-slip stress regime, and $RSR = 2.5$ for a thrust faulting stress regime.

4.6.3 Effect of reef facies in the NL siting region

In the NL siting region, the Upper Dogger includes the «Herrenwis Unit» in the south-eastern part. This is a reef facies with presumably higher static Young's modulus. At the location of STA2-1 the «Herrenwis Unit» is only 10 m thick. West of STA2-1 at BAC1-1 it does not exist, but at STA3-1 and BUL1-1 that are east of STA2-1 it has a thickness of approximately 40 m.

To investigate the potential effects of the lateral stiffness contrast, the stiffer «Herrenwis Unit», i.e. the reef facies, was implemented into the model and assigned a stiffness value of $E = 30$ GPa, which contrasts with the P50 value of the other parts of the Upper Dogger formations with $E = 19$ GPa. The assigned 30 GPa for the stiffness of the «Herrenwis Unit» as a lateral subunit of the model layer Upper Dogger is the P95 value and thus a quite conservative assumption. The effect on the stress result is, however, small.

Fig. 4-30 shows the comparison between the best fit stress model for NL with homogeneous values for the Upper Dogger layer (upper figure) and the model variant with the «Herrenwis Unit» implemented as a stiffer part of the layer. The comparison shows that this results in an increase of approximately 1.5 MPa in the horizontal differential stress due to the increase of a higher S_{Hmax} magnitude in the reef facies. This increase is local and limited to this layer and it does not affect the stress state below and above.

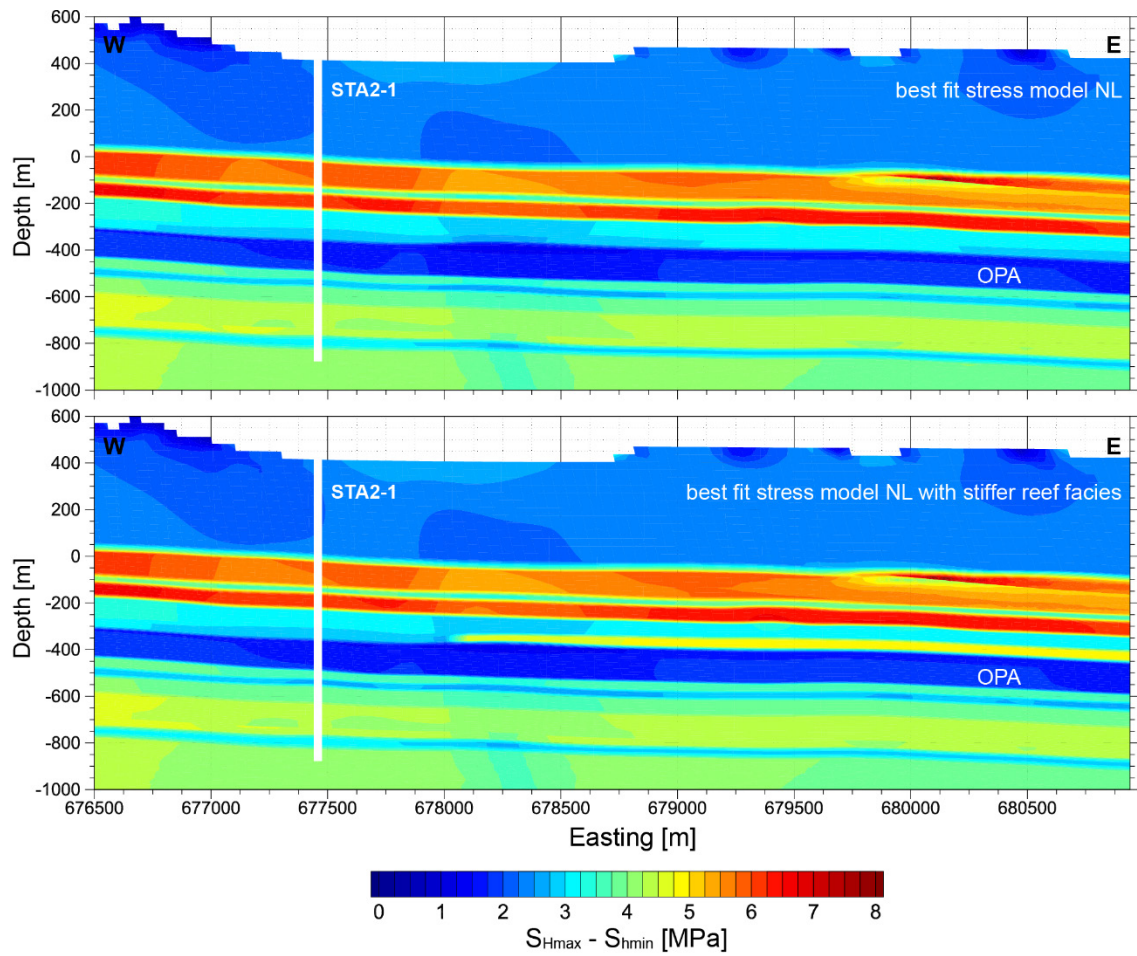


Fig. 4-16: Effect of stiffer reef facies in NL along a cross-section through STA2-1

Best fit stress model for NL (upper figure) compared with a variant that has implemented a stiffer reef facies with $E = 30$ GPa in contrast to $E = 19$ GPa. In the lower figure the yellow layer above the Opalinus Clay east of STA2-1 indicates the increase of horizontal differential stress in the eastern part of the «Herrenwis Unit», i.e. the reef facies.

4.7 Model limitations and uncertainties of the best fit models

4.7.1 Fault kinematics and fault implementation

As described at the beginning of Chapter 4 the stress models cannot provide any information on fault kinematics or local details of the effect of faulting on the stress field in the fault damage zone or the fault core. The latter is a resolution limit of the model that has the key objective of predicting the 3D stress field beyond the boreholes in the larger intact rock volume and not local stress changes or evolution of stress over geological times in the near-field (a few hundred metres) around the fault.

Regarding fault kinematics, e.g. the quantification of fault slip rates over geological times, the model cannot provide this essentially due to the following two reasons.

The first is that the model determines a displacement at the boundary that achieves a best fit to the measured stress data from the TBO campaign. This displacement is arbitrary and does not represent the true kinematics of the region but is an integration of all shortening or dilation processes over geological timescales that affected the model volume. Therefore, fault slip rates cannot be derived. The relative displacement along the modelled faults in the three site models is in the order of a few tens of cm, depending on how the fault is oriented in the model. This low relative displacement is to some extent the inverted argument from Section 4.6.1 where it is shown that the effect of fault displacement on the total stresses is low and localised.

The second reason is that the difference of the displacements at the model boundaries that result in a best fit with respect to the stress data is <2% comparing the stress models with and without faults. This is negligible compared to other sources of model uncertainties. That is, the stress models are not sensitive to the kinematics at the faults when we consider the stresses in the volume and look for a fit to the stress magnitude data. The reason for this is that shear stresses that are built up and released at the faults in the seismic cycle are small and local compared to the elastic energy stored in the volume between the faults (Ziebarth et al. 2020). This implies that a model that aims to describe the total stresses in the volume away from the faults does not need to incorporate faults into the model geometry. The changes in the stresses due to faults in the far-field (a few hundred metres) are negligible.

4.7.2 Uncertainties due to numerical issues and rheology assumptions

For the model discretisation, a numerical resolution of down to approximately 10 m in the vertical and 100 m in the horizontal were achieved. These numbers refer to the dimension of the finite elements with linear shape functions that were used. Linear shape functions means that within an element, i.e. between the element nodes, the field variable – here displacement – can vary linearly. To test if the numerical resolution has an influence on the the model results, a sensitivity test was set up using for the same finite elements second order shape functions. In these, the shape functions are quadratic (2nd order polynomial), which increases the model resolution significantly. These tests showed that the differences are very small except at locations where the changes in the stress field are high and localised. Locations with higher stress changes are, for instance, where faults end within the model volume or where fault curvature is high. These two local effects are seen e.g. in the N-S cross-section of the JO model shown in Fig. 4-11. Here the fault curvature and the fault tip in the model volume produce artefacts in terms of local stress concentrations. But again, comparing the results of a model with and without an active fault where these artefacts do not occur, the difference in the modelled stress field is very small and negligible in comparison to stress variability and other sources of uncertainties. The model assumes in the volume linear elasticity and at the contact fault surfaces the plastic Mohr-Coulomb failure criterion. Within the model volume, the stress state is below the strength limit everywhere.

4.7.3 Uncertainties of stress prediction in the model volume

It was shown along the borehole trajectory TRU1-1 in Fig. 4-9 that the stress model can fit the stress magnitude data from the MHF/SR tests reasonably well. Identified outliers can be fitted with adapted values for the local rock stiffness (Fig. 4-10). This adaptation exercise could be performed for each model until the model prediction agrees with the stress magnitude for each borehole and each location where stress magnitude data are available.

However, this would only provide the most likely stress state in the larger rock volume, but it would not describe the probability range of the stress state that is to be expected in the model volume. Thus, the key challenge is not to determine the best fit model, but the description of the most likely, i.e. the P50 stress state and the probability range around this median. The key control of the stress bandwidth is the probability distribution of the rock stiffness (Fig. 4-8). Since the true values and distribution of rock stiffness are not known, all data-supported model scenarios have to be tested to obtain the full bandwidth. However, a full Monte-Carlo simulation approach that scans the complete rock stiffness parameter space is not feasible given that each simulation needs several hours of CPU time and $\gg 100,000$ simulations would be necessary. The following Chapter 5 shows how the stress bandwidth is nonetheless estimated in a reasonable approximation.

5 Predicted stress magnitudes for siting regions

5.1 Prediction of stress magnitudes in Opalinus Clay

As discussed in Section 3.7, the high number of stress measurements and the consistent gradients of both S_{hmin} and S_{Hmax} allow to predict horizontal stress magnitudes of Opalinus Clay with confidence. Based on gradients presented in Tab. 3-3 and an S_v gradient of 24.5 MPa/km as an average from the three siting regions, stress magnitudes are given in 50 m intervals for depths between 400 and 1,000 m in Tab. 5-1. Note that the four bounds are renamed to reflect project-specific use of values.

The gradients listed in Tab. 3-3 are valid for all three siting regions, but the actual depths at which Opalinus Clay is encountered varies between siting regions and spatial location within siting regions.

Tab. 5-1: Depth-dependent stress magnitudes in Opalinus Clay

Based on gradients as specified in Tab. 3-3, but with renaming of categories of bounds. S_v values are derived from a gradient of 24.5 MPa/km as an average gradient from the three siting regions.

Depth below ground [m]	Minimum horizontal stress magnitude S_{hmin} [MPa]				Maximum horizontal stress magnitude S_{Hmax} [MPa]				Average vertical stress magnitude S_v [MPa]
	Min. possible value	Likely lower value	Likely upper value	Max. possible value	Min. possible value	Likely lower value	Likely upper value	Max. possible value	
400	6.7	7.4	8.0	8.7	6.7	7.8	9.2	10.5	9.6
450	7.6	8.4	9.0	9.8	7.6	8.8	10.4	11.9	10.8
500	8.4	9.3	10.0	10.9	8.4	9.7	11.5	13.2	12.0
550	9.3	10.2	11.0	12.0	9.3	10.7	12.7	14.5	13.2
600	10.1	11.1	12.0	13.1	10.1	11.7	13.8	15.8	14.4
650	11.0	12.1	12.9	14.2	11.0	12.7	15.0	17.1	15.6
700	11.8	13.0	13.9	15.2	11.8	13.6	16.1	18.5	16.8
750	12.6	13.9	14.9	16.3	12.6	14.6	17.3	19.8	18.0
800	13.5	14.9	15.9	17.4	13.5	15.6	18.4	21.1	19.2
850	14.3	15.8	16.9	18.5	14.3	16.6	19.6	22.4	20.4
900	15.2	16.7	17.9	19.6	15.2	17.5	20.7	23.7	21.6
950	16.0	17.7	18.9	20.7	16.0	18.5	21.9	25.1	22.8
1,000	16.9	18.6	19.9	21.8	16.9	19.5	23.0	26.4	24.0

5.2 Prediction of stress magnitudes in other formations

For formations other than Opalinus Clay, stress models are used to bracket stress magnitudes at any location.

The results of the stress models using either P50 rock stiffness values for all layers (Fig. 4-9) or individual ones to achieve a best fit (Fig. 4-10) show that a fit of the stress magnitude data can be achieved. However, this does not answer the question of the two key challenges how to a) assess if the estimated stress magnitudes are representative for a larger rock volume and b) at which local rock stiffness they have been measured. The stress magnitude data show that they follow a distribution within each lithology and their values are predominantly controlled by the by the distribution of rock stiffness. The latter also follow a distribution and thus, for a prediction of the stress state beyond the boreholes a stress bandwidth must be provided that reflects a probability distribution, rather than a single value that results from the best fit model scenario.

A Monte-Carlo approach evaluating $\gg 100,000$ individual model scenarios to scan the complete rock stiffness variability in each stress model layer, cannot be performed given that each simulation takes 6 – 12 hours. Thus, the stress bandwidth is approximately estimated by using only 13 simulations. They cover a range of possible model scenarios and the matrix in Fig. 5-1 shows the set-up of these scenarios. The horizontal axis in this figure denotes the real but unknown rock stiffness values at the location of the MHF stations where the stress magnitudes have been estimated. The vertical axis denotes the rock stiffness at the location of the MHF stations that are assumed in the stress model.

		Real but unknown rock stiffness at MHF stations				
		P05	P25	P50	P75	P95
Rock stiffness at MHF stations in the model	P05	CASE 3		stress under-estimation		
	P25					
	P50			CASE 1 best-Fit model		
	P75					
	P95			stress over-estimation		CASE 2

Fig. 5-1: Set-up of 13 model scenarios to estimate the stress bandwidth

On the horizontal axis the real but unknown stiffness probabilities at the MHF stations are given whereas the vertical axis gives the homogeneous value used in the stress model for the lithology in which the MHF station is located. Red colours indicate model scenarios that overestimate the stress prediction, blue colours indicate an underestimation. White boxes show model scenarios that are very unlikely and not used for the bandwidth estimation.

If the real stiffness at a MHF station were to be P50 and the stiffness in the stress model is P50 for all layers, a displacement boundary condition can be estimated that results in a perfect fit of the estimated stress magnitudes. For all other MHF stations in the model scenario that have a higher real rock stiffness than the P50 value, the resulting stress is overestimated, and for all other MHF stations in the simulation that have a real lower rock stiffness than the P50 value the resulting stress is underestimated.

Thus, in principle one can distinguish three general cases:

CASE 1 – Centre: Assume that all MHF stations have P50 stiffness values

For all MHF stations it is assumed that the real but unknown rock stiffness is P50 (central column) and the best fit displacement is also determined using P50 values. Keeping the displacement boundary conditions that result from the model calibration but running four further model scenarios with the P05, P25, P75 and P95 rock stiffness values would then cover the bandwidth of the stress magnitude distribution in each lithology (central column in Fig. 5-1). The upper two simulations would result in an overestimation of the modelled stress and the lower two simulations in an underestimation of the modelled stress.

CASE 2 – High end: Assume that all MHF stations have $\geq$ P95 stiffness values

For all MHF stations it is assumed that the real but unknown rock stiffness is $\geq$ P95. In this example P95 is assumed (right column) and the best fit displacement is determined using the P95 rock stiffness values for the stress model. Keeping the displacement boundary conditions that result from the model calibration but running four further model scenarios with the, P75, P50, P25, and P05 rock stiffness values would then cover the bandwidth of the stress magnitude distribution in each lithology (right column in Fig. 5-1). Only the model scenario at the bottom of that column would result in a best fit; the other four simulations would underestimate the modelled stresses.

CASE 3 – Low end: Assume that all MHF stations have $\leq$ P05 stiffness values

For all MHF stations it is assumed that the real but unknown rock stiffness is $\leq$ P05. In this example P05 is assumed (left column) and the best fit displacement is determined using the P05 rock stiffness values for the stress model. Keeping the displacement boundary conditions that result from the model calibration, but running four further model scenarios with the, P25, P50, P75 and P95 rock stiffness values would then cover the bandwidth of the stress magnitude distribution in each lithology (left column in Fig. 5-1). Only the model scenario at the top of that column would result in a best fit; the other four simulations would overestimate the modelled stresses.

The matrix in Fig. 5-1 has 25 combinations, but the model scenarios in each corner are very unlikely. For example, the case in the bottom left corner would assume that all MHF stations are located by chance at locations where the rock stiffness is $\leq$ P05 and that the rest of the model volume has P95 rock stiffness values. These are two extreme assumptions with a very low probability. For the same reasoning all other model scenarios that include a P05 or P95 rock stiffness value and not a P50 value as a counterpart are disregarded and denoted with white fields in the matrix. The bandwidth is estimated from the remaining 13 model scenarios, i.e. the median and the distribution. Even though some cases are probably less likely than others, weights are not applied for the estimation of the stress bandwidth. Assuming an equal distribution of each model scenario is a conservative assessment.

5.3 Example of stress bandwidth in borehole TRU1-1

Fig. 5-2 shows the result along the borehole trajectory of TRU1-1 compared with the stress magnitude data from the MHF test stations and with the P05 – P95 distribution of rock stiffness. The light grey area covers the P05 – P95 stress model results and rock stiffness and the dark grey area the P25 – P75 distribution. The black line in the centre is the median P50. The results show that key driver for the stress bandwidth is the bandwidth of the rock stiffness. They also show that the stress bandwidth fits to all stress magnitude data except the data record at 916 m TVD close to the bottom of the Opalinus Clay layer. This measurement is an outlier beyond the P05 rock stiffness and thus also an outlier beyond the P05 – P95 stress bandwidth. As shown in Fig. 4-10, this measurement can be fitted when a rock stiffness of $E = 3$ GPa is assumed, which is below the P05 value of $E = 7.8$ GPa estimated for the Opalinus Clay in the ZNO model.

The figures in App. H display the stress bandwidth for the other seven boreholes compared with stress magnitude data. They show similar results to the example from TRU1-1.

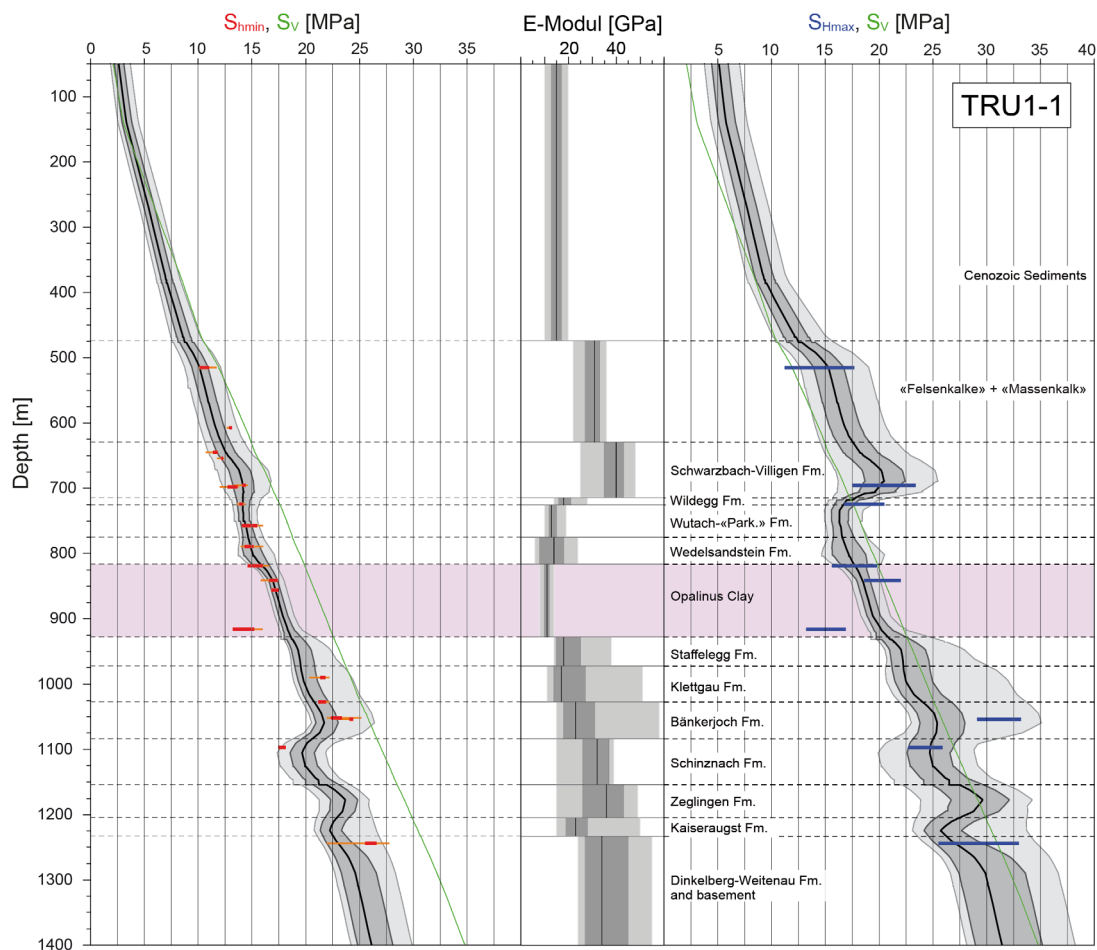


Fig. 5-2: Bandwidth of modelled stress magnitudes along the TRU1-1 trajectory

Left figure shows the P05 – P95 probability distribution of the modelled S_{hmin} magnitudes, the centre the distribution of stiffness, and the right figure the modelled S_{Hmax} distribution. Dark bold line is the median. Dark grey areas denote the P25 – P75 distribution and light grey the P05 – P95 distribution. Horizontal red and blue lines are the measured and derived magnitudes values for S_{hmin} and S_{Hmax} , respectively. The image in the middle shows the P05 – P95 distribution of rock stiffness for the ZNO siting region along the borehole trajectory TRU1-1.

The stiff layers of the Malm and the Bänkerjoch Formation show a higher stress variability, i.e. a wider stress bandwidth compared to the weaker clay-rich formations. This is due to the higher variability of the rock stiffness in the competent layers and in particular the relatively high P95 rock stiffness values for these. As a result, the stiff layer shields the weaker clay-rich layers. In addition, these also have a narrower P05 – P95 distribution of rock stiffness. Both result in the significantly smaller bandwidth of modelled stress for the Opalinus Clay.

5.4 Prediction of the tectonic stress regime in the three siting regions

As the stress models provide in-situ stress field predictions for the entire model volumes, they can be used to derive stress bandwidth along arbitrary generic trajectories. As an example, Fig. 5-3 shows the bandwidth of the Regime Stress Ratio RSR (see Section 4.6.2) values along a vertical trajectory into the high-level section of the current repository project for license application in the respective siting regions (location indicated by Orange points in Fig. 4-2, Fig. 4-3, and Fig. 4-4).

In Fig. 5-3 the three Andersonian classes are indicated with a colour-code. Red is for a normal faulting stress regime, green is for a strike-slip stress regime and blue is for a thrust faulting stress regime. With depth, the light grey area is the P05 – P95 probability range of the RSR value, dark grey is the P25 – P75 probability range, and the black line is the median P50 value. For the JO siting region, the stress regime in the Opalinus Clay the median P50 indicates normal faulting stress regime, but at higher probabilities transtensional and strike-slip is also possible. In contrast in the Opalinus Clay in NL it is a normal faulting stress regime with high confidence. This agrees with the stress magnitude data at the individual siting regions (see App. F) and can be explained with the differing depth of the Opalinus Clay (JO most shallow, NL deepest). It is well known also from other sedimentary basins, that the stress regime changes with depth from thrust faulting via strike-slip to normal faulting since the vertical stress is steadily increasing with depth whereas the horizontal stress gradients are less steep. 0 also provides the P05 – P95 distributions for the stress magnitudes.

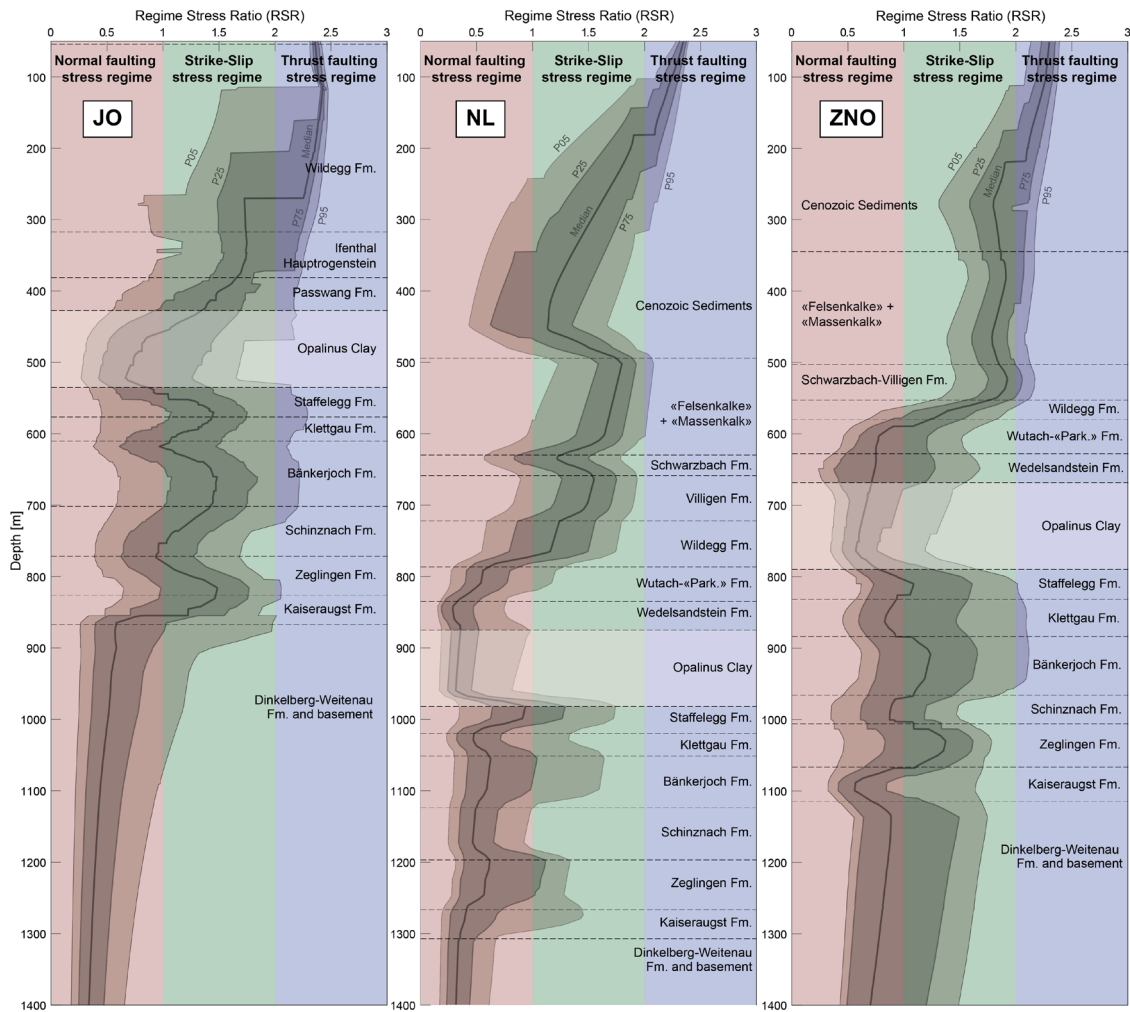


Fig. 5-3: Prediction of bandwidth of the Regime Stress Ratio RSR along vertical trajectory in each siting region

Location of the vertical trajectory is indicated by Orange point in Figs. 4-2 to 4-4. P05 – P95 probability distribution of the RSR value derived from the modelled stress tensor along the vertical trajectories in each siting region. Dark line is the median P50. Dark grey area denotes the P25 – P75 distribution and light grey the P05 – P95 distribution. Note the difference of the RSR bandwidth in the Opalinus Clay between the three siting regions.

6 Conclusions

The new stress data from the TBO campaign has confirmed the previously inferred NNW-SSE orientation of the maximum horizontal stress (S_{Hmax}) in Northern Switzerland.

The stress magnitudes in the three siting regions are now much better constrained with a nearly tenfold increase in minimum horizontal stress magnitude (S_{hmin}) data points, and the addition of sleeve reopening tests to bracket S_{Hmax} magnitudes with much greater confidence compared to previous campaigns.

Based on this substantial data complemented with 3D geomechanical-numerical modelling of the in-situ stress field, the following main conclusions can be drawn:

1. The Opalinus Clay exhibits very consistent depth gradients of the horizontal stress magnitudes, irrespective of siting region. The prevailing stress regime in the Opalinus Clay at the borehole locations is normal faulting ($S_v \geq S_{Hmax} \geq S_{hmin}$) for all three regions, and not strike-slip faulting ($S_{Hmax} \geq S_v \geq S_{hmin}$) as anticipated before the TBO campaign.
2. Characteristics of the in-situ stress field are similar in all three siting regions, with depth and mechanical layering coupled to tectonic loading controlling the stress magnitudes.
3. The contemporary 3D in-situ stress field can be predicted spatially using geomechanical-numerical models with a similar degree of reliability in all three siting regions.
4. Faults incorporated in the models indicate no relevant influence on the in-situ stress field in the far-field (a few hundred metres away from the faults).

The high number of stress measurements together with the consistent depth gradients of S_{hmin} and S_{Hmax} allow to estimate the bandwidth of expected horizontal stress magnitudes in Opalinus Clay at a specific depth directly from interpreted test results (Tab. 5-1).

For all formations other than Opalinus Clay, the 3D geomechanical-numerical model results can be used to bracket the horizontal stress magnitudes. Such predictions are provided in this report, along synthetic vertical trajectories in the three siting regions (App. I).

7 References

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App. A Borehole failure interpretations

The following figures show the different borehole failure modes that have been interpreted as stress induced failures.

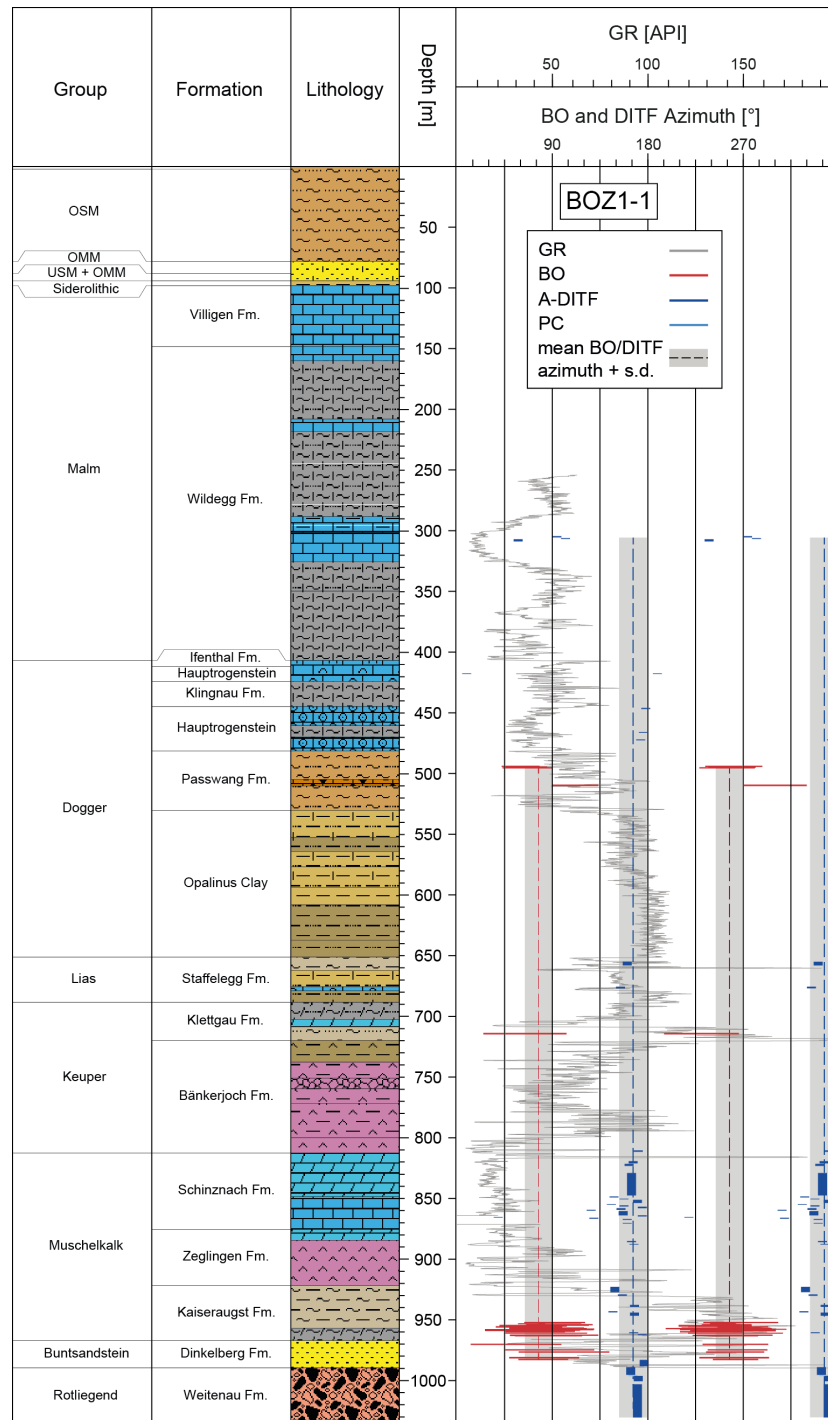


Fig. A-1: Borehole failure modes along the BOZ1-1 trajectory

Lateral extent of the red lines is the picked width of the BOs.

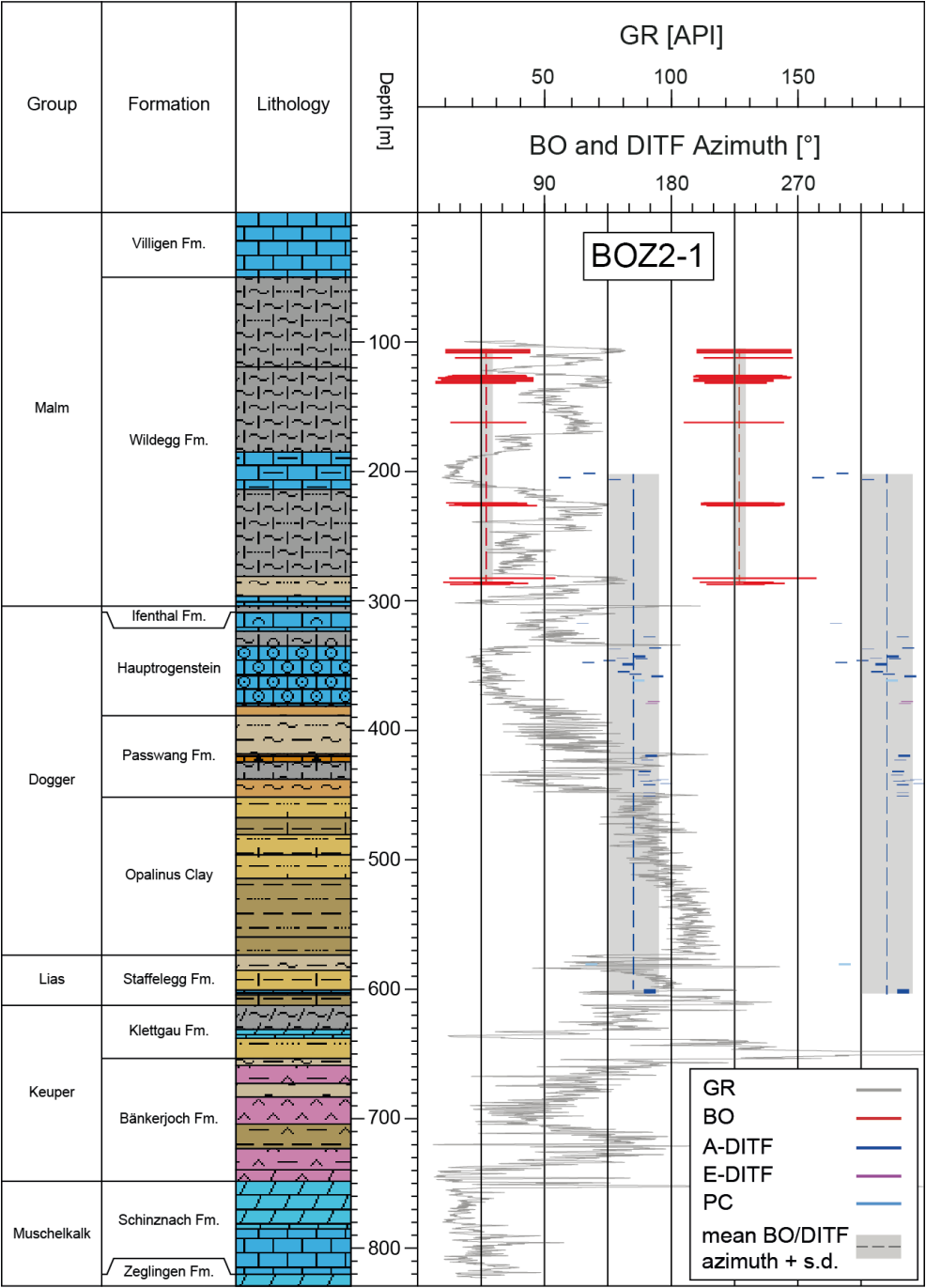


Fig. A-2: Borehole failure modes along the BOZ2-1 trajectory
Lateral extent of the red lines is the picked width of the BOs.

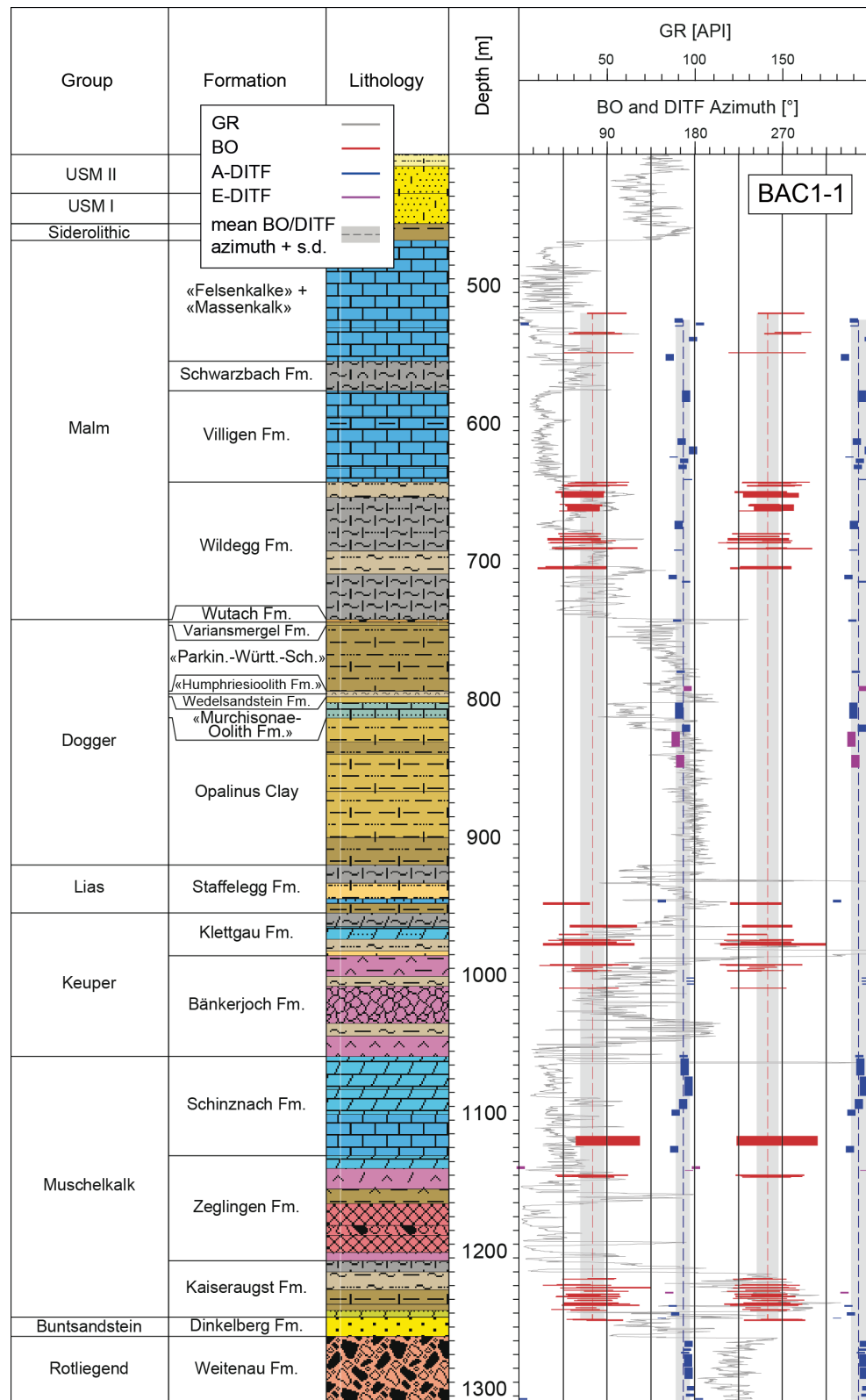


Fig. A-3: Borehole failure modes along the BAC1-1 trajectory
Lateral extent of the red lines is the picked width of the BOs.

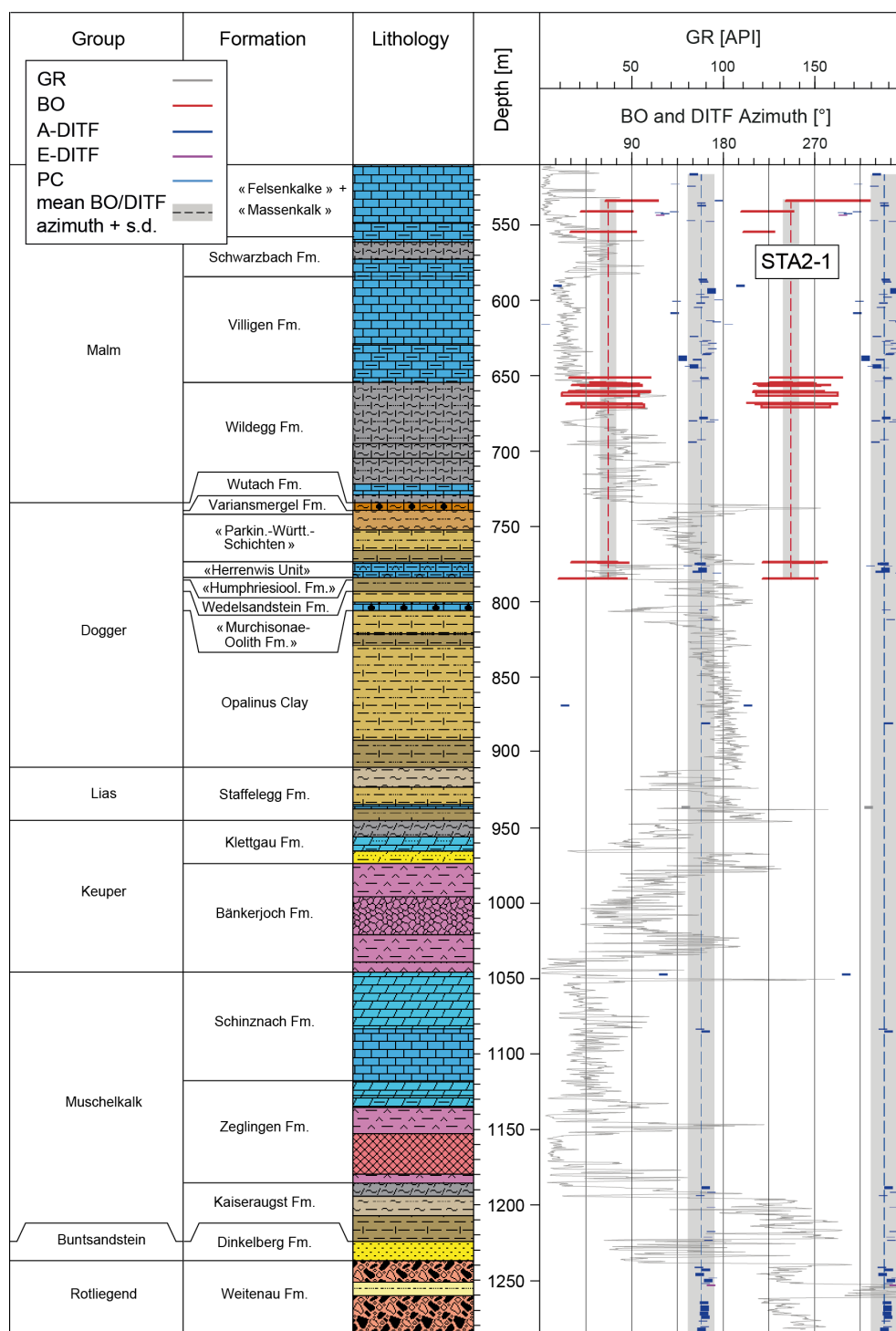


Fig. A-4: Borehole failure modes along the STA2-1 trajectory
Lateral extent of the red lines is the picked width of the BOs.

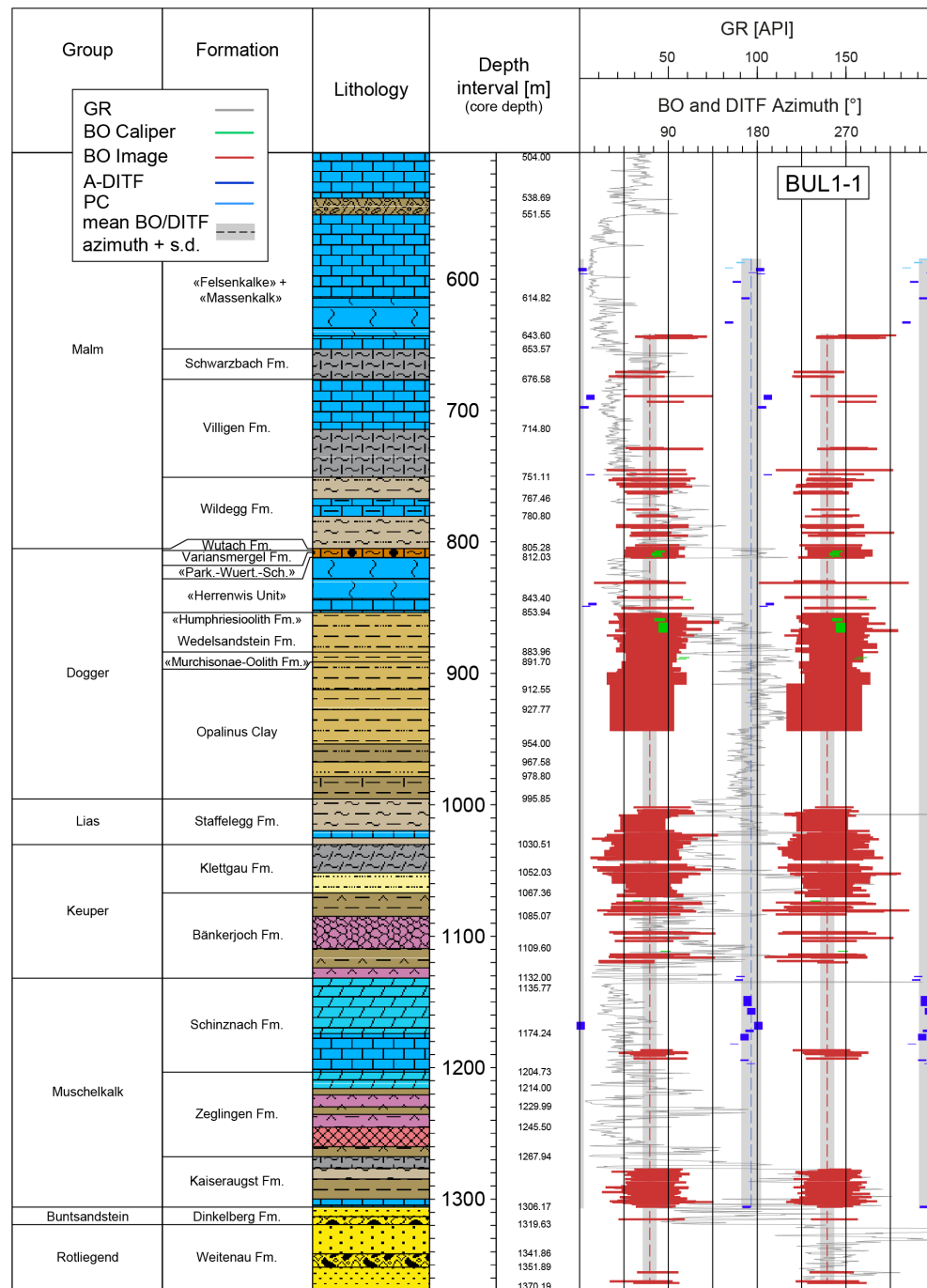


Fig. A-5: Borehole failure modes along the BUL1-1 trajectory
Lateral extent of the red lines is the picked width of the BOs.

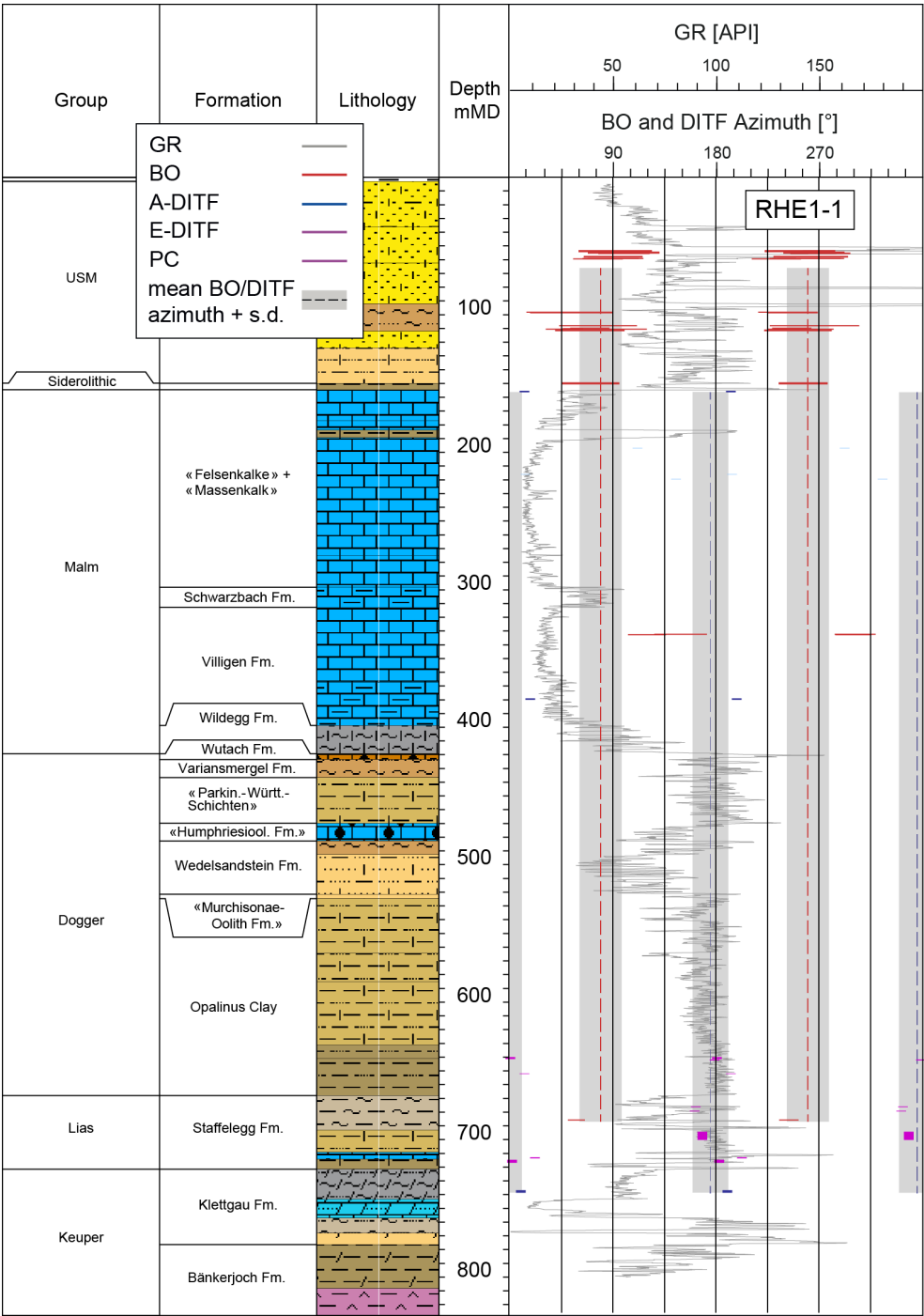


Fig. A-6: Borehole failure modes along the RHE1-1 trajectory
Lateral extent of the red lines is the picked width of the BOs.

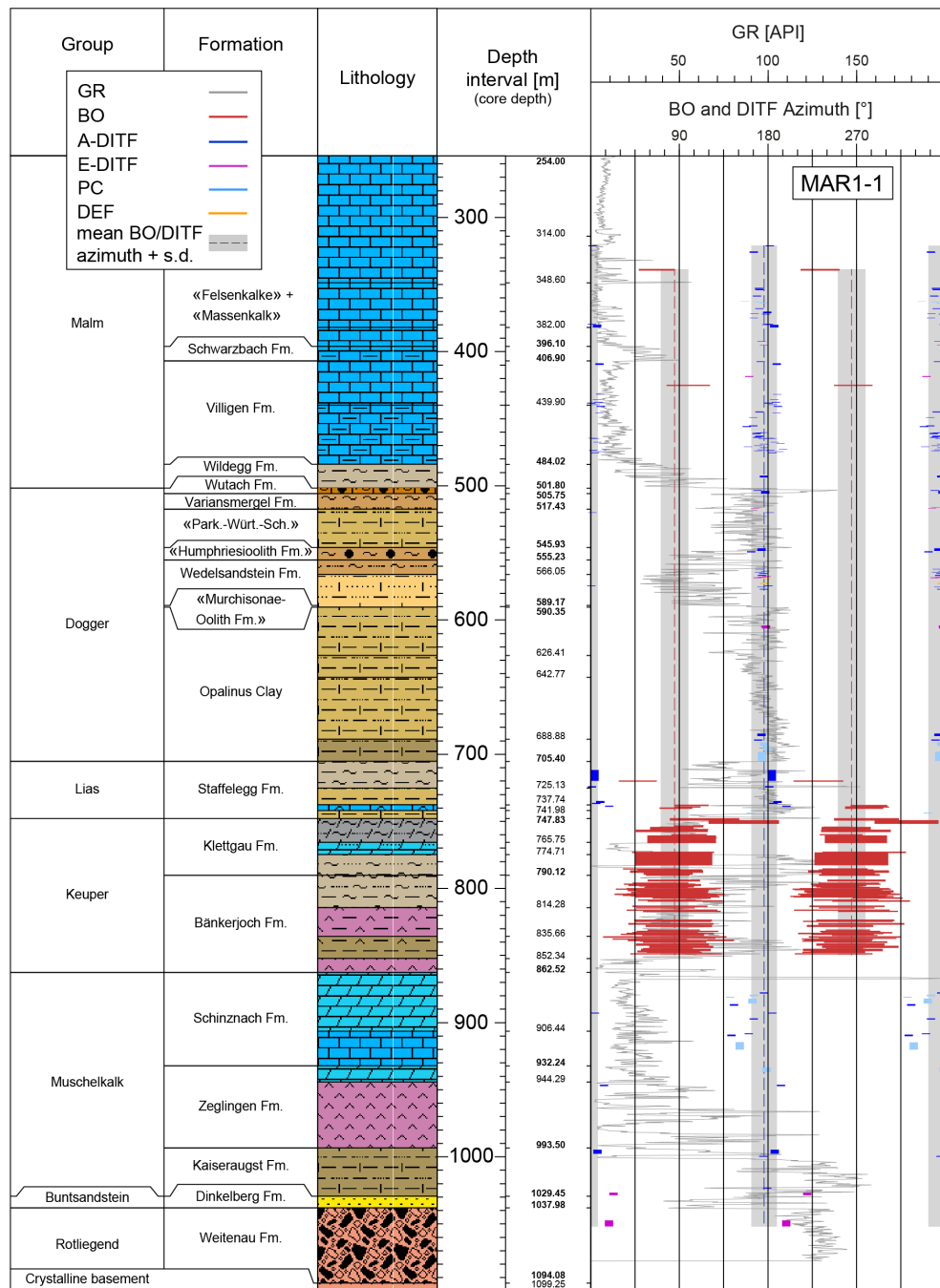


Fig. A-7: Borehole failure modes along the MAR1-1 trajectory
Lateral extent of the red lines is the picked width of the BOs.

The following figures show the rose diagrams of the picked failure models that have been interpreted as stress-induced failures for the individual boreholes.

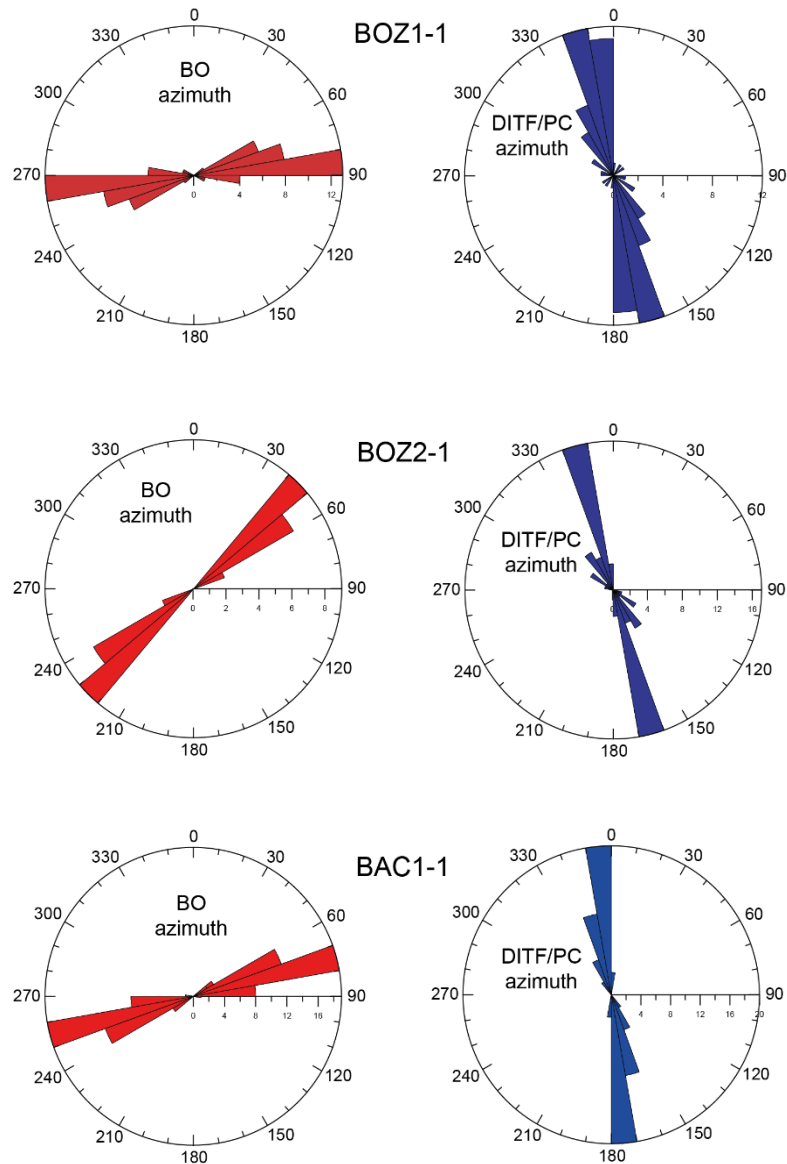


Fig. A-8: Rose diagrams of borehole failure orientations for each borehole

Rose diagrams show only the orientations of the individual picks of the borehole failures (BO Borehole Breakout, DITF Drilling Induced Tensile Fracture, PC Petal Centreline). For the estimation of the mean orientation, weights are used according to the length of the picks.

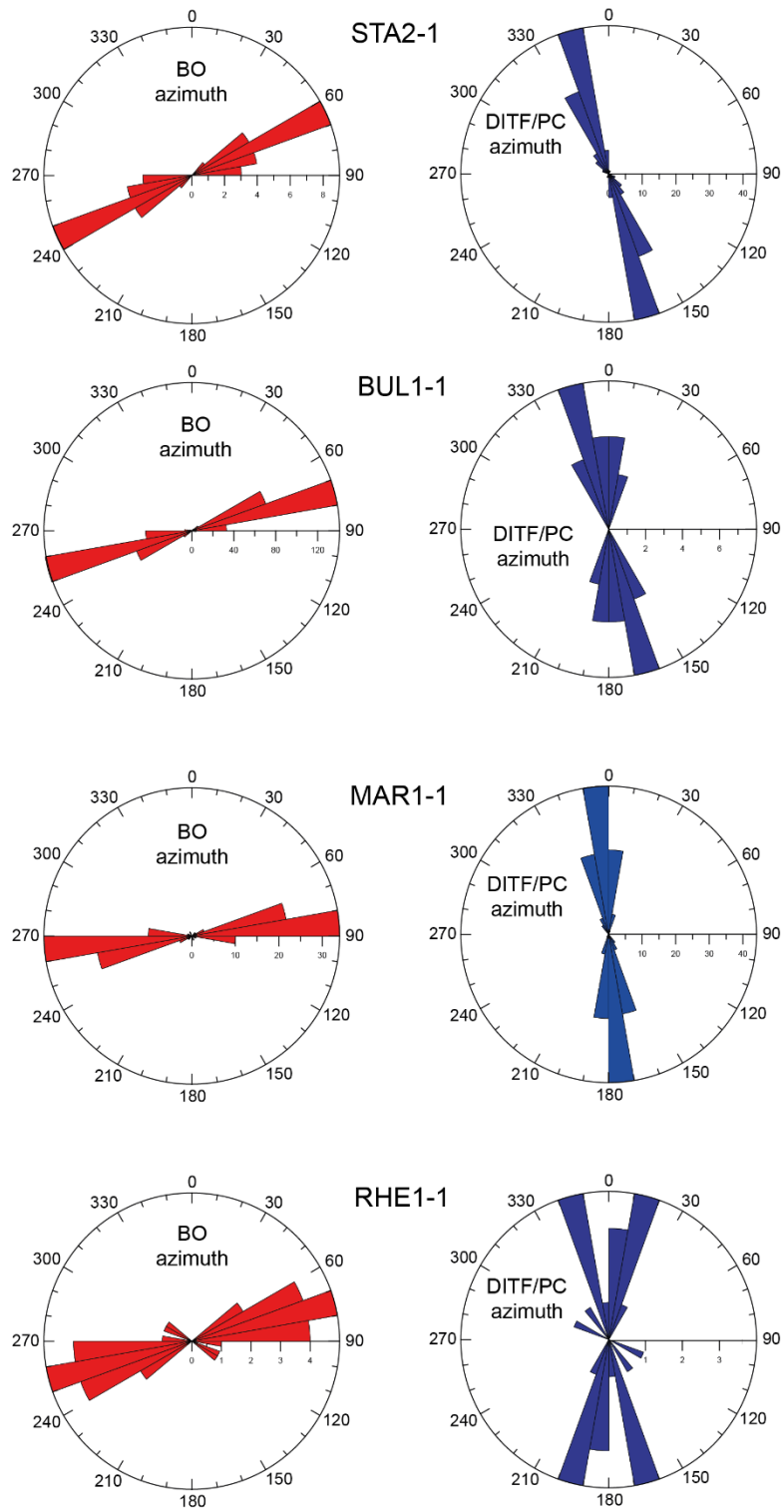


Fig. A-8: Cont.

**App. B MHF formation coverage by boreholes and siting regions
(digital)**

Excel file with MHF coverage per formation, facies when relevant, and per siting region.

App. C Stress magnitude data (digital)

One Excel file per siting region with the details of each MHF station.

- C.1 Stress magnitude data in the JO siting region**
- C.2 Stress magnitude data in the NL siting region**
- C.3 Stress magnitude data in the ZNO siting region**

App. D Sleeve reopening results (digital)

Excel file with pressure details for sleeve reopening interpretation leading to maximum horizontal stress magnitudes.

- D.1 Pressure details for the sleeve reopening interpretations for boreholes in JO**
- D.2 Pressure details for the sleeve reopening interpretations for boreholes in NL**
- D.3 Pressure details for the sleeve reopening interpretations for boreholes in ZNO**

App. E CDF of S_{hmin} and S_{hmax} gradients for the Opalinus Clay

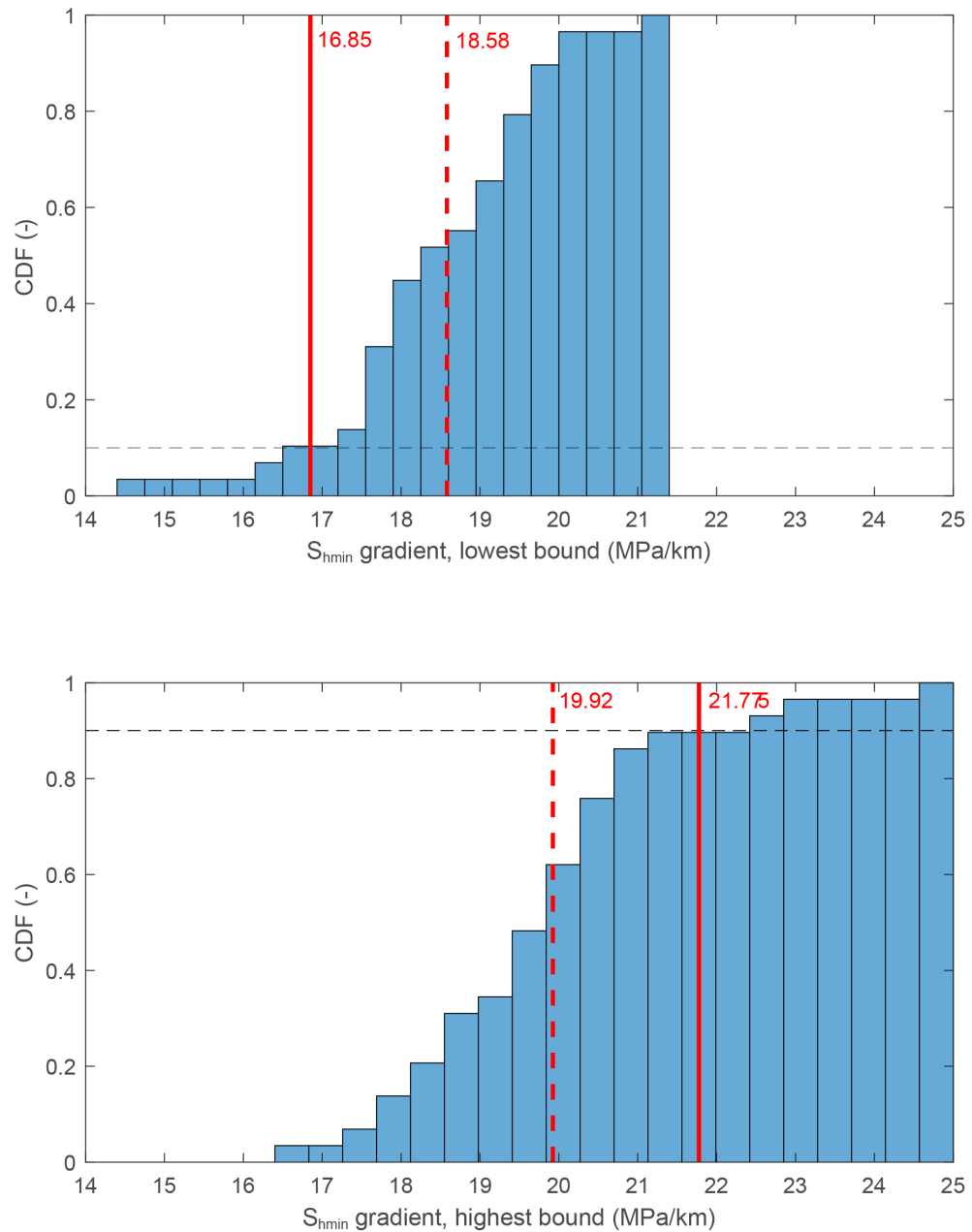


Fig. E-1: Cumulative distribution functions (CDF) of the gradient of the minimum horizontal stress (S_{hmin}) measured by MHF in the Opalinus Clay (TBO boreholes and Benken borehole)

CDFs using the wide range of the measured S_{hmin} magnitudes. The top panel presents the lowest bound and the bottom panel the highest bound. On each panel, the median of the distribution is plotted as a vertical dashed red line. On the top panel, the P10 value of that distribution is plotted as a continuous red line. On the bottom panel, the P90 value is also plotted as a continuous red line.

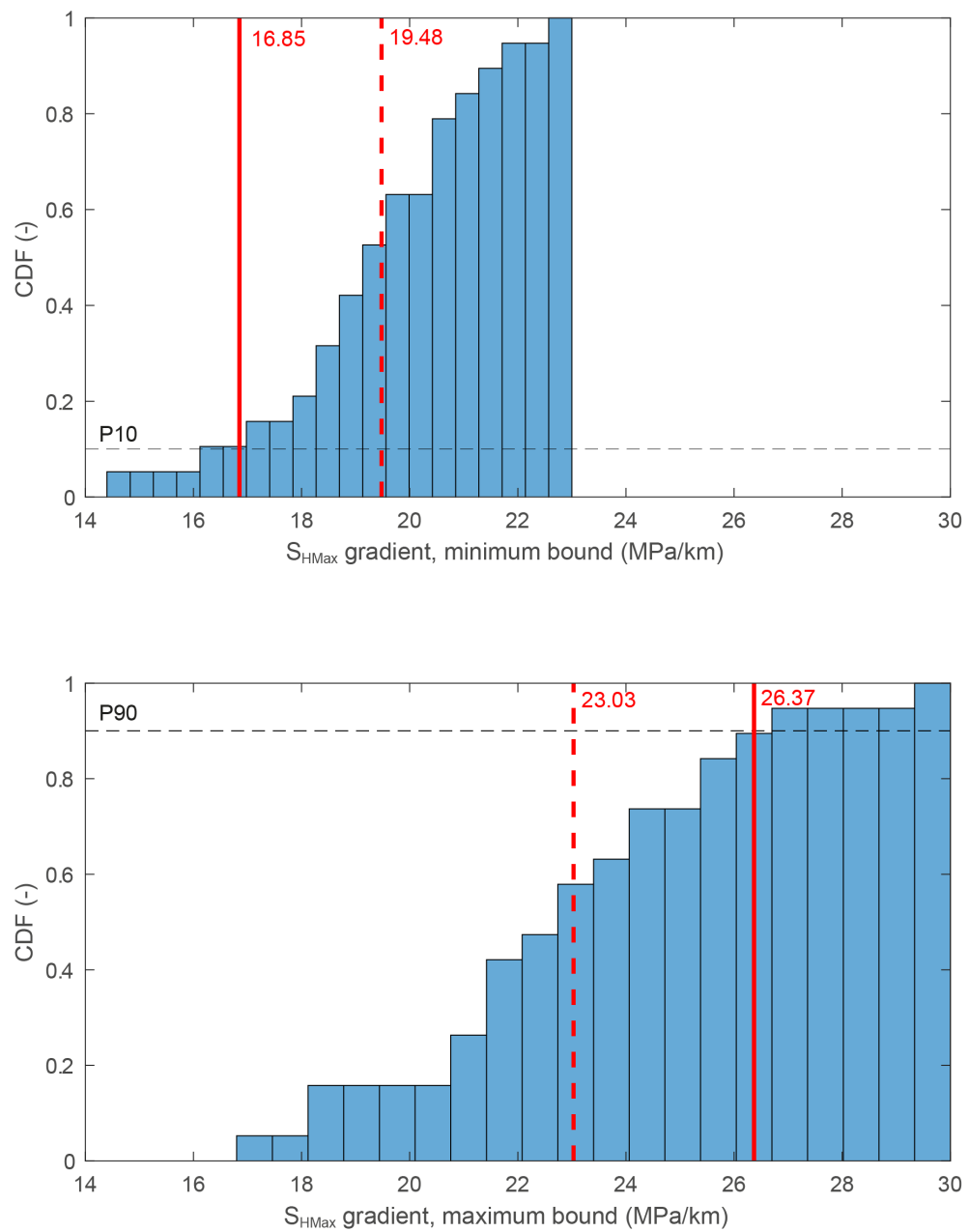


Fig. E-2: Cumulative distribution functions of the gradient of the maximum horizontal stress (S_{Hmax}) interpreted from SR measurements in the Opalinus Clay (TBO boreholes only)

The top panel presents the CDF of the minimum bound and the bottom panel that of the maximum bound. On each panel, the median of the distribution is plotted as a dashed vertical red line. On the top panel, the P10 value of that distribution is plotted as a continuous red line. On the bottom panel, the P90 value is also plotted as a continuous red line.

App. F Rock properties (digital)

The tables for the overview of the rock properties in the three siting regions are digital Excel sheets. Here all elastic and plastic properties are listed, including information that has not been used in the stress models such as tensile and compressive strength.

F.1 Overview of rock properties for the JO siting region

F.2 Overview of rock properties for the NL siting region

F.3 Overview of rock properties for the ZNO siting region

App. G Principle of FAST Calibration

The in-situ stress field in the upper crust is mainly controlled by volume forces due to gravity and surface forces due to plate tectonics. The latter are commonly introduced by Dirichlet displacement boundary conditions at the lateral model boundaries. Estimating these displacements to achieve a best fit with respect to stress magnitude data is referred to in the following as model calibration. The tool FAST Calibration (Fast Automatic Stress Tensor Calibration) provides an automatic statistical calibration following the approach described by Reiter & Heidbach (2014), Hergert et al. (2015), Ziegler et al. (2021) and Ziegler & Heidbach (2021). It is a Matlab tool and is meant to work with the visualisation software Tecplot 360 EX 2019 R1 and higher in conjunction with the Tecplot 360 Add-on GeoStress v2.0 (Heidbach et al. 2020). Technical details of the tool and examples are presented in the FAST Calibration v2.0 manual (Ziegler & Heidbach 2021).

For the calibration process, data records of the magnitude of maximum and minimum horizontal stress, S_{Hmax} and S_{Hmin} are essential at individual points within the model volume. The calibration is achieved by a comparison of the modelled stress to the observed S_{Hmax} and S_{Hmin} magnitudes in dependence of the Dirichlet displacement boundary condition. Thus, the models' calibration depends on only two displacements which facilitates the calibration process as the best fit boundary conditions can be found by a system of linear equations. The automated setup and solving of this linear equation system is the core of the FAST Calibration tool. Note that two implicit assumptions are that 1) the rheology is linear elastic in the model volume and 2) that the stress state is controlled by a uniform lateral displacement.

The calibration procedure is illustrated in Fig. G-1. Three different test model scenarios with different arbitrary but reasonable displacement boundary conditions are solved (Fig. G-1a). At several locations within the model volume stress data records are available (Fig. G-1b). For each of the test model scenarios the modelled stress state is compared with these stress data records. Each comparison provides a mean deviation for S_{Hmax} and S_{Hmin} , respectively (Fig. G-1c). A system of linear equations is set up in the domain of the displacement boundary conditions (x and y) and the deviations of observed and modelled data (z) (Fig. G-1d). For the smallest deviation of each, S_{Hmax} or S_{Hmin} , an infinite number of corresponding displacement boundary conditions exist. However, only one set satisfies both the requirements for the smallest deviation in observed and modelled S_{Hmax} and S_{Hmin} . This set of displacement boundary conditions is applied to compute the best fit model.

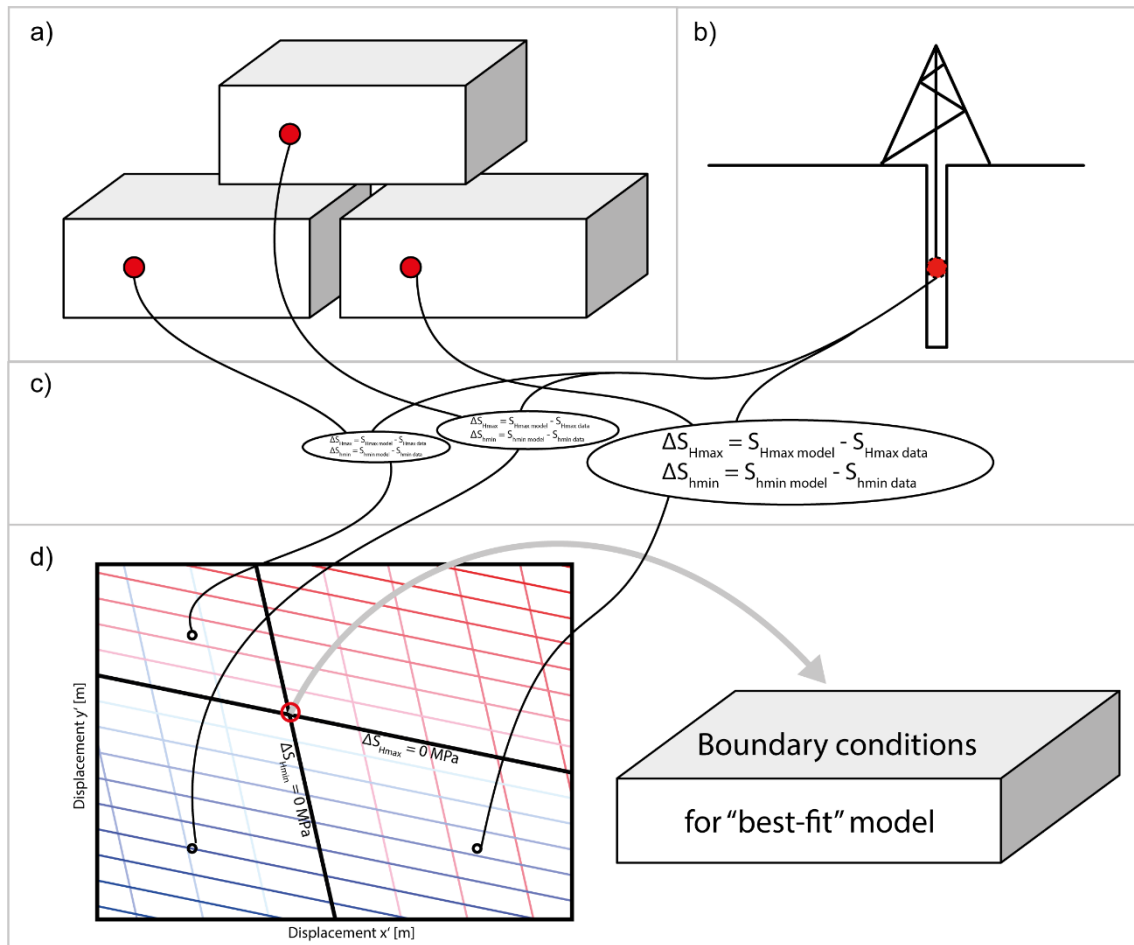


Fig. G-1: Basic workflow of the tool FAST calibration

The stress state from three test model scenarios with arbitrary displacement boundary conditions (a) and observed stress data records (b) are compared (c). A set of linear equations is set up that provide the best fit boundary conditions (d).

App. H Stress model results along borehole trajectories (digital)

For each of the eight boreholes of the TBO campaign where MHF/SR tests were performed we provide layered pdf files with the results of the stress model compared to the estimated magnitude of S_{hmin} and S_{hmax} . Per default we show in the layered pdf's the best fit model compared to the estimated stress magnitude data. The other layers contain the P50 values for the Poisson's ratio and the Youngs modulus, the stress bandwidth estimates, and the model variant where faults are inactive (model NL). Along the borehole trajectory of TRU1-1, the pdf file contains two additional layers for the two models that use individual values for the rock stiffness and the one with the weak lens as explained in Section 4.5 and shown in Fig. 4-9 and Fig. 4-10, respectively.

H.1 Stress model results along the borehole trajectory of BOZ1-1

H.2 Stress model results along the borehole trajectory of BOZ2-1

H.3 Stress model results along the borehole trajectory of BAC1-1

H.4 Stress model results along the borehole trajectory of BUL1-1

H.5 Stress model results along the borehole trajectory of STA2-1

H.6 Stress model results along the borehole trajectory of STA3-1

H.7 Stress model results along the borehole trajectory of MAR1-1

H.8 Stress model results along the borehole trajectory of TRU1-1

App. I Prediction of stress magnitude bandwidths along vertical trajectory (digital)

The arbitrary position is indicated in Fig. 4-2 for the JO siting region, Fig. 4-3 for the NL siting region, and in Fig. 4-4 for the ZNO siting region.

Digital files (xlsx) contain information on the exact location of the vertical trajectory in each site, with bandwidths of stress magnitudes at specific depths.

- I.1 Prediction of stress magnitude bandwidths along a vertical trajectory for the JO siting region**
- I.2 Prediction of stress magnitude bandwidths along a vertical trajectory for the NL siting region**
- I.3 Prediction of stress magnitude bandwidths along a vertical trajectory for the ZNO siting region**