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Stress variability due to deterministically modelled structures at Forsmark

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This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the author. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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Summary

This report presents an updated assessment of in situ stress variability at the Forsmark site, based on the interaction between the regional stress field and deterministically modelled geological structures, referred to as deformation zones (DZs). The study incorporates the latest Deterministic Model for Structures (DMS), which includes 163 DZs, 14 of which have been revised based on recent geological and geophysical data. The DZs are classified into three orientation- and dip-based sets and are modelled within a framework that excludes the smallest zone (ZFM1189) for computational reasons. Nine DZs that fall outside the simulation domain were also excluded.

The baseline in situ stress model is established from the most reliable overcoring measurements, and the minimum principal stress corresponds to the vertical stress. Distinct stress gradients are defined above and below 500 m depth, with horizontal stresses generally exceeding the vertical component throughout the modelled domain. Numerical simulations are conducted using velocity boundary conditions to reproduce the stress state at repository depth and to evaluate the effects of a four-stage glaciation cycle. Six simulation cases are analysed to explore the influence of varying stress magnitudes and orientations, including $\pm 15^\circ$ rotations of the maximum horizontal stress and upper and lower bounds for the principal stress magnitudes.

The results demonstrate that increasing the stress magnitudes leads to greater DZ shear displacements and more extensive plastic deformation, particularly in gently dipping zones of Set 1 and within the Singö fault. Glaciation amplifies shear near the ground surface and down to depths of approximately 600 m. Stress rotations are most pronounced in the shallow subsurface but diminish with depth, showing limited influence at repository level. Simulated maximum principal stresses exceed the baseline targets by 15 – 20 MPa above about 150 m depth and converge more closely at repository depth (~470 m). However, the tendency for simulations to overpredict near-surface stresses suggests that the stiffness of the rock mass or of the DZs may be overestimated in the upper part of the model.

Clockwise rotation of the maximum horizontal stress increases DZ shear and deepens plasticity, whereas counterclockwise rotation reduces both. Upper-bound stress scenarios intensify DZ activity and increase stress scatter, while the lowest stress scenario (Case 5) exhibits substantially reduced DZ shear by up to 80%, and restricts plasticity to fewer structures. Of the lower-stress scenarios, Case 4 shows better agreement with measured stress magnitudes. Comparing the Base case simulation here with the Base case results of the previous study (Valli et al. 2023), DZ shear is increased by about 30% and DZ Set 1 plasticity is increased, due to +32% higher major and +30% higher intermediate principal stresses at repository depth.

Based on these findings, the constitutive representation of the rock mass and shear strength and stiffness of the DZs should be re-evaluated, particularly the assumption of constant stiffness, which may be contributing to unrealistic near-surface stress concentrations. Incorporating stress-dependent stiffness and acknowledging the possibility of reduced shear strength in shallow DZs, potentially due to past shear events, would likely improve future modelling accuracy.

Sammanfattning

Denna rapport presenterar en uppdaterad bedömning av variationen i de in situ-rådande spänningarna vid Forsmarksområdet, baserad på samspelet mellan det regionala spänningsfältet och de deterministiskt modellerade geologiska strukturerna, benämnda deformationszoner (DZ). Studien inkluderar den senaste modellen för Deterministiskt Modellerade Strukturer (DMS), vilken omfattar 163 DZ, varav 14 har reviderats utifrån nya geologiska och geofysiska data. DZ:erna är indelade i tre klasser baserat på orientering och stupning och modelleras inom ett ramverk, som av beräkningsskäl utesluter den minsta zonen (ZFM1189). Nio stycken DZ, vilka ligger utanför simuleringsdomänen, har också exkluderats.

Baseline-modell för de in situ-rådande spänningarna har skapats utifrån de mest tillförlitliga överborrningsmätningarna, där den minsta huvudspänningen motsvarar den vertikala spänningen. Olika spänningsgradienter definieras ovan och under 500 meters djup. De horisontella spänningarna överstiger generellt den vertikala komponenten i hela den modellerade domänen. Numeriska simuleringar genomförs med hjälp av hastighetsrandvillkor för att återskapa spänningstillståndet på förvarsdjup och för att utvärdera effekterna av en fyrstegs glaciationscykel. Sex simuleringsfall analyseras för att undersöka inverkan av varierande storlek på spänningar och orienteringar, inklusive rotationer på $\pm 15^\circ$ av den maximala horisontella spänningens riktning samt övre och nedre gränser för huvudspänningarnas storlekar.

Resultaten visar att ökande spänning leder till större skjuvförskjutningar i DZ:erna och mer omfattande plastisk deformation, särskilt i flackt stupande zoner i Set 1 och inom Singöförkastningen. Glaciation förstärker skjuvningsen nära markytan och ned till ungefär 600 meters djup. Rotationer i spänningsfältet är mest uttalade i det ytliga berget och avtar mot djupet för att visa begränsad påverkan på förvarsnivå. Simulerade maximala huvudspänningar överskrider målvärdena med 15–20 MPa ovanför cirka 150 meters djup och konvergerar mer mot dessa vid förvarsdjup (~470 m). Tendensen att simuleringarna överskattar spänningarna nära markytan tyder dock på att bergmassans, eller DZ:ernas, styvhet kan vara överskattad i den övre delen av modellen.

En medurs rotation av den maximala horisontella spänningen ökar skjuvningsen i DZ:erna och fördjupar plasticiteten, medan en moturs rotation minskar båda. Scenarier med spänningar nära övre gränsvärdet intensifierar aktiviteten i DZ och ökar spridningen i spänningarna, medan scenariot med lägst spänning (Fall 5) uppvisar avsevärt, upp till 80 %, reducerad skjuvning i DZ, och begränsar plasticiteten till färre strukturer. Av lågspänningsscenarierna visar Fall 4 bättre överensstämmelse med uppmätta spänningsmagnituder. Vid jämförelse mellan basfallet i denna studie och resultaten från basfallet i den föregående studien (Valli et al. 2023) har skjuvningsrörelsen i DZ ökat med cirka 30% och även plasticiteten i DZ Set 1 har ökat. Detta till följd av 32% högre största huvudspänning och 30% högre mellanliggande huvudspänning på förvarsdjup.

Baserat på dessa resultat bör den konstitutiva beskrivningen av bergmassan samt deformationszonernas skjuvhållfasthet och styvhet omvärderas. Speciellt bör antagandet om konstant styvhet, vilket kan bidra till orealistiska spänningskoncentrationer nära markytan ses över. Att införa spänningsberoende styvhet och att beakta möjligheten till reducerad skjuvhållfasthet i ytnära DZ, potentiellt till följd av tidigare skjuvhändelser, skulle sannolikt förbättra noggrannheten i framtida modellering.

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1 Introduction

1.1 Background

The safe final disposal of spent nuclear fuel is critical in the design of a deep bedrock nuclear waste repository and is affected by several factors, including the in situ stress state as well as any identified geological features such as structures/deformation zones (DZ) at the selected site. The Swedish Nuclear Fuel and Waste Management Company (SKB) has selected the Forsmark site for the construction of a repository at a preliminary target depth of -470 m. The Forsmark site is in Northern Uppland approximately 100 km north of Stockholm (Figure 1-1). Site investigations have yielded a large amount of data that has resulted in the development of a Deterministic Model for Structures (DMS), which includes detailed three-dimensional models of all the deformation zones (DZ) at the Forsmark site, currently totalling 163 DZ (Modelldatabasen 2025). Such models have been used in previous studies for stress modelling purposes where the interaction of geological features such as faults or deformation zones and the stress state was simulated (Tonon et al. 2001), (Tonon and Amadei 2003), (Hakami 2006), (Hakami and Min 2009), (Valli et al. 2011), (Valli et al. 2016), (Hakala et al. 2019), (Kaisko et al. 2023). A previous version of the DMS has been used for stress modelling in Valli et al. (2023).

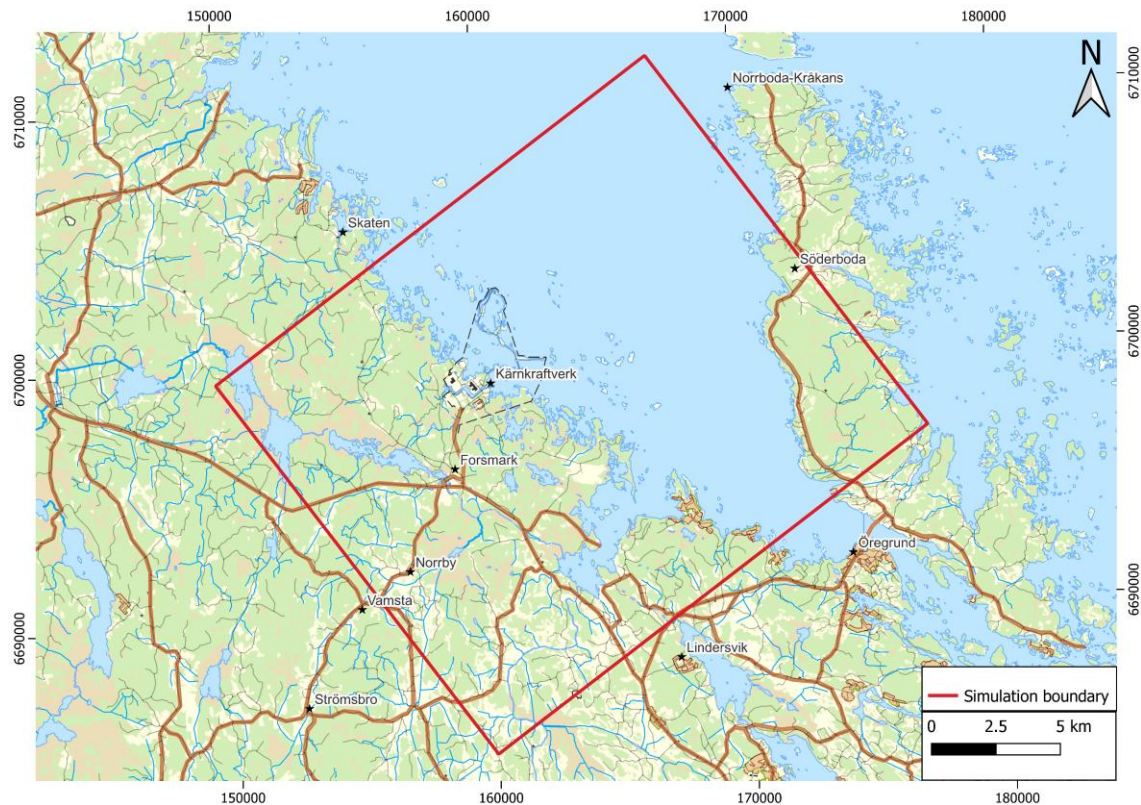


Figure 1-1. The Forsmark site and the simulation area.

1.2 Goals

The primary objective of this study was to update the Forsmark numerical 3D rock stress model by updating the previous simulations in Valli et al. (2023) with the latest DMS update to study interaction of the in situ stress state and the DZs in the Forsmark area.

Six simulation cases were examined, consisting of a Base Case and five additional stress-field scenarios designed to account for uncertainties in the current in situ stress model (Table 1-1). The analysis focused on the following aspects:

DZ shear displacements,
the variation of the in situ stress state,
the correlation with the in situ stress measurements,
the sensitivity of the results to the orientation of applied thrust.

Table 1-1. The target stress fields for the simulated cases.

Stress Case	Depth range (m)	Maximum horizontal stress		Minimum horizontal stress		Vertical stress σ_v (MPa)
		σ_H (MPa)	Trend (°)	σ_h (MPa)	Trend (°)	
Base Case (Baseline stress model)	0–500	$0.1z + 6$	145	$0.06z + 1$	55	$0.0265z$
	>500	$0.03z + 41$	145	$0.015z + 23.5$	55	$0.0265z$
	At 470	53	145	29.2	55	12.5
Case 1 (Trend – 15°)	0–500	$0.1z + 6$	130	$0.06z + 1$	40	$0.0265z$
	>500	$0.03z + 41$	130	$0.015z + 23.5$	40	$0.0265z$
	At 470	53	130	29.2	40	12.5
Case 2 (Trend + 15°)	0–500	$0.1z + 6$	160	$0.06z + 1$	70	$0.0265z$
	>500	$0.03z + 41$	160	$0.015z + 23.5$	70	$0.0265z$
	At 470	53	160	29.2	70	12.5
Case 3 ($\sigma_{Hmax} = \sigma_H + 6$ MPa $\sigma_{hmax} = \sigma_h + 5$ MPa)	0–500	$0.1z + 12$	145	$0.06z + 6$	55	$0.0265z$
	>500	$0.03z + 47$	145	$0.015z + 28.5$	55	$0.0265z$
	At 470	59	145	34.2	55	12.5
Case 4 ($\sigma_{Hmin} = \sigma_H - 6$ MPa $\sigma_{hmin} = \sigma_h - 5$ MPa)	0–500	$0.1z$	145	$0.06z - 4$	55	$0.0265z$
	>500	$0.03z + 35$	145	$0.015z + 18.5$	55	$0.0265z$
	At 470	47	145	24.2	55	12.5
Case 5 (Stress at 560 m from P-25-02 OC meas. at KFM24)	At 560	24.2	121	14.8	31	14.6

2 Initial data

2.1 Deformation zones

The DZs in the most recent DMS are based on pre-existing models (Stephens and Simeonov 2015) but have been updated using the most recently available data in the Sicada database as of July 2025. All the DZs within the simulation area have been included in the simulation model, apart from ZFM1189 (Section 3.2) This results in a total of 153 DZs being modelled in the numerical simulation domain out of the 154 in the DMS within the simulation volume. Figure 2-1 illustrates the 14 updated DZ's along with the 140 DZ's unchanged from the study by Valli et al. (2023) (Table 2-1 and Table 2-2).

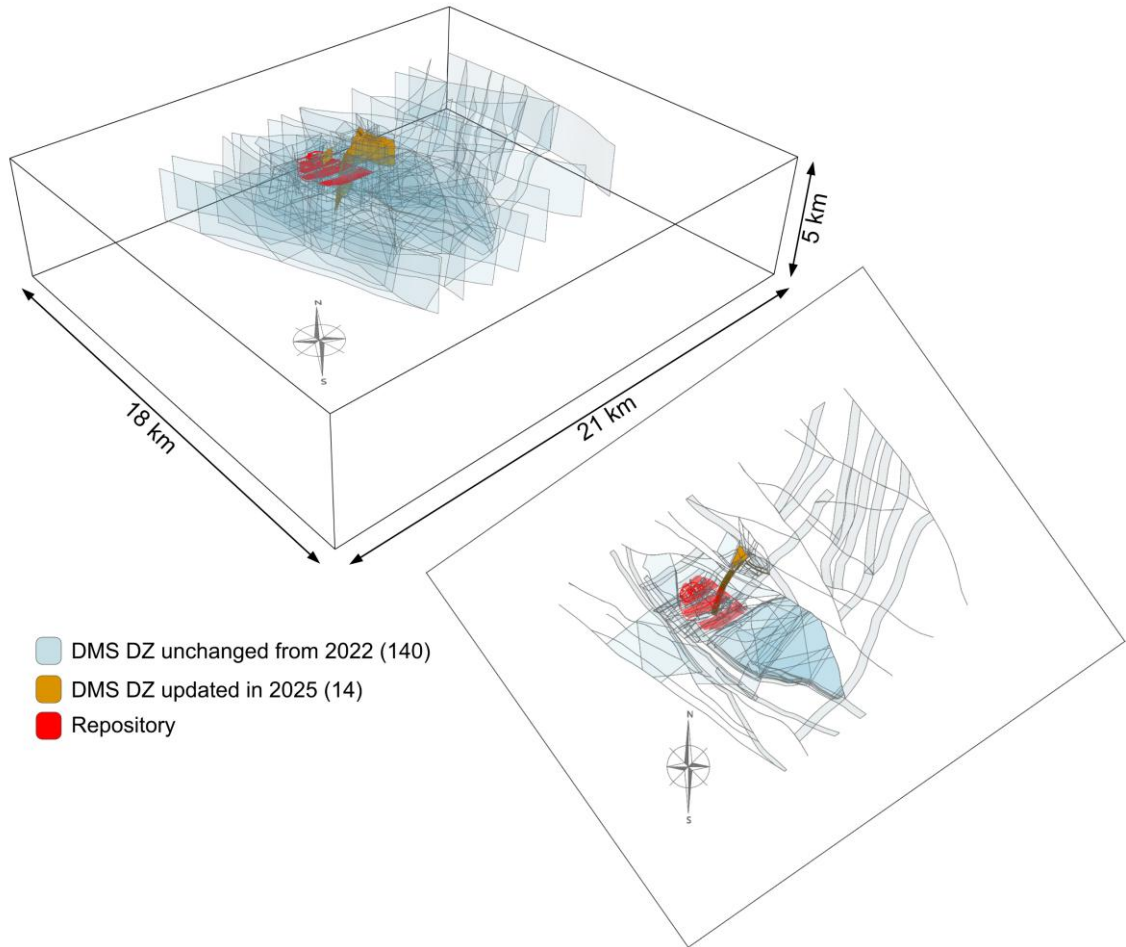


Figure 2-1. The DZs of the updated DMS, with a top-down view as an inset in the bottom-right corner.

Table 2-1. Description of the updates in 14 DZs according to the latest DMS.

DZ	Geometrical Changes	Description	In Repository Area?	Number Of DZ Intersections
ZFMNNW1209	Considerable	Major change in size and orientation	No	5
ZFMNE0870	Considerable	Divided into two smaller zones (ZFMNE0870A and ZFMNE0870B)	No	4
ZFMNE3137	Considerable	Significant geometry and orientation changes	No	6
ZFMWNNW3268	Considerable	One boundary changed due to ZFMNE3137 change	No	4
ZFMWNNW3267	Considerable	Considerable change in extension and a minor change in plane	No	6
ZFMENE3115	Considerable	Major change in size and orientation	No	6
ZFMNE3112	Considerable	Major change in size and orientation	No	9
ZFMWNNW8042	Considerable	Reduced size	No	6
ZFMNNE0725	Minor	Extended 100m at its bottom (level -2000 circa)	Yes	8
ZFMWNNW0835	Minor	Extended at one vertical end by approx. 75m	No	3
ZFMNNW1204	Minor	Extended at the top boundary by approx. 35m	Yes	2
ZFMNE2309	Minor	One corner extended at edge by 100m	Yes	1
ZFM871	Minor	One corner extended at edge by 100m	No	3
ZFMWNNW3262	Minor	One corner extended at edge by 70m	No	1

Table 2-2. The orientations, whether the fault intersects the surface and the set numbers (described in Section 3.7) of the updated faults.

DZ	Set	Dip (°)	Dip Direction (°)	Intersects rock surface?
ZFMNNW1209	2	83	243	Yes
ZFMNE0870	3	76	324	Yes
ZFMNE3137	3	90	321	Yes
ZFMWNNW3268	2	90	201	Yes
ZFMWNNW3267	2	90	214	Yes
ZFMENE3115	3	84	328	Yes
ZFMNE3112	3	89	325	Yes
ZFMWNNW8042	2	88	28	Yes
ZFMNNE0725	3	83	291	Yes
ZFMWNNW0835	2	88	210	Yes
ZFMNNW1204	2	85	77	No
ZFMNE2309	3	90	127	Yes
ZFM871	1	19	166	No
ZFMWNNW3262	2	86	208	Yes

2.2 In situ stress

The Forsmark site *in situ* stress state interpretation was originally established in 1991 when Stephansson et al. (1991) used data in a Rock Stress Database to evaluate the stress state in Fennoscandia. Based on about 500 entries from sites in Sweden, Finland, and Norway, it was concluded that within the upper 1,000 m the horizontal stress components are high, and both the maximum and minimum horizontal stresses commonly exceed the vertical stress, assuming the vertical stress corresponds to the overburden weight (Martin 2007).

This has been followed with several stress measurement campaigns in Forsmark, consisting of overcoring (~130 measurements), hydraulic fracturing (HF) (~70 measurements) and hydraulic tests on pre-existing fractures – HTPF (~170 measurements). The conclusions of Stephansson et al. (1991) were supported by the overall results of these measurements, since some HF showed intermediate stresses or minimum horizontal stresses lower than the vertical stress (Chapter 6.4 in Martin (2007), R-07-26). Additionally, survey programs of borehole breakouts and core diskings, evaluation of nonlinear strains in laboratory samples and determination of stress magnitudes to cause core diskings (Martin 2007) were performed to aid in the interpretation of the *in situ* stress.

The latest stress state interpretation for the Forsmark area is detailed in Hakami et al. (2025), which is a re-evaluation of the available stress measurement dataset. This interpretation is defined as the Baseline Stress Model and the *in situ* stress magnitudes are determined by the following:

1. Overcoring measurement data are used while hydraulic fracturing data are disregarded.
2. Low reliability overcoring data is excluded according to the reliability ranking system of Sjöberg et al. (2025).
3. A stress model applicable to domain FFM01 is established, and the data are sorted accordingly. Overcoring measurements with a “B–Good” reliability ranking for both the maximum and intermediate principal stresses are used to derive the best-fit linear trends for these stress components down to a depth of 500 m.
4. The minimum principal stress is assumed to equal the vertical stress, taken as the weight of the overburden.
5. Ring diskings observations are checked for inconsistencies with the model developed in Step 3. Due to no clear contradictions, the model is retained.
6. Below 500 m depth, the stress model cannot rely on overcoring data due to the lack of deep measurements. Instead, it is based on assumed relationships between the principal stress components and supplemented by literature sources.
7. Core diskings observations from the investigation boreholes are evaluated to ensure they do not contradict the model developed in Steps 3 and 6.
8. Borehole breakout observations at all depths are assessed for consistency with the model from Steps 3 and 6, taking into account expected rock-type variations. As no clear contradictions are found, the model is retained.
9. Microcrack volume data are reviewed to verify that they do not conflict with the selected stress model. These data primarily provide qualitative support for the constant stress gradient assumptions applied in Steps 3 and 6.

2.3 Rock properties

Glamheden et al. (2007) and Glamheden et al. (2008) describe the rock mechanics characterization of the Forsmark site including surveying and measurement programs, laboratory tests and interpretation of the in situ stress state, intact rock, fracture and rock mass mechanical properties. The rock mass quality in Forsmark is very good and the rock is stiff, strong and homogeneous based on the laboratory tests of rock samples and fractures and geomechanical classification indices. The rock mass properties have been estimated with empirical and theoretical methods and integrated through a process called harmonization (Glamheden et al. 2007). Theoretical analysis of rock mass properties parallel and perpendicular to the major principal stress and tensile strength tests conducted both parallel and perpendicular to foliation resulted in similar values regardless of direction, indicating a reasonably isotropic rock mass. Volumes with lower rock mass quality are mainly related to the increased fracture intensity in DZs (Glamheden et al. 2007).

3 Simulation approach and input data

3.1 Approach

Much of the general description related to the simulation approach applied in this study is the same or similar to the previous study published in Valli et al. (2023). As described in Valli et al. (2023) and originally in Heidbach et al. (2018), the current stress state in the Fennoscandia area is dominated and driven by Mid-Atlantic ridge push and collision of the Eurasian and African plates in the Alps. Additionally, earlier glaciation cycles have changed stress conditions remarkably and potentially promoted the slip of brittle deformation zones thereby causing changes in the stress field. In the thrust fault conditions that have been dominant for a long time, shallow dipping deformation zones have been, and are still, more prone to slip than subvertical zones. As a result, the *in situ* stress state is affected by the background stresses and potentially perturbed by deformation zone slip, which has been studied by numerical simulations of the interaction of geological features and the stress state (Tonon et al. 2001), (Tonon and Amadei 2003), (Hakami 2006), (Hakami and Min 2009), (Valli et al. 2011), (Valli et al. 2016), (Hakala et al. 2019), (Kaisko et al. 2023). This study applies the same methodology as described in Valli et al. (2023) by modelling the interpreted deformation zones in the focus area and applying velocity boundary conditions to generate the interpreted *in situ* stress state at repository depth, simulating the stages leading up to the currently interpreted stress state. Simulation results are interpreted using the methods applied in the previous study. Note that DZs are modelled as surfaces using the surface geometry of the DMS and therefore the potential thickness of DZs is not explicitly included which would lead to further complexity in the simulation model.

All the stages previously simulated in the Valli et al. (2023) study were performed, including the development of the *in situ* stress state using velocity boundary conditions, the following glaciation and finally, the re-establishment of the *in situ* stress state using velocity boundary conditions. Displacements were reset to zero after initial equilibrium.

3.2 Geometry

The DZs were modelled to match the original DMS geometry as closely as possible while still being computationally reasonable (Figure 3-1). The overall mesh size was < 20 m in the repository area, increasing to ca. 750 m at the boundaries of the model (Figure 3-2). Only large-scale deformation zone undulation was modelled, small-scale asperities were not included. Geometrical accuracy was within 10 m (at max, generally max. deviation is 5 m) near the underground facilities and at a distance of 2000 m from the repository, DZ geometry deviated at maximum 40 m. Due to geometrical issues with intersecting DZs leading to very narrow and poor quality elements, some additional simplification of the fault geometries was necessary. This required trimming the deformation zone surfaces or in one case, excluding the deformation zone entirely: ZFM1189 was excluded (Figure 3-3). Exclusion of this DZ does not, like the other simplifications, affect the simulation outcome given the overall size of the model. Additionally, ZFM1189 is the smallest DZ in the DMS, with a surface area of 0.017 km². Finally, all joint Forsmark (JFM) features were excluded along with nine deformation zones that fell outside the modelling volume of interest:

- ZFMNE3542,
- ZFMNNE3546A,
- ZFMNNW3524,
- ZFMNNW3534,
- ZFMNW3511,
- ZFMNW3552,
- ZFMWNW3512,
- ZFMWNW3519,
- ZFMWNW3520.

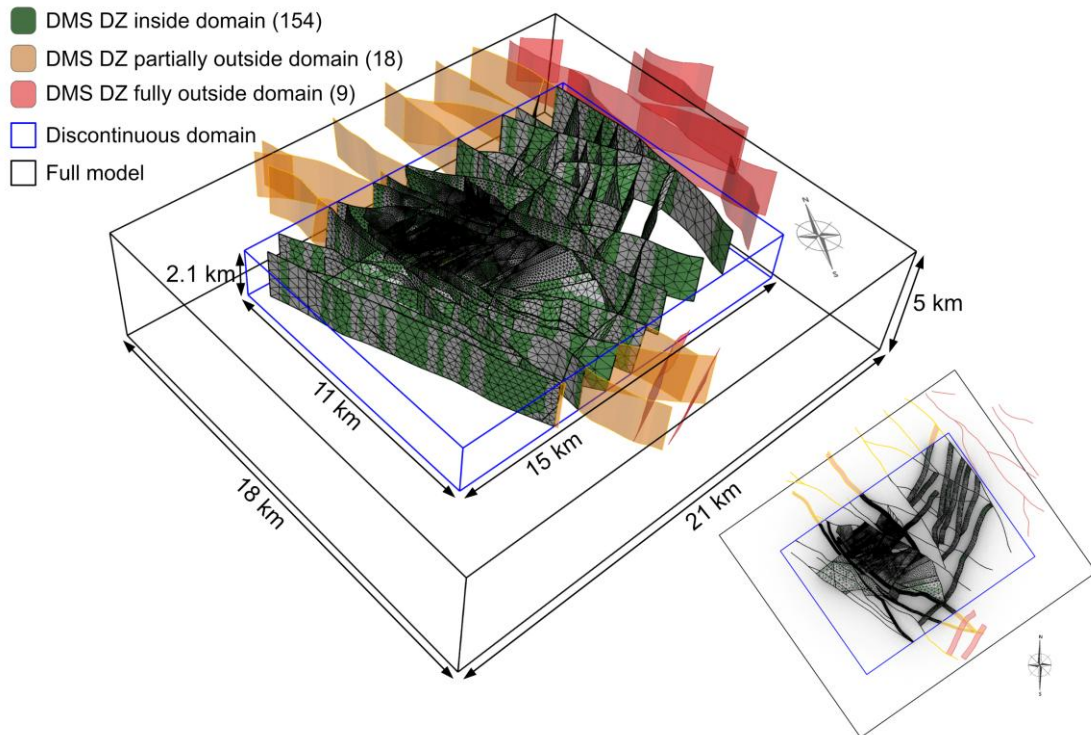


Figure 3-1. Deformation zone geometry. Note that deformation zone geometry that extended well outside the area of interest was excluded: the discretized geometry is simulated.

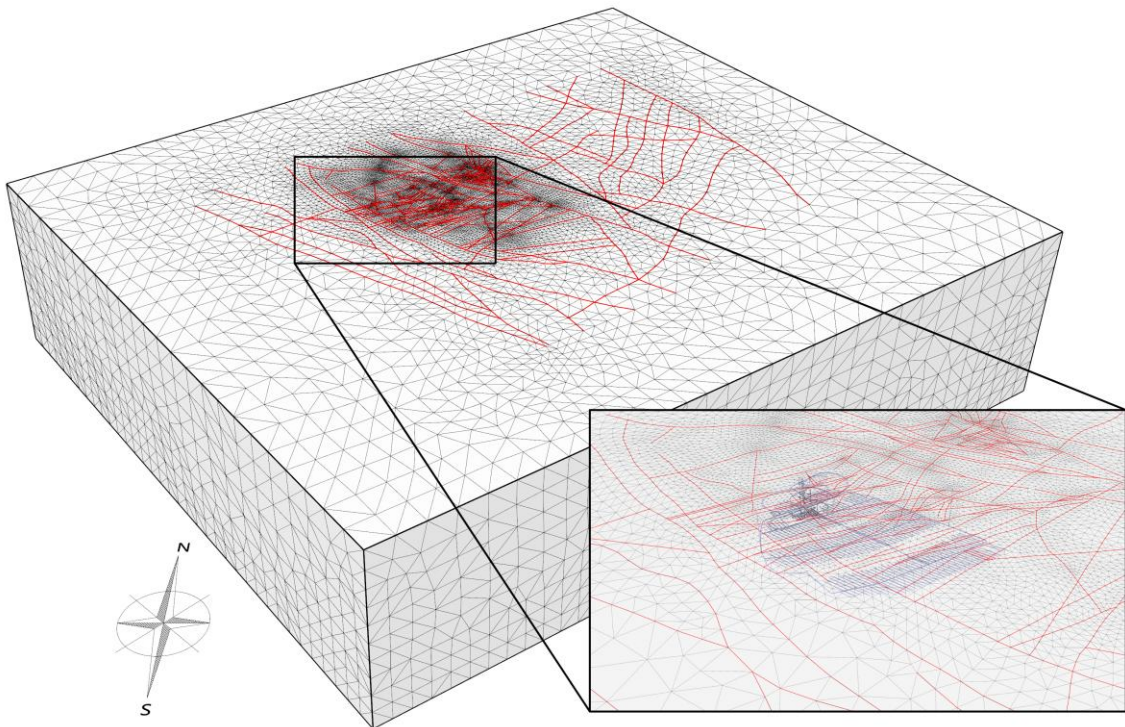


Figure 3-2. Model external boundary meshing.

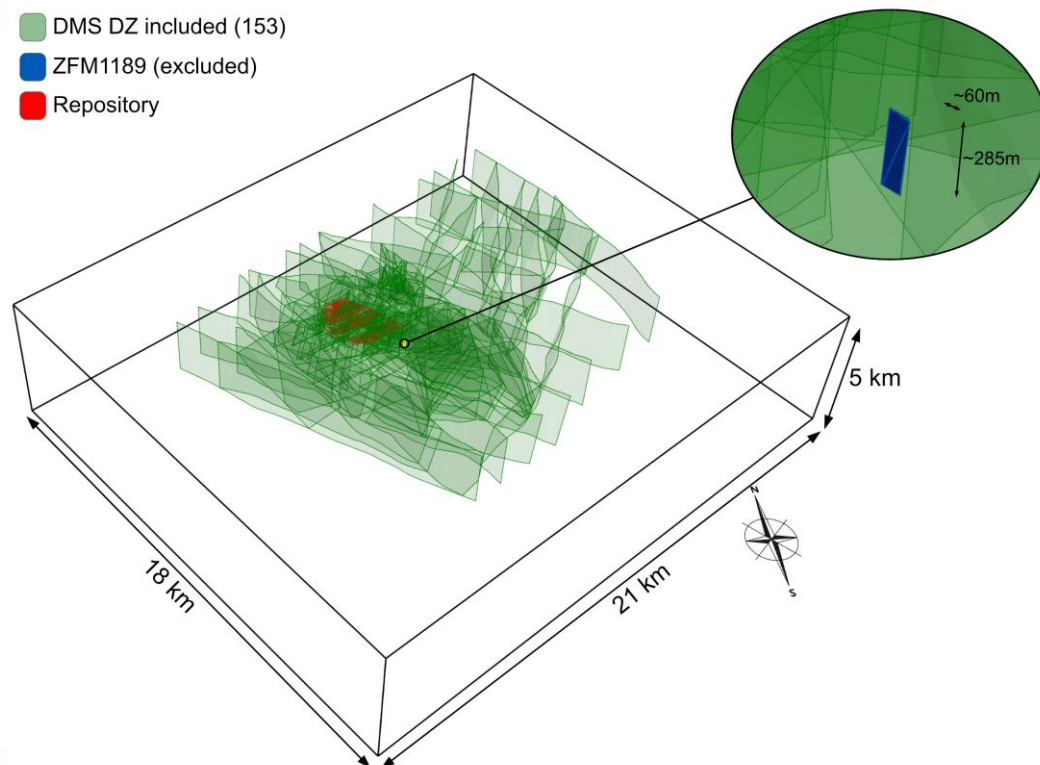


Figure 3-3. Excluded deformation zone ZFM1189 in the DMS geometry.

3.3 Rock mass properties

As in the previous study, the rock mass was considered to be isotropic and elastic and was divided into four different geological domains: the general far-field rock mass and three fracture domains surrounding the facilities (FFM01, FFM02, FFM06) (Figure 3-4). The applied elastic parameters consider the fracturing and only the DZs were modelled explicitly. Young's modulus values were estimated based on Modelling stage 2.3 (Glamheden et al. 2008) and Poisson's ratio values were based on empirical analysis of fracture domains in Glamheden et al. (2007) (Table 3-1). FFM01 and FFM06 were considerably stiffer than FFM02, and the stiffness increased with depth. Rock mass density was 2650 kg/m³.

Table 3-1. Rock mass elastic parameters after Glamheden et al. (2007) and Glamheden et al. (2008).

Depth range	Above 400 m		Below 400 m	
Elastic parameters	E (GPa)	ν ()	E (GPa)	ν ()
Fracture domain				
Rock mass	65	0.24	65	0.24
FFM01	65	0.24	70	0.24
FFM02	55	0.18	-	-
FFM06	65	0.30	70	0.24

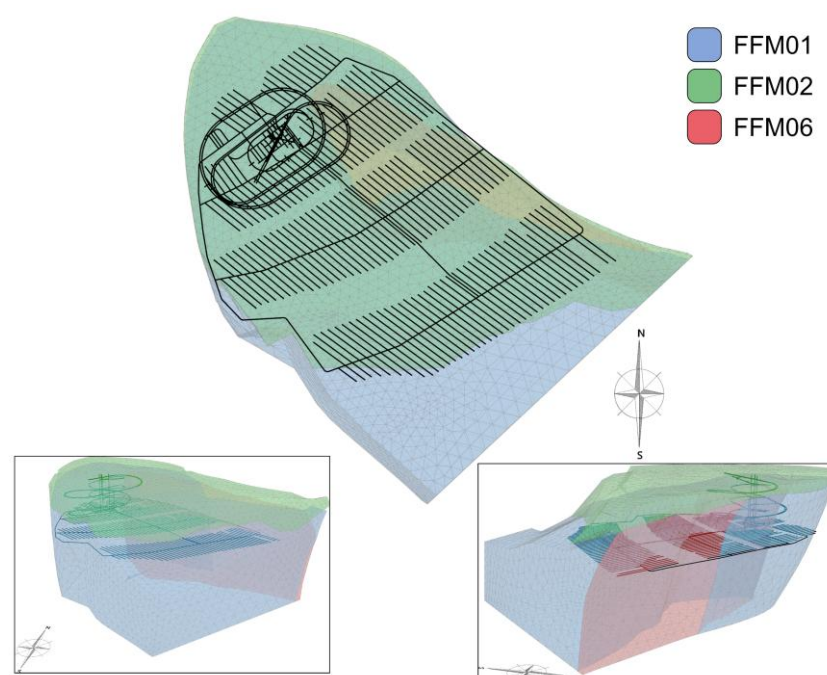


Figure 3-4. Fracture domains surrounding the facilities.

3.4 Deformation zones

Like in the previous study, all DZs except the Singö DZ were assigned the same basic deformation and strength parameter values based on the Forsmark site descriptive model v2.2 and its completion at the end of site investigations (Glamheden et al. 2007), (SKB 2008), (Table 3-2). The initial values for cohesion and friction were maintained in contacts after failure (perfectly elastoplastic constitutive model). Note that the parameters were not varied in any of the cases of this study.

Table 3-2. Stiffness and strength values for DZs. kn: normal stiffness, ks: shear stiffness, coh: cohesion, fric: friction angle, ten: tensile strength.

Parameter	kn (MPa/mm)	ks (MPa/mm)	coh (MPa)	fric (°)	ten (MPa)
Deformation zone					
All, except Singö	80	20	0.7	36	0.001
Singö	0.2	0.01	0.4	31.5	0.001

3.5 In situ stress state and ground water pressure

The Baseline Stress Model for Forsmark area is detailed in Hakami et al. (2025), which is a re-evaluation based on the reliability assessment (Sjöberg et al. 2025) of the available stress measurement dataset used in the previous study by Valli et al. (2023). The stress interpretation is summarized in Table 3-3 and presented graphically in Figure 3-5. Two separate stress gradients have been defined for the horizontal stress components (σ_H and σ_h) within the depth intervals 0 – 500 m and 500 – 1000 m, respectively. The vertical stress component (σ_v), in contrast, is assumed to increase linearly with depth using a single constant gradient across the entire depth range in agreement with the weight of the overburden. Gravity was applied as 9.81 m/s².

Table 3-3. The Baseline in situ stress model based on Hakami et al. (2025).

Depth range (m)	σ_H (MPa)	σ_H trend (°)	σ_h (MPa)	σ_h trend (°)	σ_v (MPa)
0-500	$0.1 \cdot z + 6, (\pm 6)$	145 ± 15	$0.06 \cdot z + 1, (\pm 5)$	55 ± 15	$0.0265 \cdot z, (\pm 0.0005 \cdot z)$
500-1000	$0.03 \cdot z + 41, (\pm 6)$	145 ± 15	$0.015 \cdot z + 23.5, (\pm 5)$	55 ± 15	$0.0265 \cdot z, (\pm 0.0005 \cdot z)$

z is depth below rock surface in metres and $\pm$ represents the uncertainty of each variable

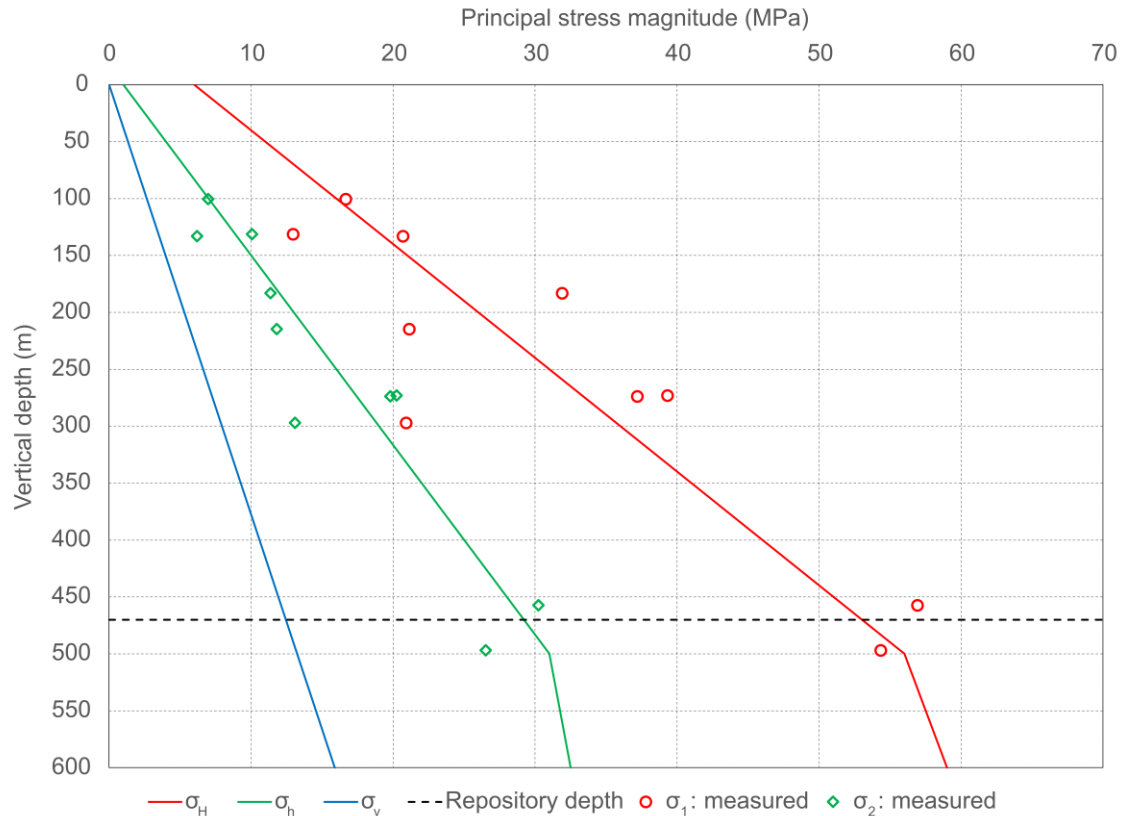


Figure 3-5. The baseline in situ stress model based on Hakami et al. (2025) (and the selected measurements for the interpretation of σ_H and σ_h). The principal stress fit equations are presented in Table 3-3.

The stress state in the simulations was established by applying thrust to opposite vertical model boundaries. “Thrust” in the context of the simulations in this study is the application of a velocity boundary condition in the normal direction of the model boundary surfaces. Put simply, the model was compressed from all sides at varying velocities to achieve a target stress state at a given location. For the simulation target stresses, the principal stresses are defined based on the horizontal stresses defined in Hakami et al. (2025), where $\sigma_1 = \sigma_H$, $\sigma_2 = \sigma_h$ and $\sigma_3 = \sigma_v$. The velocities along the major and minor horizontal stress orientations were different but were not depth dependent: depth dependency had been concluded to be of negligible impact in the previous study (Hakala et al. 2019). The effect of thrust orientation compared to DZ-geometry was studied by varying the thrust orientation by $\pm 15^\circ$ (Figure 3-6). The thrust was servo-controlled and stopped when primary *in situ* conditions were reached at repository depth (470 m) at the centre of the repository (Figure 3-7). “Servo-controlled” refers to the use of a purpose-built script written to cycle or solve the model an arbitrary number of cycles to a target stress state resulting in small increments of displacement. After an increment of thrust displacement has been applied, the model boundaries are fixed in the normal direction and the model is cycled to a quasistatic state. Based on the difference of the current stress state at the monitoring point and the target magnitude, the thrust velocities for the opposing boundaries are recalculated and applied for the next increment. Smaller differences result in the servo decreasing velocities on the corresponding boundaries or if the target magnitude is close to be exceeded, extensional boundary conditions are applied. The script obtains the average principal stresses based on the average of the tensors within a set radius of a sphere at the monitoring location.

Once the maximum and intermediate principal stresses were within set tolerances (0.2 MPa), the script terminates, the boundaries are fixed in their normal directions (surface free, all others fixed in normal direction) and the model is equilibrated. The target stresses were individually determined for each principal stress and based on the Hakami et al. (2025) interpretation, with a target range of $\pm 1\%$ at the monitoring location. The different variants of *in situ* stress states are summarized in Section 3.7.

Full hydrostatic water pressure was assumed for all DZs with a water level equal to the rock surface and variable excess pore pressure was applied during the glaciation cycle (Section 3.6). Water density was 1000 kg/m^3 .

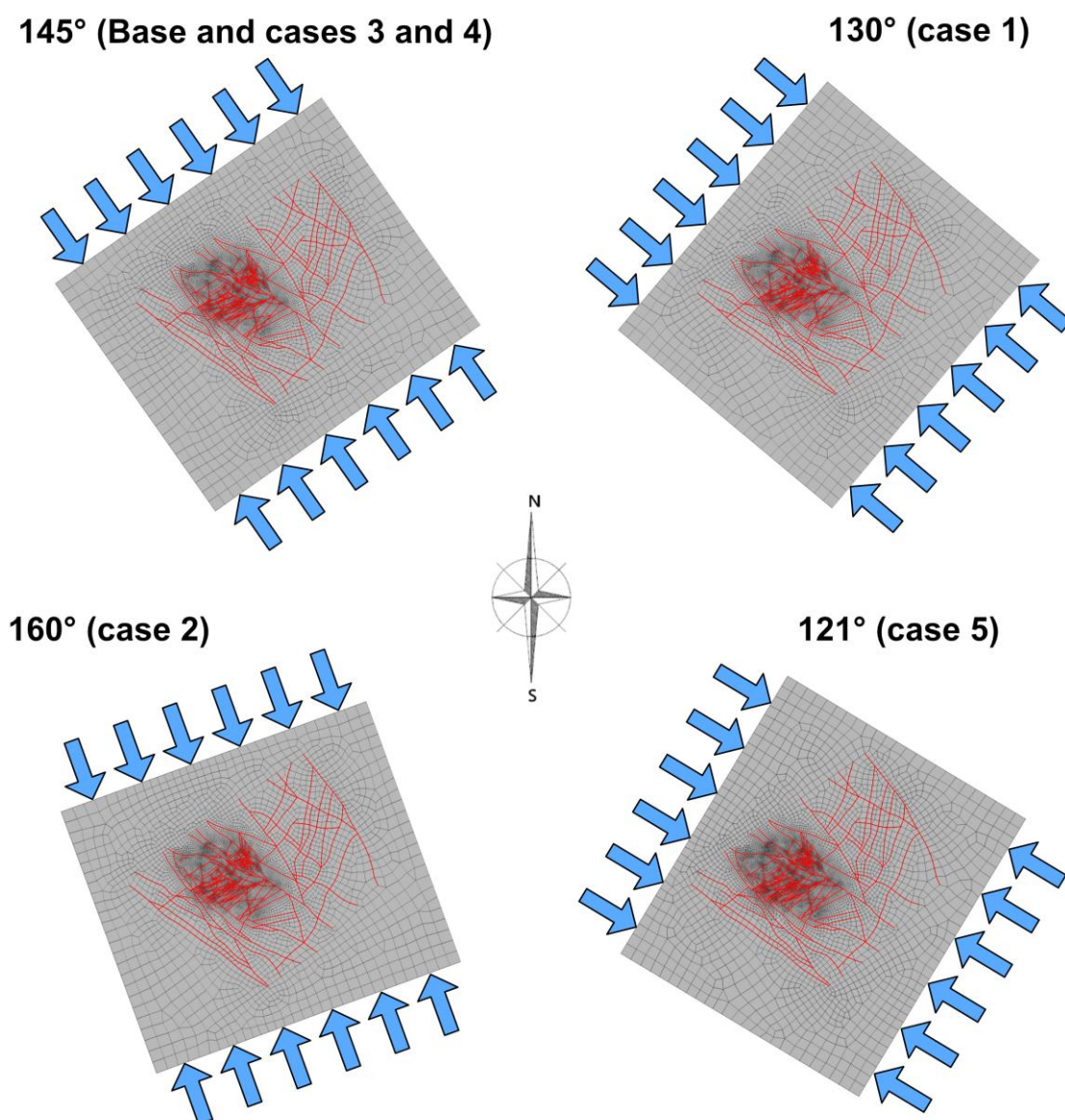


Figure 3-6. The varying major thrust orientations used in the simulations.

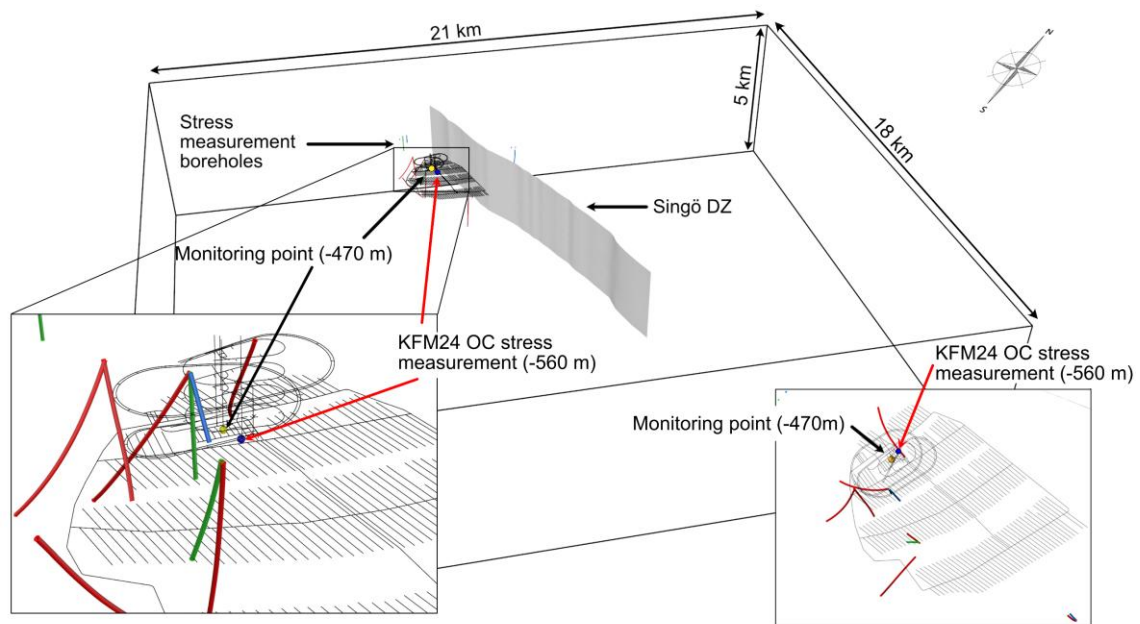


Figure 3-7. Location of the monitoring points used to control thrust, viewed from above in the inset in the bottom right.

3.6 Glaciation

The same glacial cycle as simulated in Valli et al. (2023) was applied in this study. As before, the simulation cycle for the glaciation consisted of four phases; Forebulge, Glacial maximum, Edge passing and the Removal of glaciation (Table 3-4, Figure 3-8, Figure 3-9). The glacially induced stresses were assumed to be constant with depth and equal to the values calculated for the 500 m level. The maximum error caused by this assumption was about 0.5 MPa. The glacially induced excess pore pressure model was the same as the alternative pore pressure model in Hökmark et al. (2010), equivalent to 98% of the glacially induced vertical load (Figure 3-10). In this pore pressure model the pressure was constant with depth except in the edge passing phase. Unlike the thrust in the formation of the *in situ* stress state, the glacially induced stresses and pore pressures corresponding to each simulation phase were applied directly to model elements. The vertical stresses in the glaciation phases were achieved by applying a layer on top of the model that was assigned a density required to generate the vertical load required to reach the specified vertical stress at each respective stage. Similar to the thrust, the density was increased or decreased incrementally to avoid dynamic effects. Pore pressure changes were applied incrementally along with the stress changes. This approach maintained a quasistatic state. In the removal phase all excess stresses and pore pressures were removed.

Table 3-4. Additional stresses induced by the simulated second glaciation cycle.

	Forebulge			Second maximum			Edge passing		
	Stress (MPa)	dip [°]	dd [°]	Stress (MPa)	dip [°]	dd [°]	Stress (MPa)	dip [°]	dd [°]
σ_1	0	0	3	28.9	0	95	11	0	76
σ_2	-5.4	0	93	24.8	0	185	7.6	0	166
σ_3	0.3	90	0	25.7	90	0	-0.2	90	0

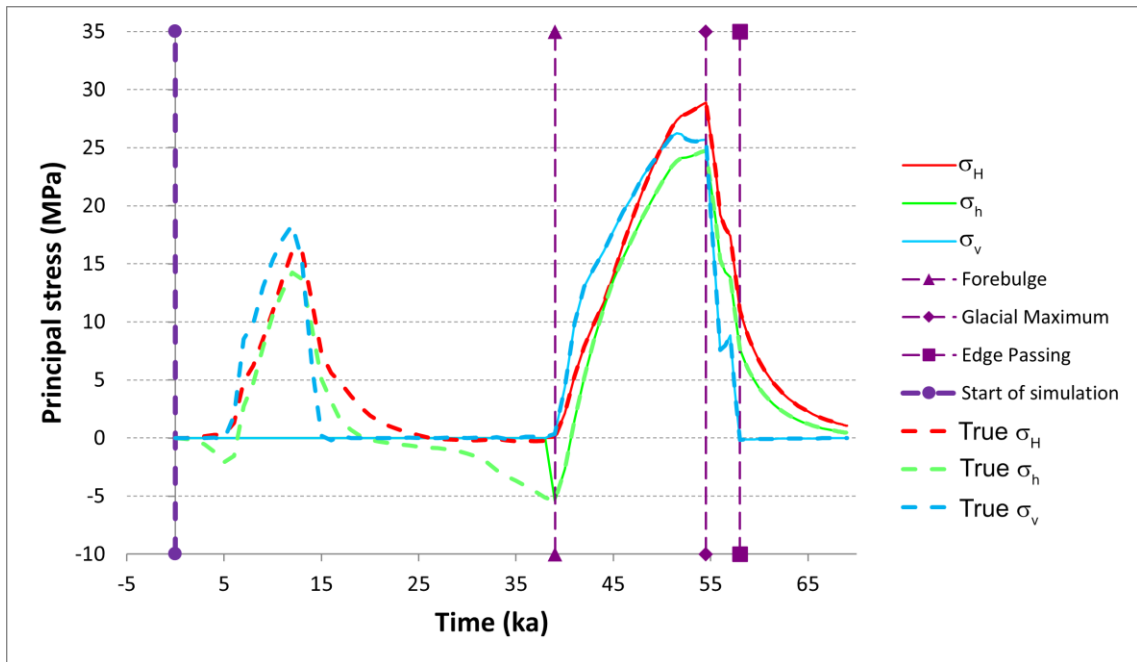


Figure 3-8. Development of glacially induced changes of horizontal and vertical stresses at 500 m depth level after Hökmark et al. (2010). Compression = positive.

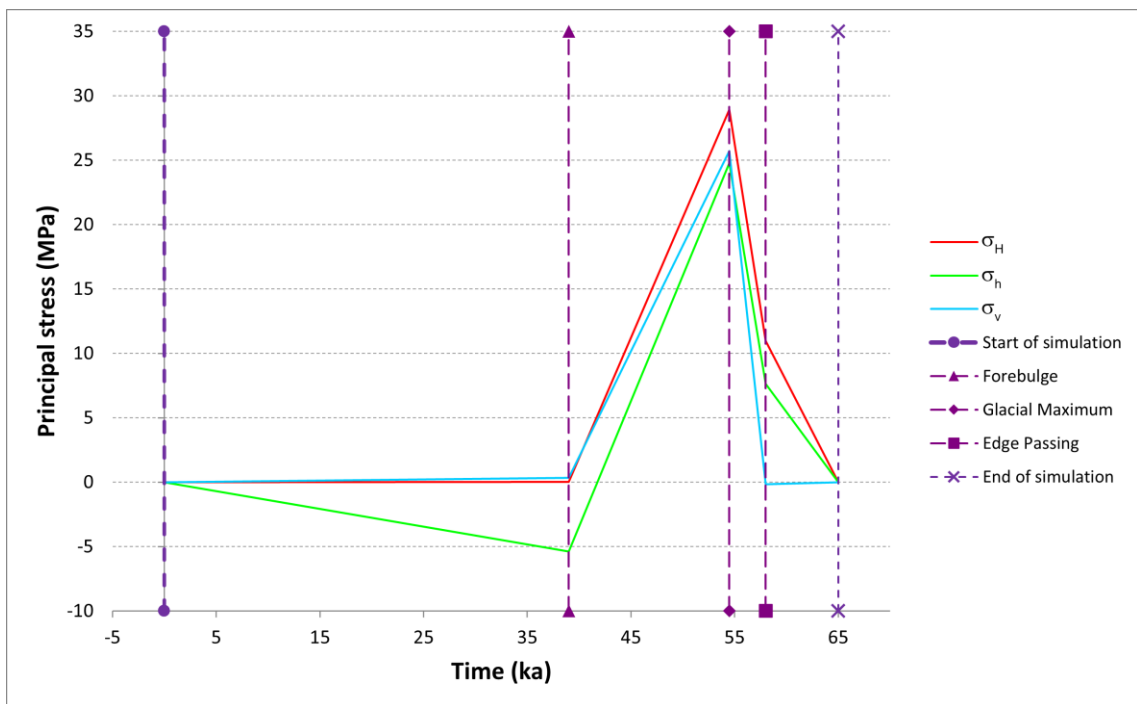


Figure 3-9. The development of the simulated glacially induced changes of horizontal and vertical stresses at the 500 m depth level. Compression = positive.

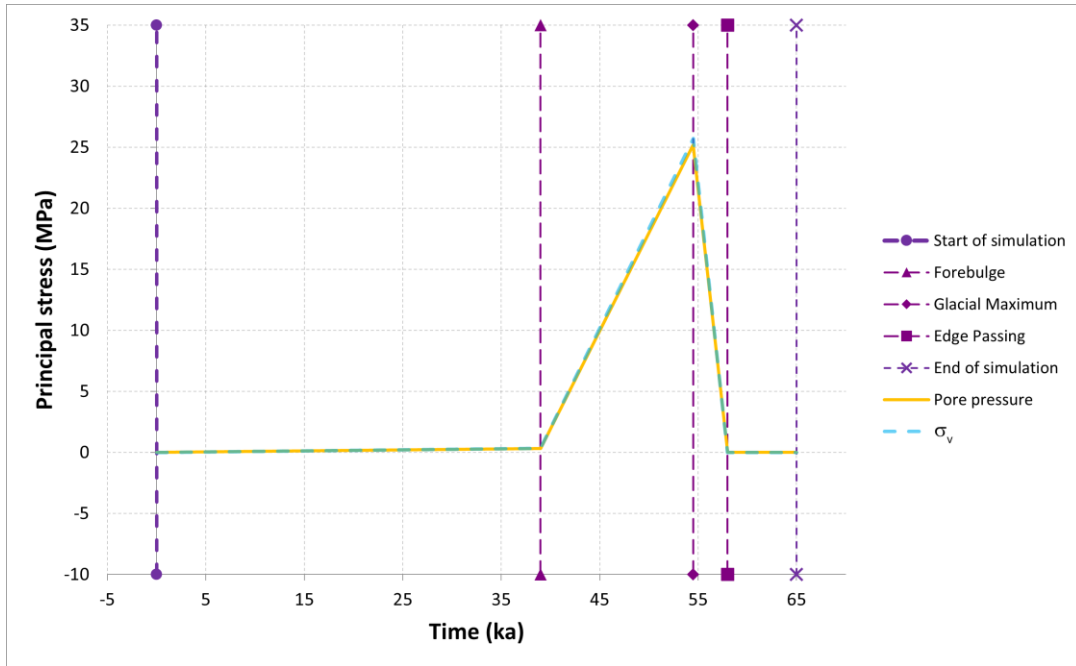


Figure 3-10. Glacially induced excess pore pressure model for Forsmark, after Hökmark et al. (2010). Compression = positive.

3.7 Simulation cases

The simulations included 153 undulating DMS deformation zones grouped into three sets:

- Set 1 dipping mostly to the southeast with a dip less than 50° i.e., these deformation zones have a dip direction close to the mean major thrust trend of 145° , ranging from 0 to 360° ,
- Set 2 is subvertical ($50 - 90^\circ$) dipping mainly to the northeast (dip direction $170 - 260^\circ$ & $350 - 080^\circ$), i.e., the strike is along the major thrust trend,
- Set 3 is also subvertical ($50 - 90^\circ$) and dips mainly towards the southeast (dip direction $080 - 170^\circ$ & $260 - 350^\circ$), i.e., the strike is perpendicular to the major thrust trend.

This geometry was used in six simulation cases (Table 3-5). Mesh size was optimised to improve computation time by grading the mesh outwards from the repository area from an edge length of < 20 m to ca. 750 m at the boundaries of the model (Section 3.2). Rock mass and deformation zone properties were defined as described in Section 3.3 and Section 3.4. Before applying thrust, the model was first computed to elastic equilibrium with only the lithostatic stress gradient according to a rock mass density of 2650 kg/m^3 .

The model was compressed to four different repository level target *in situ* stress states based on the Baseline stress model (Hakami et al. 2025) interpretation and a target stress state based on the results of two overcoring stress measurements carried out in borehole KFM24. The mean magnitudes and orientations are applied in the Base case, while the cases 1 to 4 are mostly within the variation limits of the Baseline stress model. The compressive velocities on opposite model boundaries were equal in magnitude and constant at all depths. The applied glaciation cycle was according to Hökmark et al. (2010) and applied as stress increments. Special care was taken to prevent dynamic, overstressed, conditions. In cases 1 and 2 the major thrust trend is rotated horizontally $\pm 15^\circ$ from the mean trend of 145° . This is performed using model geometries where the internal part of the model is identical throughout the cases, but the external part of the model domain is modified so that the boundaries are orthogonal to the applied major thrust trend (see Figure 3-6). Cases 3 and 4 represent upper- and lower-bound variations of the Base Case stress field. In these cases, the maximum principal stress is taken to correspond to the major horizontal stress ($\sigma_1 = \sigma_H$), and the intermediate principal stress to the minimum horizontal stress ($\sigma_2 = \sigma_h$). In Case 3, σ_1 is increased by 6 MPa and σ_2 by 5 MPa relative to the Base Case. In Case 4, σ_1 is decreased by 6 MPa and σ_2 by 5 MPa relative to the Base Case. Case 5 corresponds to the overcoring stress measurements conducted at a depth of about 560 m in borehole KFM24 (Ask 2025).

Table 3-5. The target stress states and applied pore pressures of all the simulated cases. Differences to the Base case are highlighted by colour: blue for a decrease, orange for an increase, according to a depth of 470 m for all cases except case 5 at a depth of 560 m.

Case	Maximum horizontal stress		Minimum horizontal stress		Vertical stress	Excess glacial pore pressure
	s_H (MPa)	Trend (°)	s_h (MPa)	Trend (°)	s_v (MPa)	
Base Case (Baseline stress model)	53.0	145	29.2	55	12.5	98 %
Case 1 (Trend - 15°)	53.0	130	29.2	40	12.5	98 %
Case 2 (Trend + 15°)	53.0	160	29.2	70	12.5	98 %
Case 3 ($\sigma_{Hmax} = \sigma_H + 6$ MPa $\sigma_{hmax} = \sigma_h + 5$ MPa)	59.0	145	34.2	55	12.5	98 %
Case 4 ($\sigma_{Hmin} = \sigma_H - 6$ MPa $\sigma_{hmin} = \sigma_h - 5$ MPa)	47.0	145	24.2	55	12.5	98 %
Case 5 (Stress at 560 m from P-25-02 OC meas. at KFM24)	24.2	121	14.8	31	14.6	98 %

4 Simulation results

4.1 Presentation of results

Only the key results of the simulated cases are included in the main text whereas the majority of the results are presented in the Appendices. Results include the following:

- 3D figures of DZ shear displacement contours with maximum values (Appendix 1).
- Equal area lower hemisphere plots of DZ normals for DZs which have sheared more than 0.1 m, defined according to whether shear of over 0.1 m has occurred anywhere along the DZ (Appendix 2).
- Cumulative shear displacement multiplied by associated area versus depth for major orientations sets of deformation zones by type (Appendix 3).
- The major principal stress magnitude, trend and σ_1/σ_2 ratio with mean and 95% variation limits for each hundred meter depth interval in a 2400 m wide vertical cylinder covering the majority of the repository area up to a depth of 2000 m (Figure 4-1) Appendix 4).
- The major principal stress magnitudes with mean and 95% variation limits for each hundred meter depth interval in a 2400 m wide vertical cylinder covering the majority of the repository area vs stress measurements up to a depth of 2000 m (Appendix 5).
- Principal stress trends and magnitudes in lower hemisphere projection polar plots for the data obtained from the cylinder presented in Figure 4-1 (Appendix 6)
- The major principal stress magnitude and trend distributions in a rectangular volume (2950 x 2160 x 100 m) encompassing the repository area from a depth range of 420 to 520 m (Figure 4-2) (Appendix 7).
- The change of the principal stress magnitudes in a horizontal cross-section at the repository (Appendix 8, Appendix 9, Appendix 10).
- The change of the major principal stress trend in a horizontal cross-section at the repository (Appendix 11).

Note that plots that include field stress measurement results include only the 48 overcoring measurements ranked as “Good” or “Moderate” by Sjöberg et al. (2025), Hakami et al. (2025).

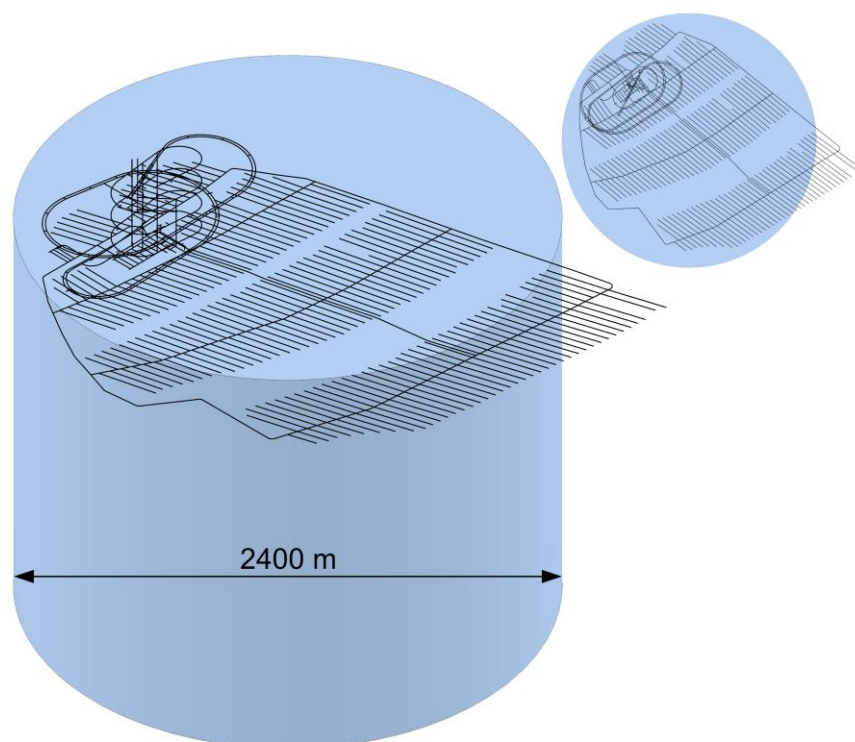


Figure 4-1. Cylindrical data acquisition volume for average stress magnitude and trend values.

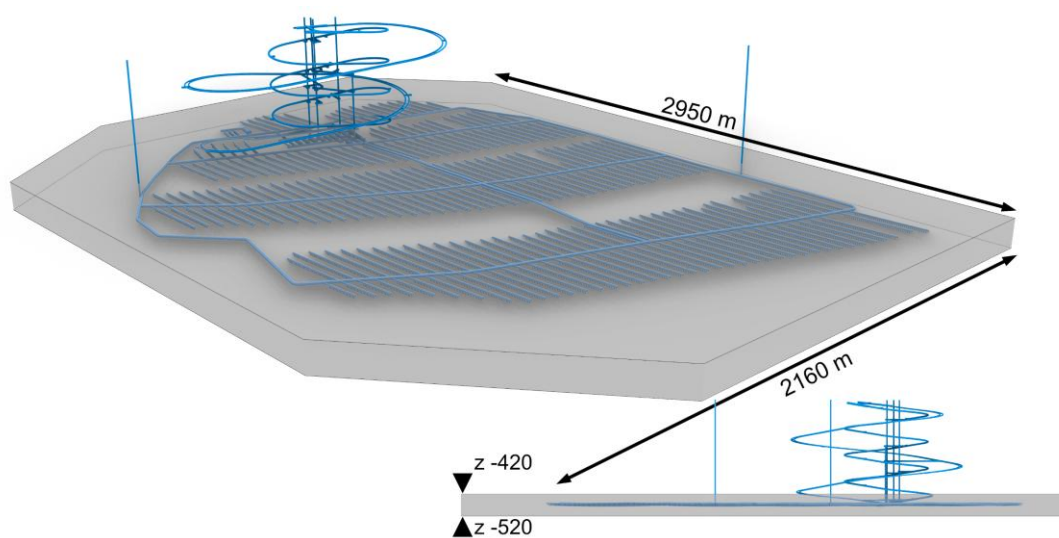


Figure 4-2. The data acquisition volume for frequency analysis of the distributions of the magnitude and trend of σ_1 at repository depth.

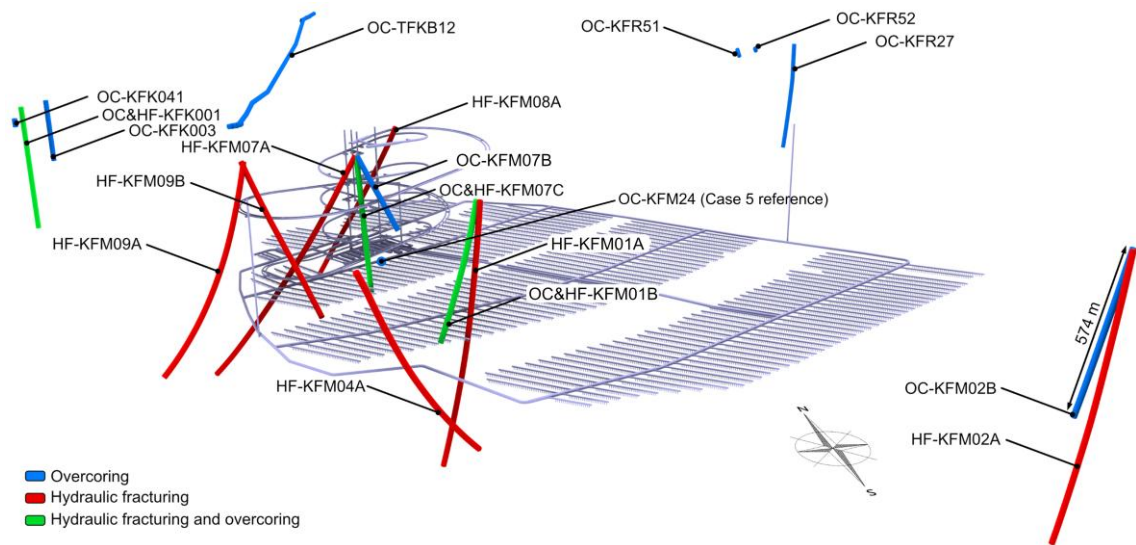
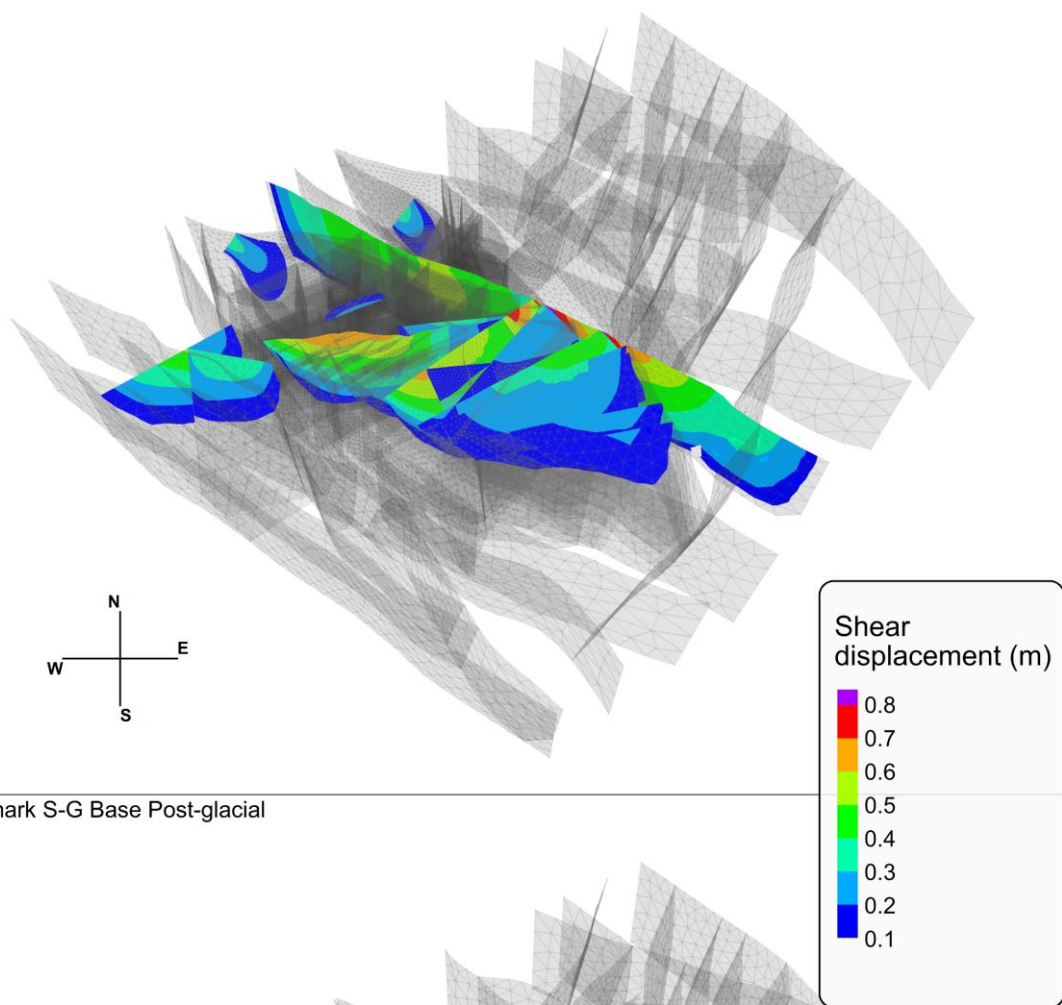


Figure 4-3. The locations of the stress measurements plotted in major principal stress magnitude and trend figures. The overcoring reference measurement in KFM24 for Case 5 is indicated separately.

4.2 Base case

The thrust for the Base case mainly caused plastic shear but also combined shear and tension of deformation zone Set 1, extending down to a depth of 600 m (Figure 4-4, Figure 4-5). Set 2, mainly the Singö deformation zone (ZFMWNW0001), exhibits elastic shear displacement to a depth of 1000 m (Figure 4-6). Set 3 does not fail in shear. The glaciation cycle increases plastic shear of Set 1 at all depths and of set 2 down to a depth of 300m (Figure 4-6).

Forsmark S-G Base Pre-glacial



Forsmark S-G Base Post-glacial

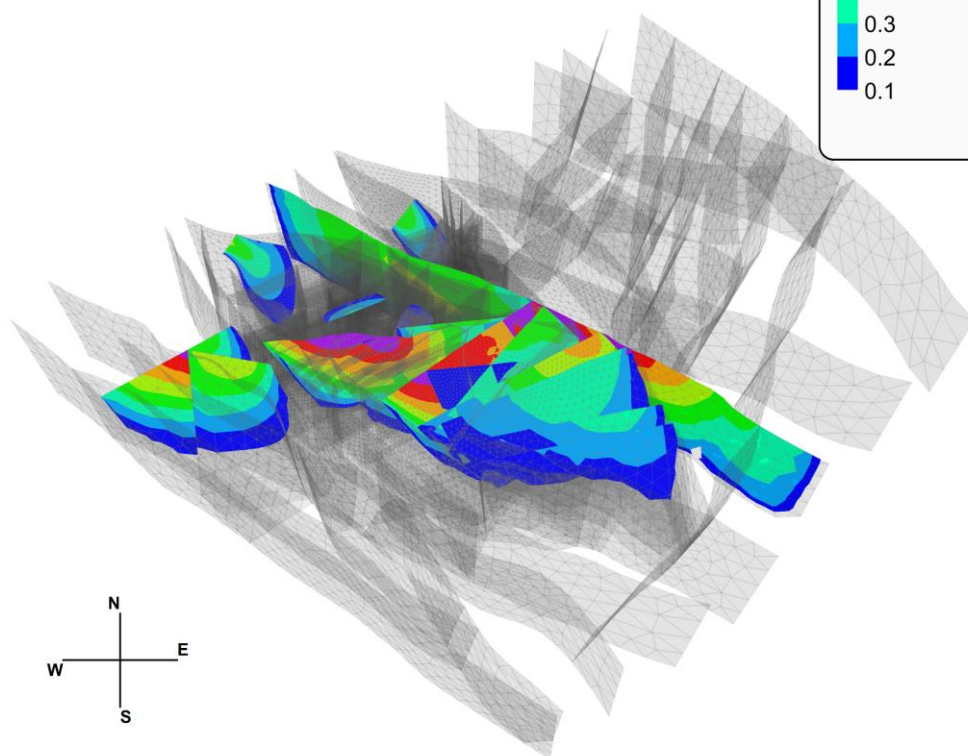
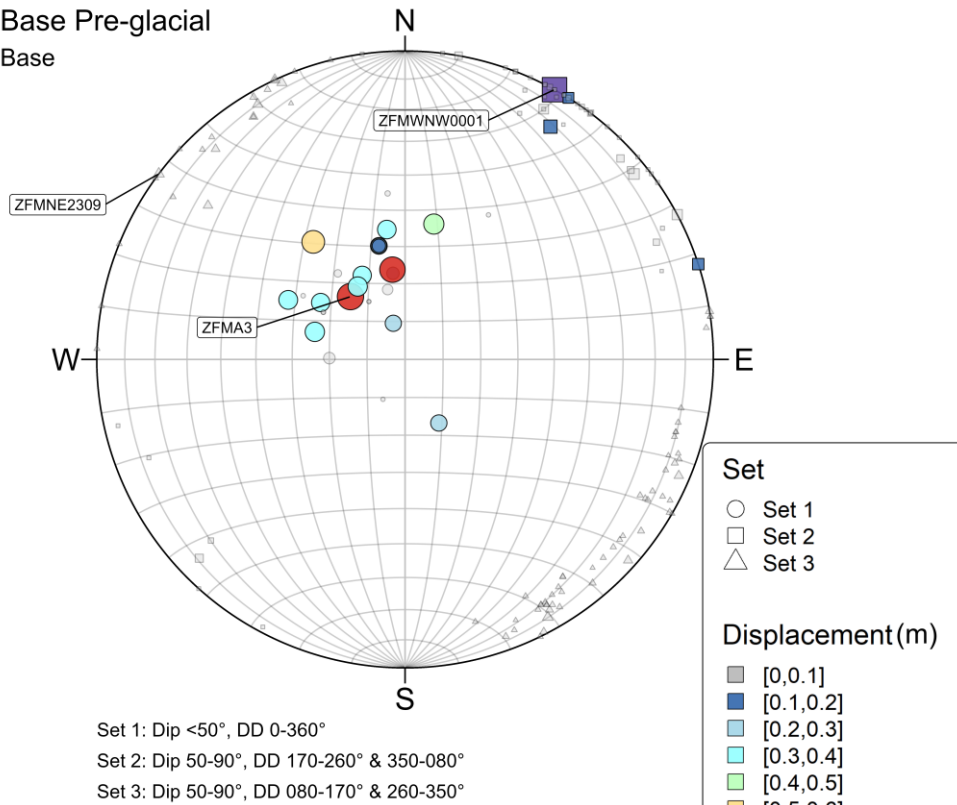


Figure 4-4. Deformation zone shear contours before and after glaciation for the Base case.

Fault shear LHP

Base Pre-glacial
Base



Base Post-glacial
Base

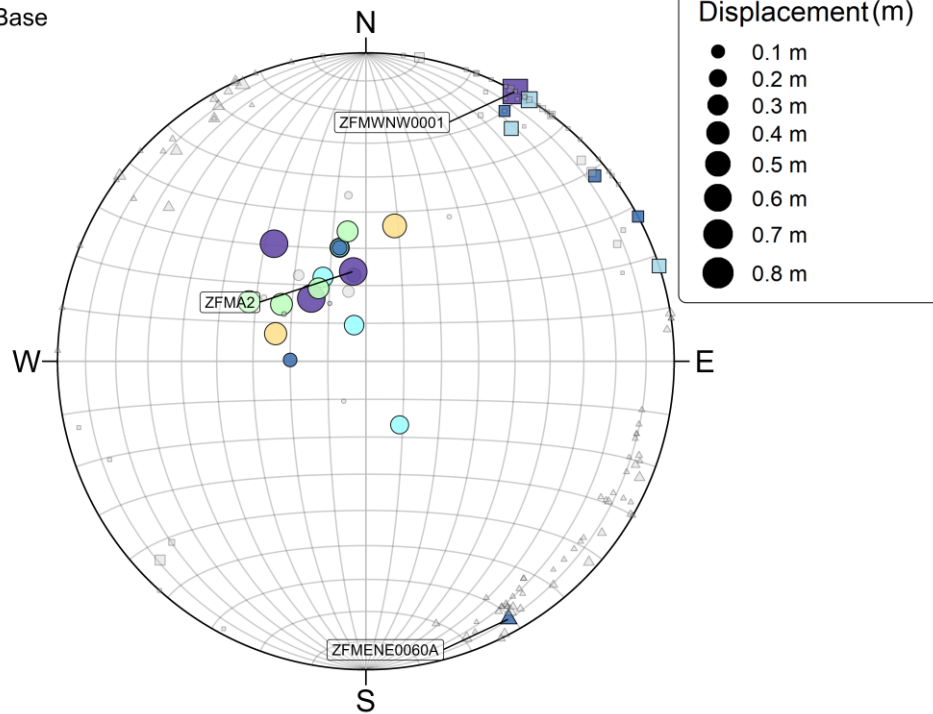


Figure 4-5. Deformation zone shear before and after glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case. Both symbol size and colour indicate displacement magnitude in metres.

Case: Base

Pre-Glacial vs Post-Glacial

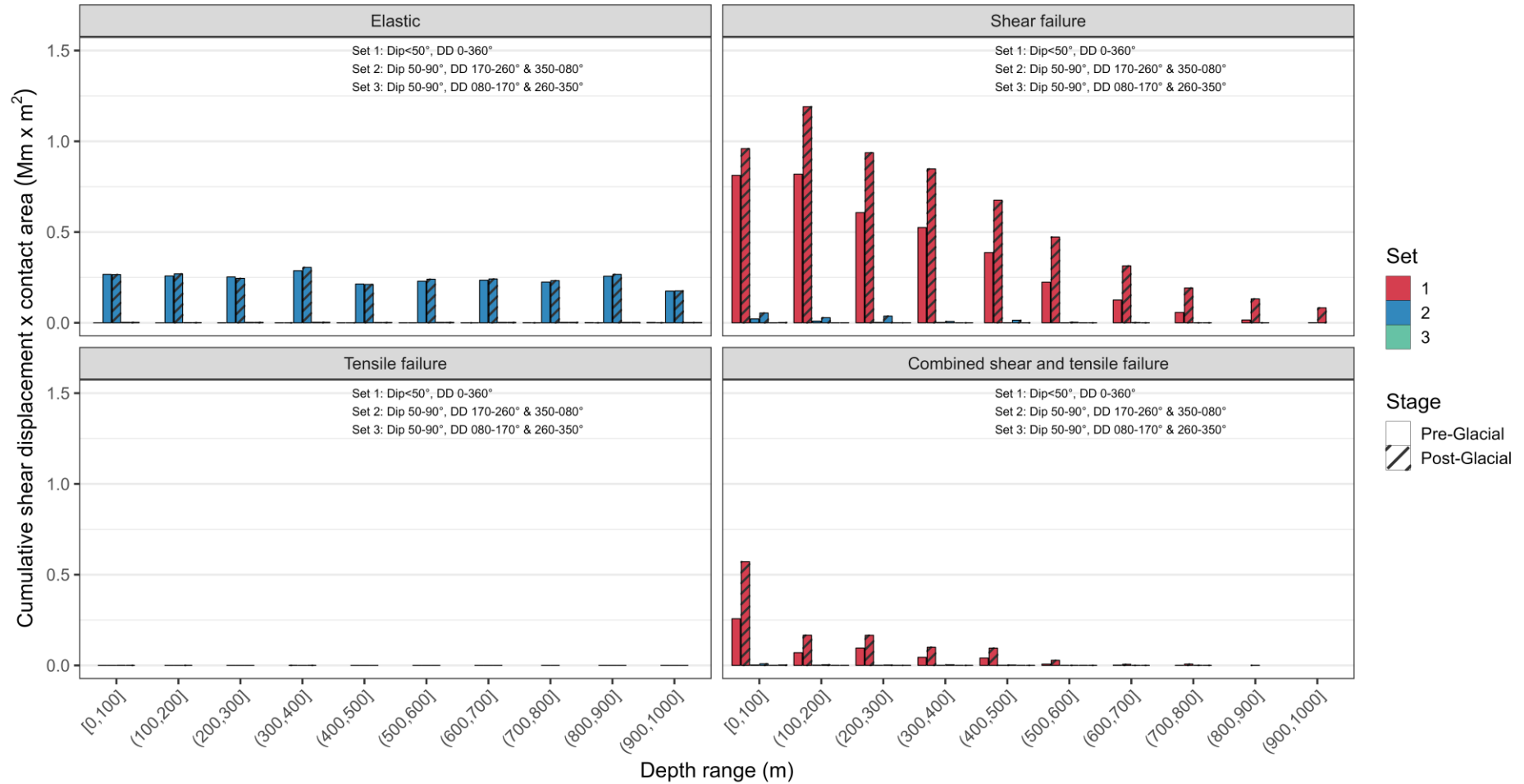


Figure 4-6. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case before and after glaciation.

Analysis of the depth-based distribution of principal stress data across the repository footprint indicates that at the pre-glacial phase the mean trend of the maximum compression rotates a maximum of 14° counterclockwise from the trend of thrust above a depth 200 m but below 200 m the mean trend is relatively constant and does not deviate significantly from the thrust direction (Figure 4-7). Compared to the stress gradients of the Baseline stress model, the σ_1 magnitude is 15-20 MPa greater at depths of 100 m to 300 m and slightly lower (~5MPa) below 700 m. The glacial cycle decreases the σ_1 mean magnitude down to the 400 m level and widens variation on the lower magnitude side, while a minor increase of magnitude variation can be seen down to a depth of one kilometre. The measured maximum and intermediate stresses are mostly within the simulated 95 % confidence bounds, although this does not apply between a depth of about 100 to 300 m (Figure 4-8). At these depths, the lower bound of σ_1 is often much lower (15 MPa) than the simulated bound while for σ_2 , the bounds deviate at maximum 10 MPa from the simulated bounds in both directions. In the repository volume (± 50 m from the repository level), the median horizontal stress magnitudes are equal to the targets and the mean trend only deviates -2° (Figure 4-9 and Figure 4-10). In the repository footprint, the variation of σ_1 is less than ± 10 MPa, ± 5 MPa for σ_2 and σ_3 and the variation of the trend of σ_1 is below $\pm 10^\circ$ (Figure 4-11 to Figure 4-14). Deformation zone set 1 causes the highest change in the trend of σ_1 . This applies both to the pre- and post-glacial stages. Above the 300 m level the simulated variation of the major principal stress trend is considerably lower than the measured variation (Figure 4-7).

Cylinder data — Case: Base

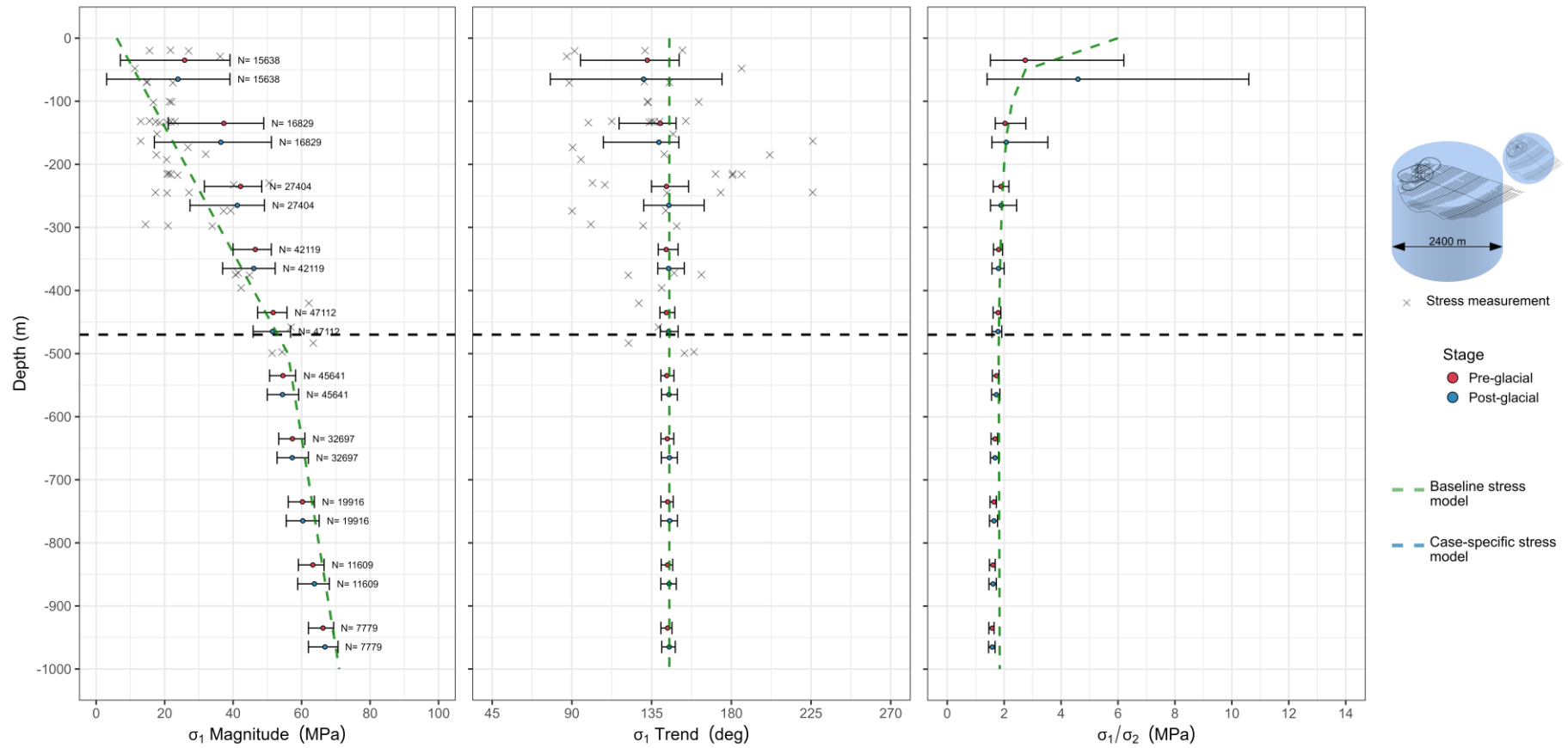


Figure 4-7. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case before and after glaciation for a cylinder covering the repository footprint (in blue in top right inset). The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey markers.

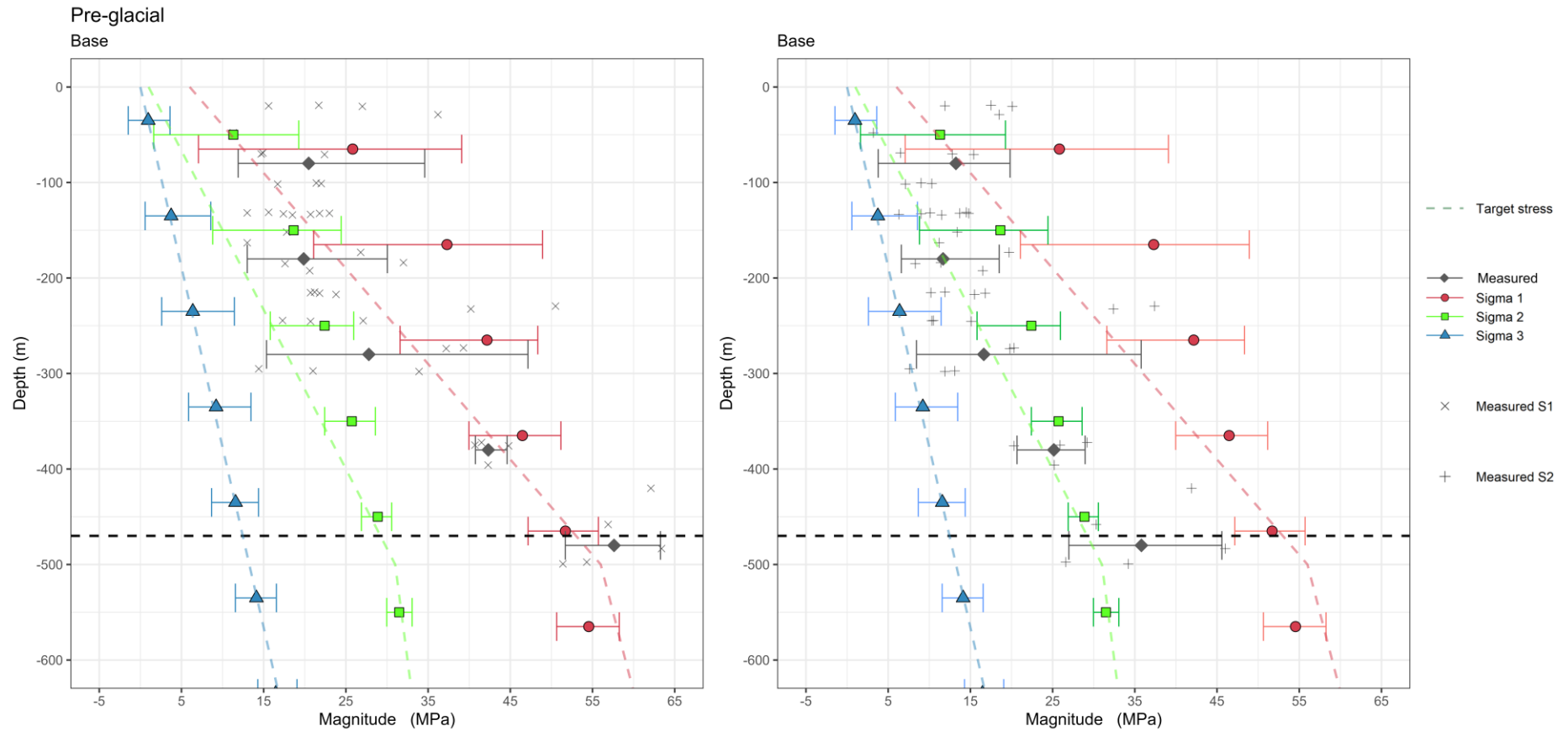
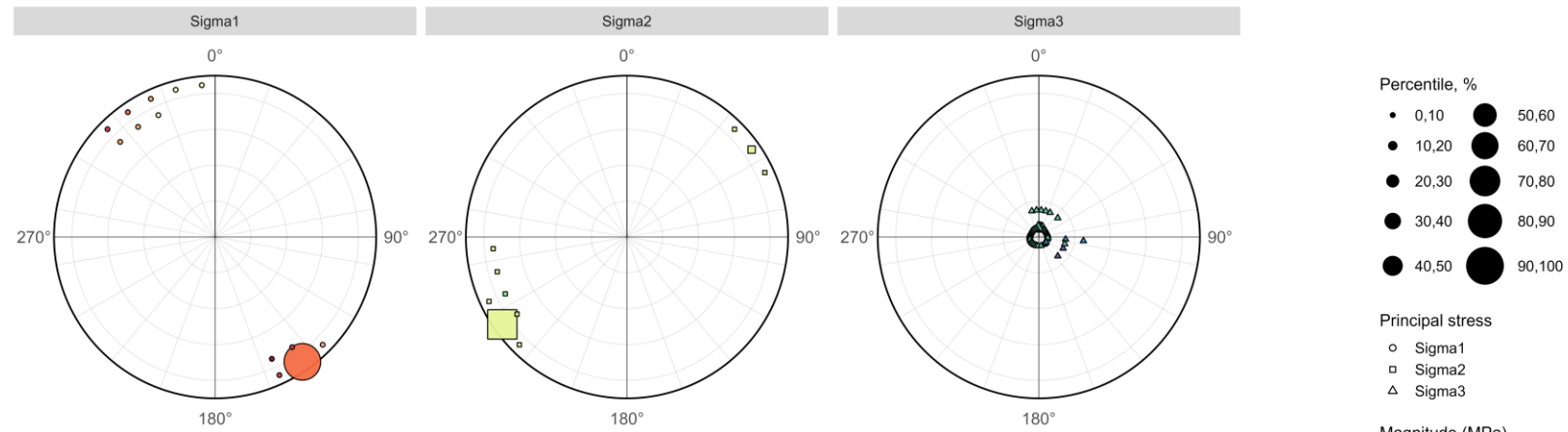


Figure 4-8. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred-meter intervals for the Base case simulations *before* glaciation from a cylinder covering the repository. Left: simulation results vs σ_1 from field stress measurements. Right: simulation results vs σ_2 from field stress measurements. The Baseline stress model is indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey cross or plus symbols, with the mean and 95% variation interval also in grey.

Case: Base - cylinder data, depth 400-500 m

Pre-glacial



Post-glacial

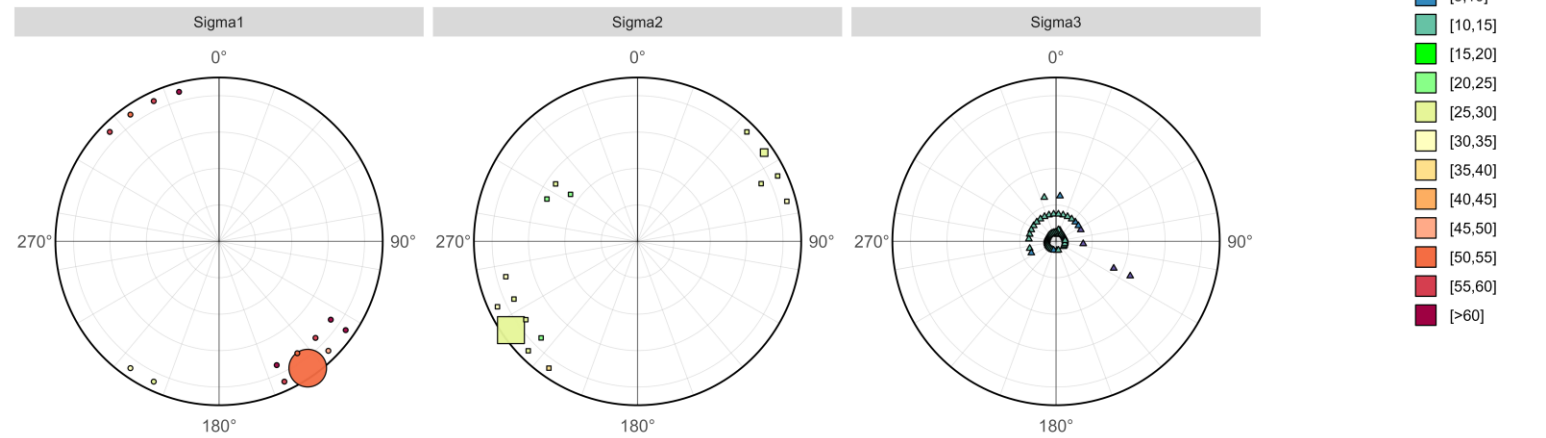


Figure 4-9. Lower hemisphere projection polar plots of the principal stresses at 20° intervals obtained from a cylinder covering the repository footprint of the Base case simulations, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Repository depth data — Case: Base

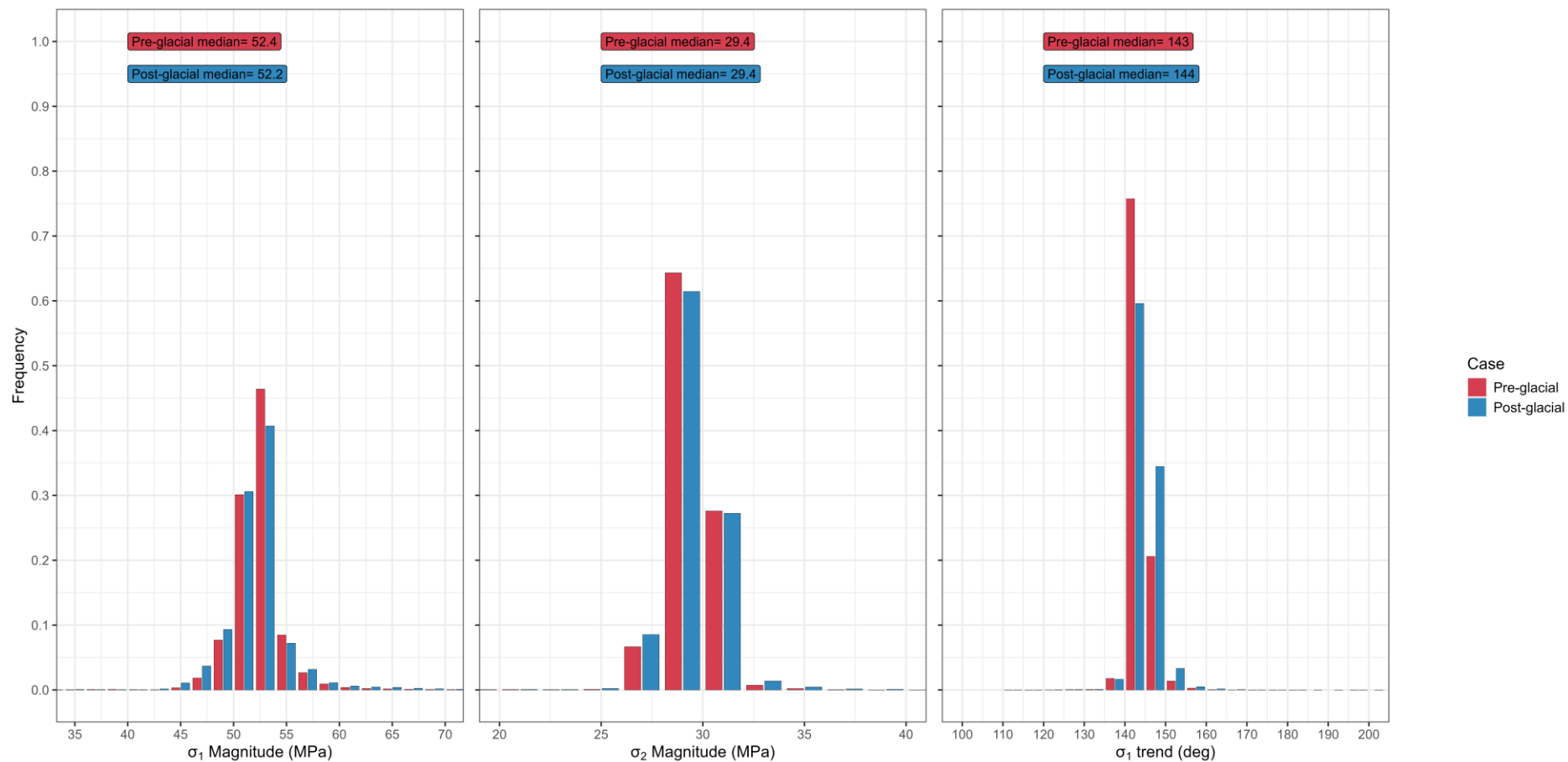
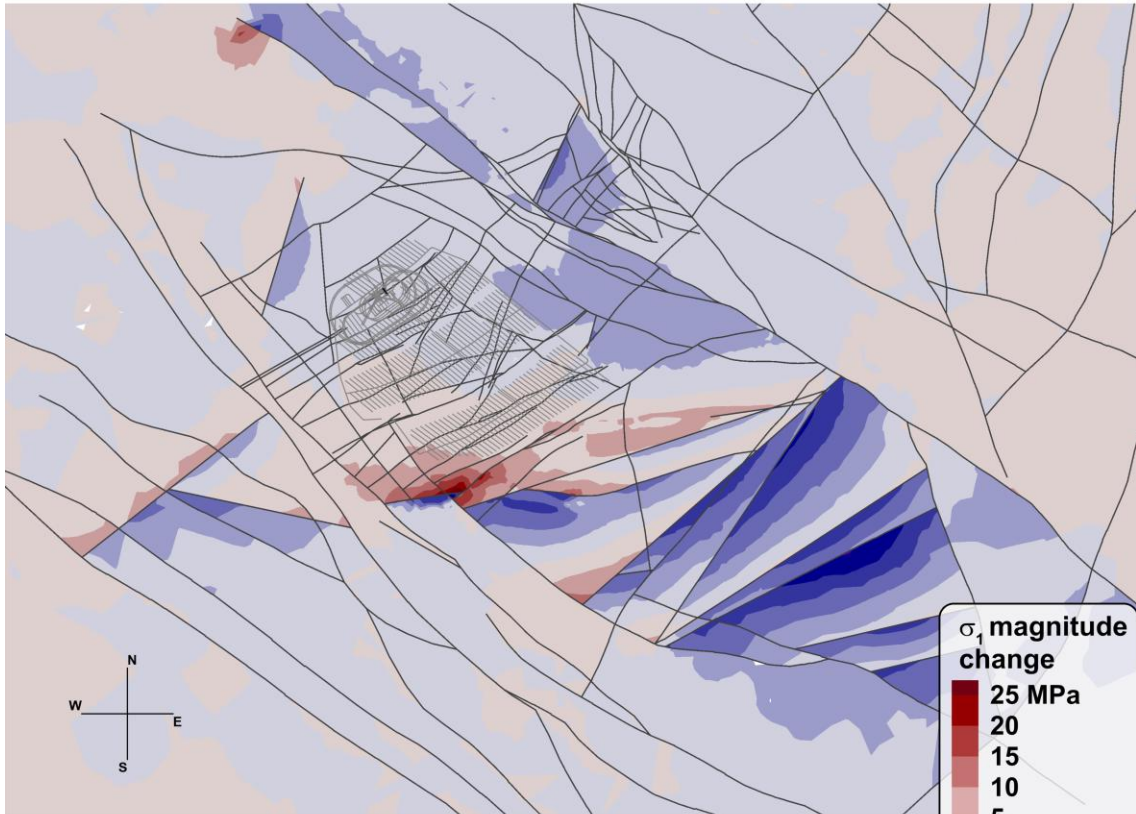


Figure 4-10. Distribution of σ_1 and σ_2 magnitude and σ_1 trend at repository depth before and after glaciation for the Base case simulations.

Forsmark S-G Base Pre-glacial



Forsmark S-G Base Post-glacial

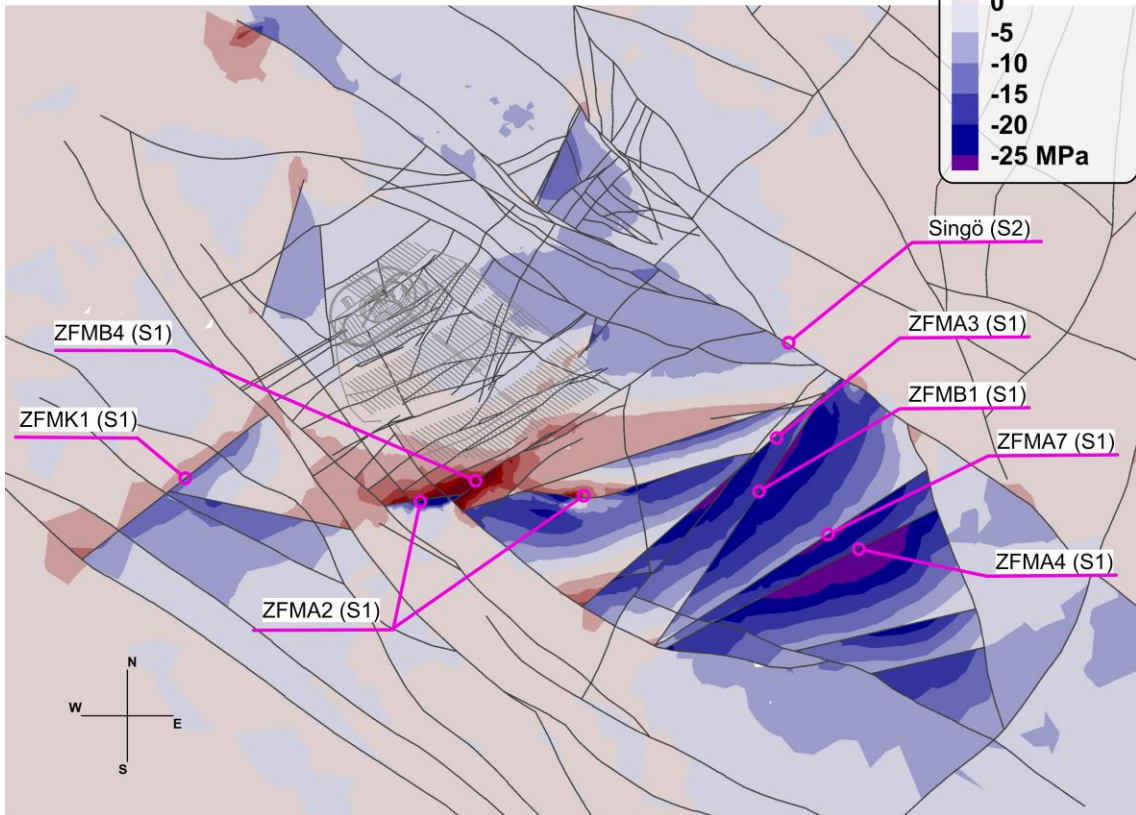
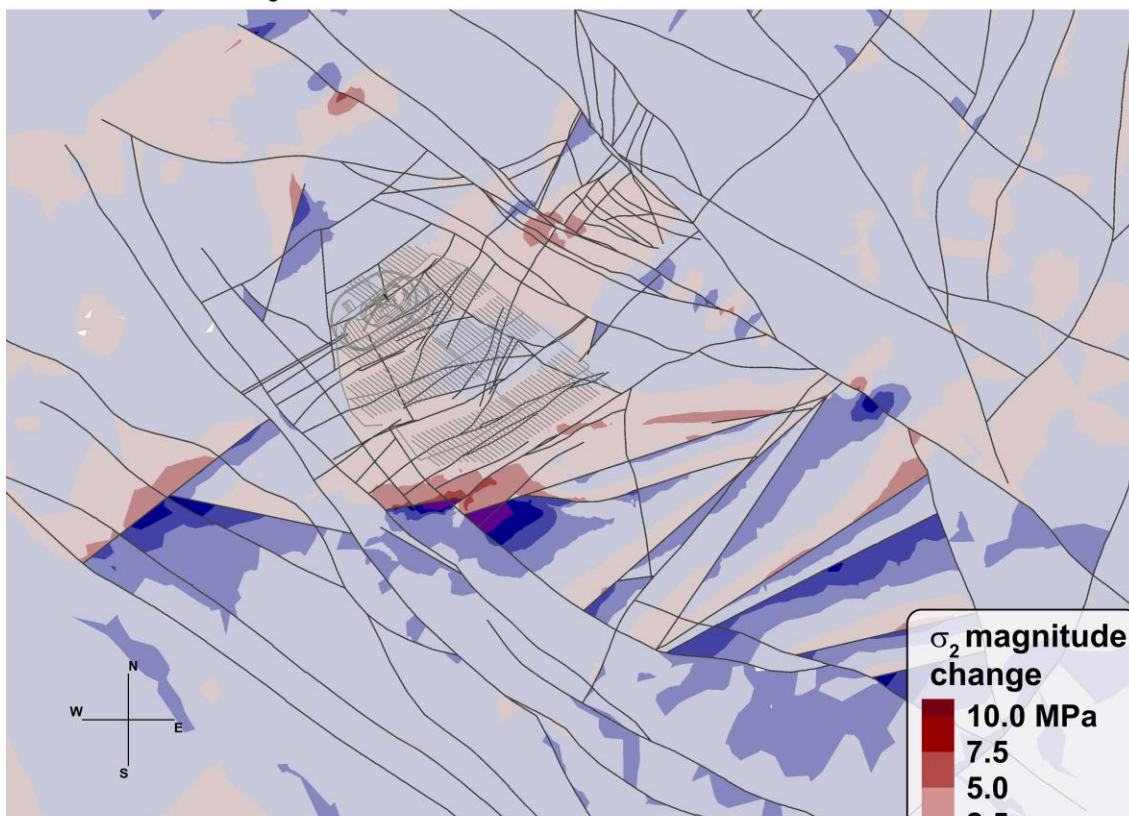


Figure 4-11. The change in σ_1 magnitude before and after glaciation for the Base case simulations in a horizontal cross-section at repository depth (470 m). The DZ that cause the largest changes are labelled by ID and set number (in parentheses). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial



Forsmark S-G Base Post-glacial

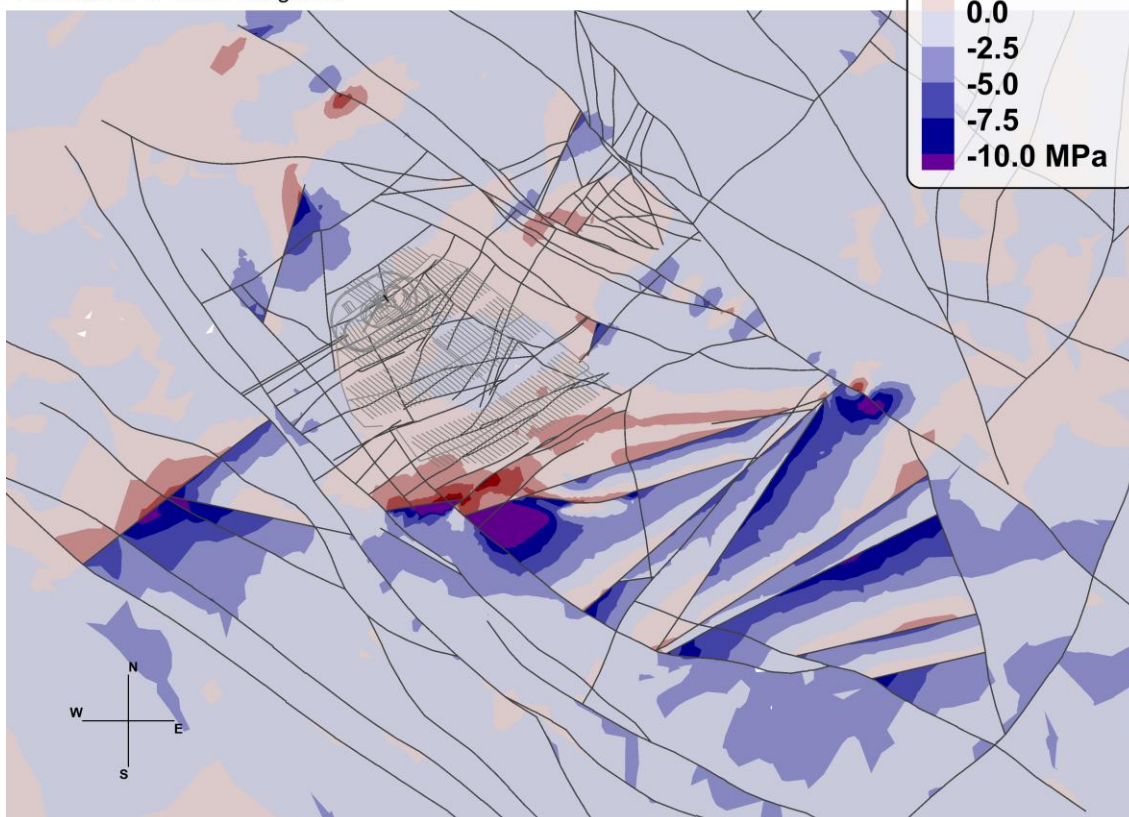
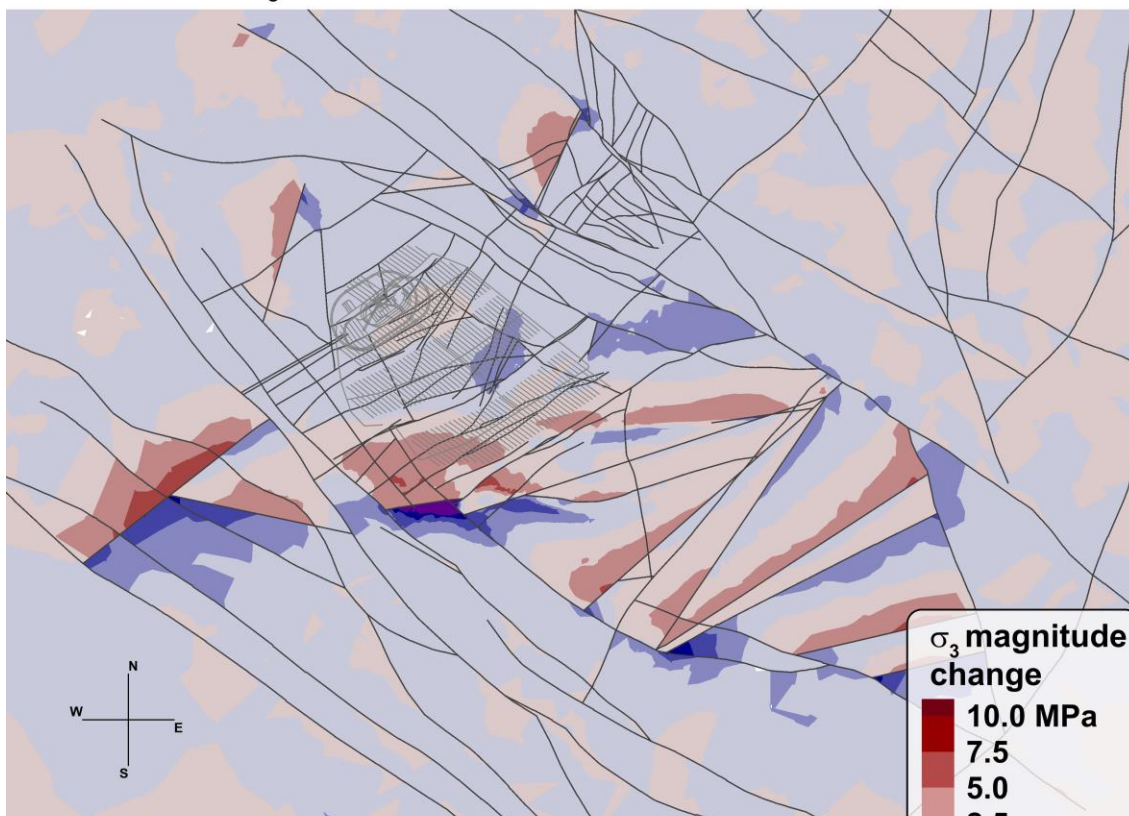


Figure 4-12. The change in σ_2 magnitude before and after glaciation for the Base case simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial



Forsmark S-G Base Post-glacial

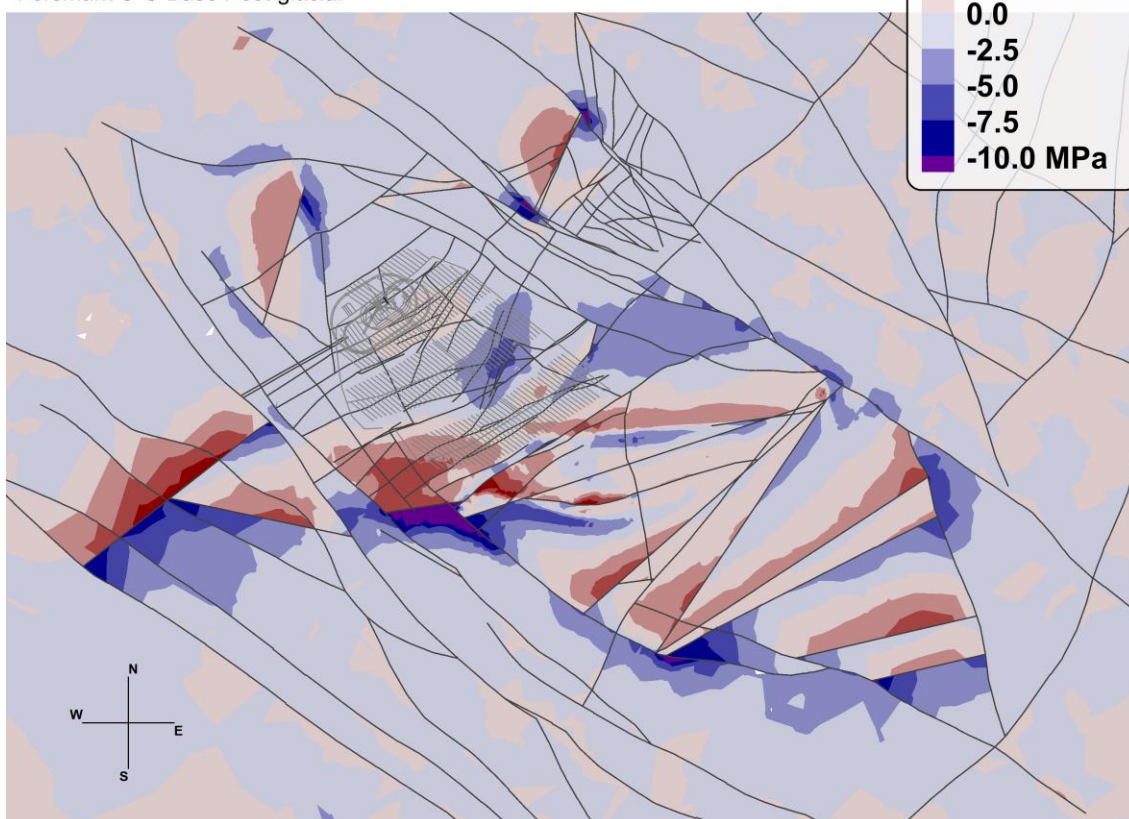
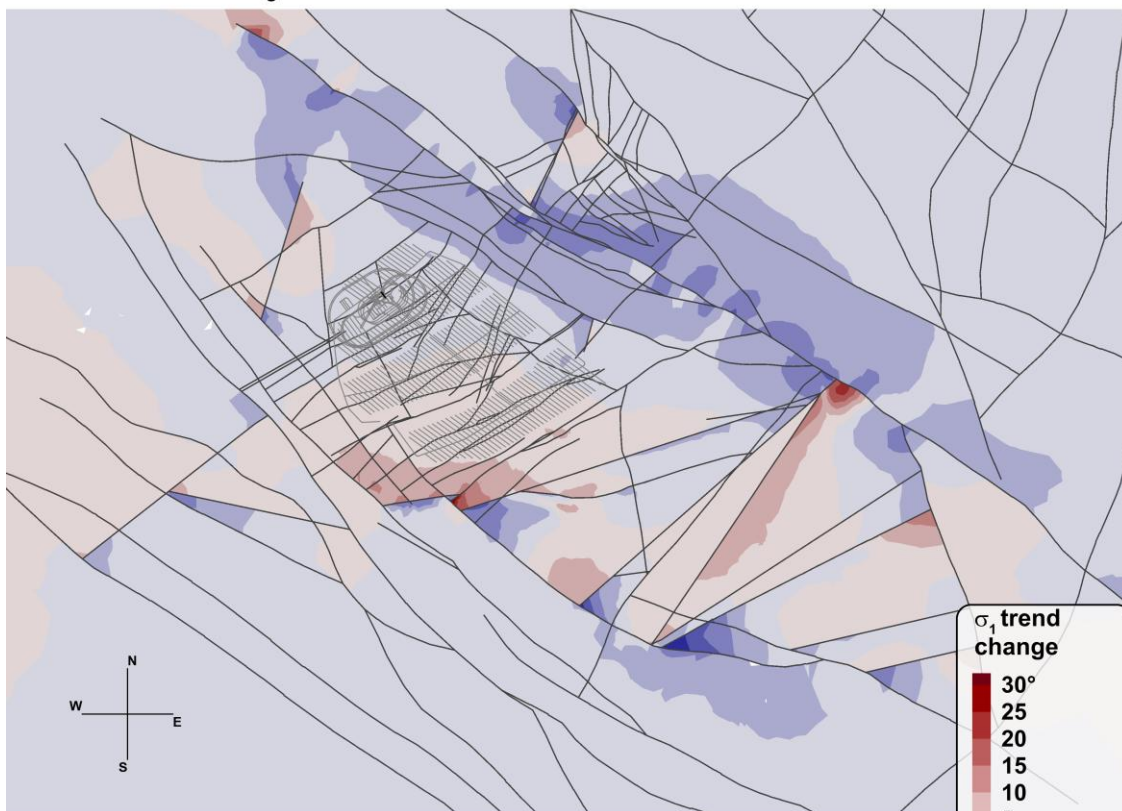


Figure 4-13. The change in σ_3 magnitude before and after glaciation for the Base case simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial



Forsmark S-G Base Post-glacial

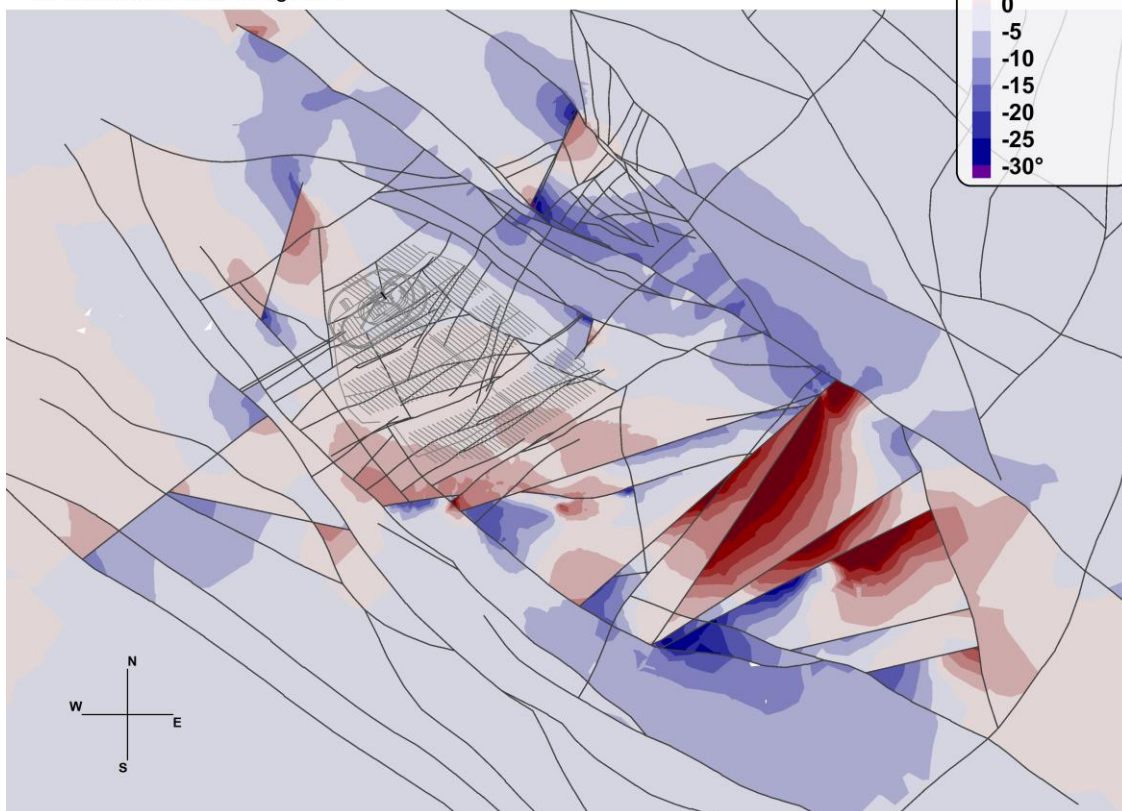


Figure 4-14. The change in σ_1 trend before and after glaciation for the Base case simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

A comparison of the simulated post-glacial maximum principal stress confidence bounds shows good agreement with the field measurements in the 0–100 m depth range. Between 100 and 300 m depth, however, the lower confidence bound of the σ_1 measurements is approximately 10 – 15 MPa lower than the lower confidence limit of the simulations. For the intermediate principal stress (σ_2), the simulation confidence limits generally encompass the measured values. In the 200–300 m interval, the lower and upper confidence limits of measured σ_2 values deviate 5 and 10 MPa when compared to the simulated bounds, respectively. In addition, measurements of σ_2 show substantial scatter up to 15 MPa in the 400–500 m depth interval, as illustrated in Figure 4-15. Overall, both the maximum and intermediate simulated stresses are significantly higher than the interpreted stress state up to a depth of about 300 m.

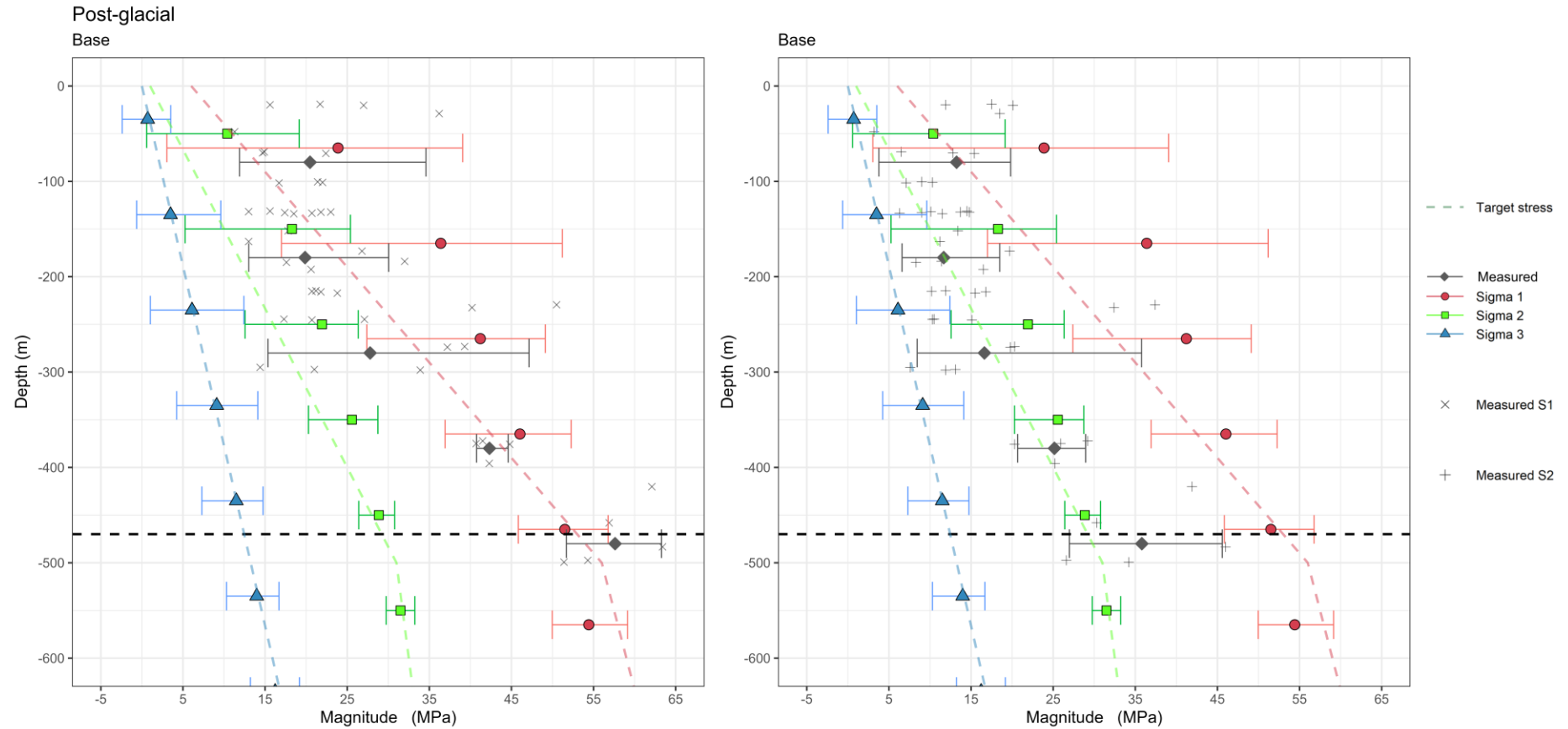


Figure 4-15. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case simulations after glaciation from a cylinder covering the repository. Left: simulation results vs σ_1 from field stress measurements. Right: simulation results vs σ_2 from field stress measurements. The Baseline stress model is indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

4.3 Cases 1 and 2: base stress with -15° and $+15^\circ$ S1 trend

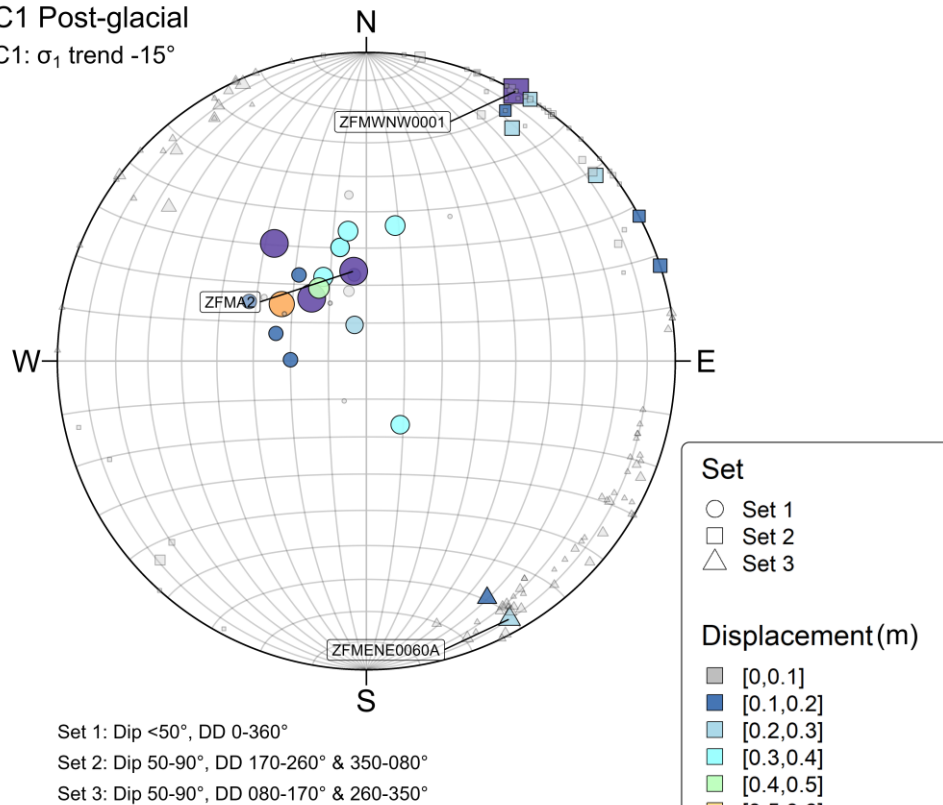
In cases 1 and 2, the thrust was either rotated -15° (counterclockwise) or $+15^\circ$ (clockwise) compared to the default orientation of 145° and the deformation zone geometry. Counterclockwise rotation reduced plastic shear of deformation zone Set 1 up to a depth of 700 m and reduced both elastic and plastic shear of set 2 considerably (Figure 4-16, Figure 4-17). Clockwise rotation reduced the plastic shear of Set 1 up to a depth of 300 m but it increased it in the 300-800 m depth range. Elastic shear of set 2 also increased consistently up to a depth of 1000 m (Figure 4-18). In these cases, set 2 activity is mainly due to shear of the Singö deformation zone. As visible in Figure 4-16, the shearing faults are mostly the same in both cases, but the clockwise rotation in case 2 causes slightly higher DZ shear.

Apart from the $\pm 15^\circ$ thrust rotation the gradient of σ_1 magnitude and trend are very close to the Base case (Appendix 4 and Appendix 6). In the repository volume the σ_1 , σ_2 and σ_3 trend median are practically equal to the Base case, but in case 2 the variation of σ_1 is smaller than the Base case and the southernmost area of the repository layout may exhibit magnitudes 5 MPa to 10 MPa higher than the median (Appendix 7 and Appendix 8).

Fault shear LHP

C1 Post-glacial

C1: σ_1 trend -15°



C2 Post-glacial

C2: σ_1 trend $+15^\circ$

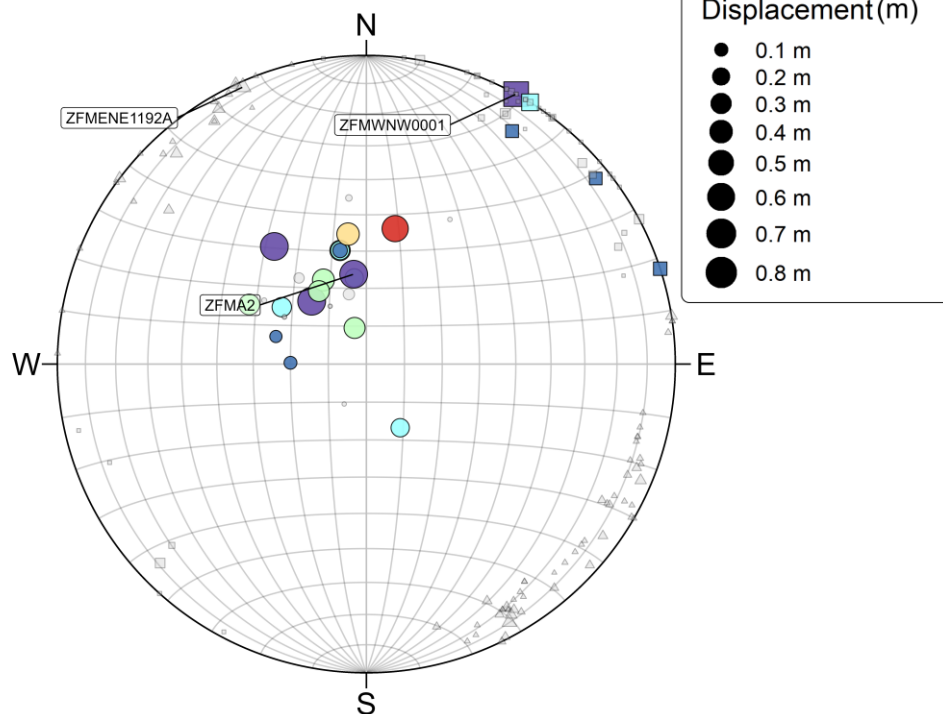


Figure 4-16. Deformation zone shear after glaciation by set group on an equal area lower hemisphere projection (LHP) for Case 1 and 2. Both symbol size and colour indicate displacement magnitude in metres.

C1: σ_1 trend -15°

Post-Glacial

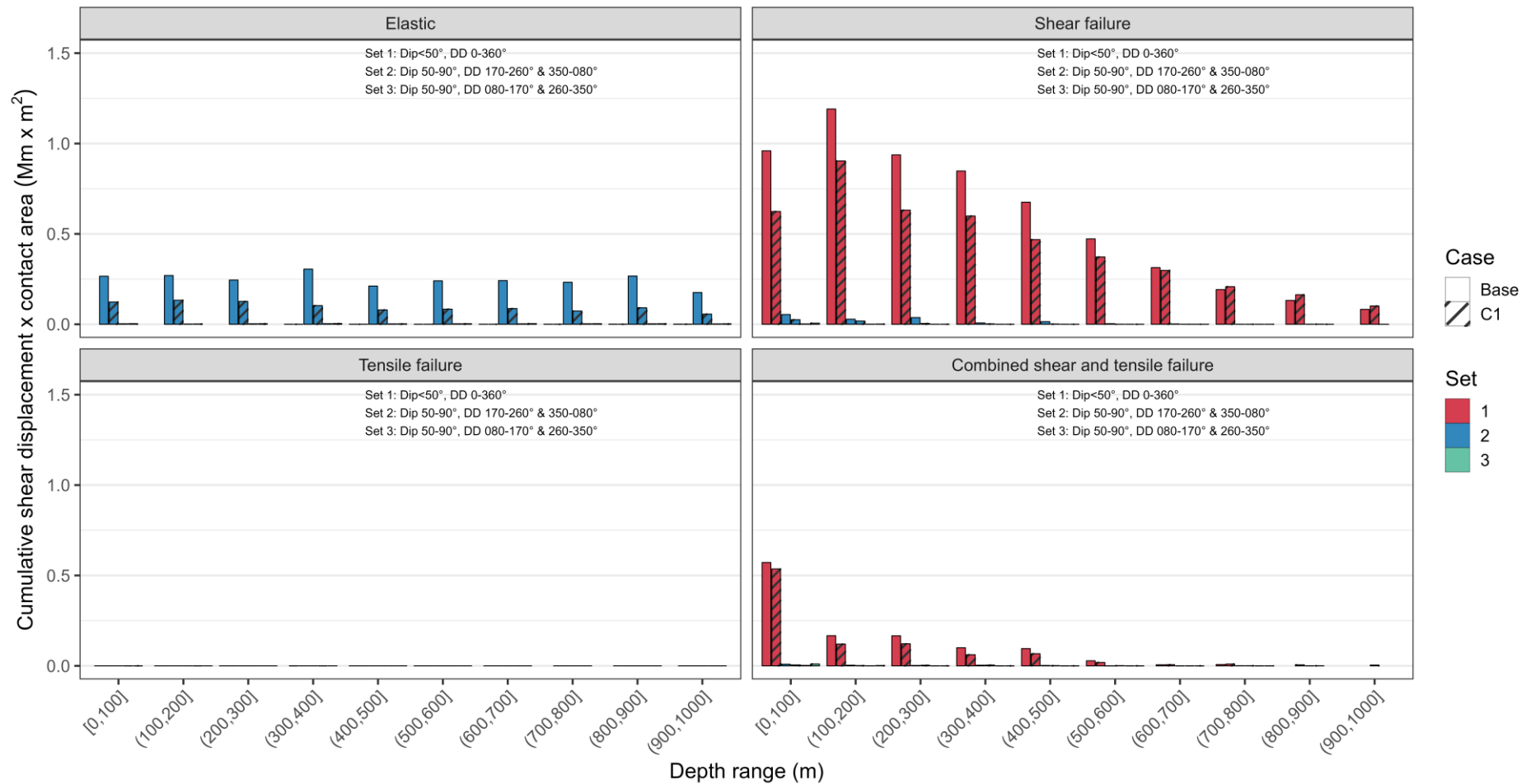


Figure 4-17. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base case and Case 1 after glaciation.

C2: σ_1 trend +15°

Post-Glacial

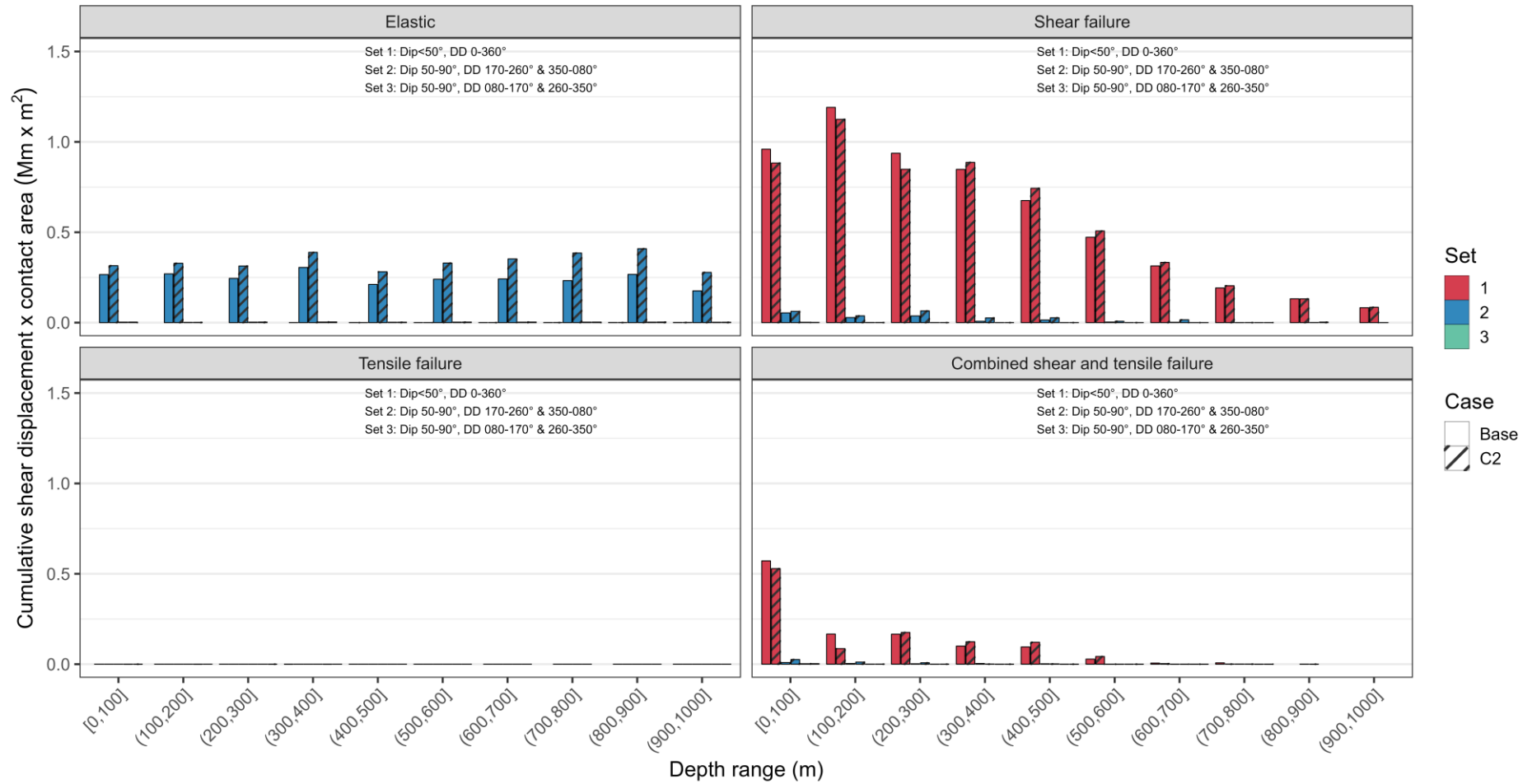


Figure 4-18. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base case and Case 2 after glaciation.

4.4 Cases 3 and 4: maximum and minimum stresses

In cases 3 and 4, the major and intermediate principal stresses are set to their maximum and minimum uncertainty ranges, respectively. As visible in Figure 4-19 and Figure 4-20, the major principal stress in both Cases 3 and 4 exceeds the target value above 300 m depth, matches the target reasonably well between 300 and 500 m, and falls below the target at depths greater than 500 m. Case 3 increases scatter in the trend of the major principal stress up to a depth of 400 m when compared to the Base case, whereas case 4 results in slightly reduced scatter up to a depth of one kilometre. Case 3 exhibits increased plastic shear of Set 1 deformation zones up to a depth of one kilometre, with increased elastic shear but reduced plastic shear of Set 2 DZ (Appendix 3). In the repository volume, the median magnitudes σ_1 and σ_2 and trend of σ_1 practically match the target values (Appendix 7).

For both cases 3 and 4, glaciation causes an increase of about +5 to +10 MPa in σ_1 locally in the southernmost area of the repository layout, and a σ_1 trend rotation under 10° (Figure 4-21 to Figure 4-24). Maximum principal stress rotation is larger in Case 3 and lower in Case 4 with respect to the base case.

Figure 4-25 shows that the measured σ_1 values lie under the 95% confidence bounds of the simulated maximum principal stresses of Case 3 at the repository depth, while some of the measured σ_2 values lie outside the 95% confidence bounds of the simulated intermediate stress. Furthermore, the mean values of the field measurements are in good agreement with the simulated maximum and intermediate principal stresses at repository level in Case 3. However, Figure 4-26 shows that all the measured σ_1 and σ_2 values lie below the lower limit of the 95% confidence bounds of the simulated maximum and intermediate principal stresses of Case 4 at the repository depth.

Cylinder data: Post-Glacial

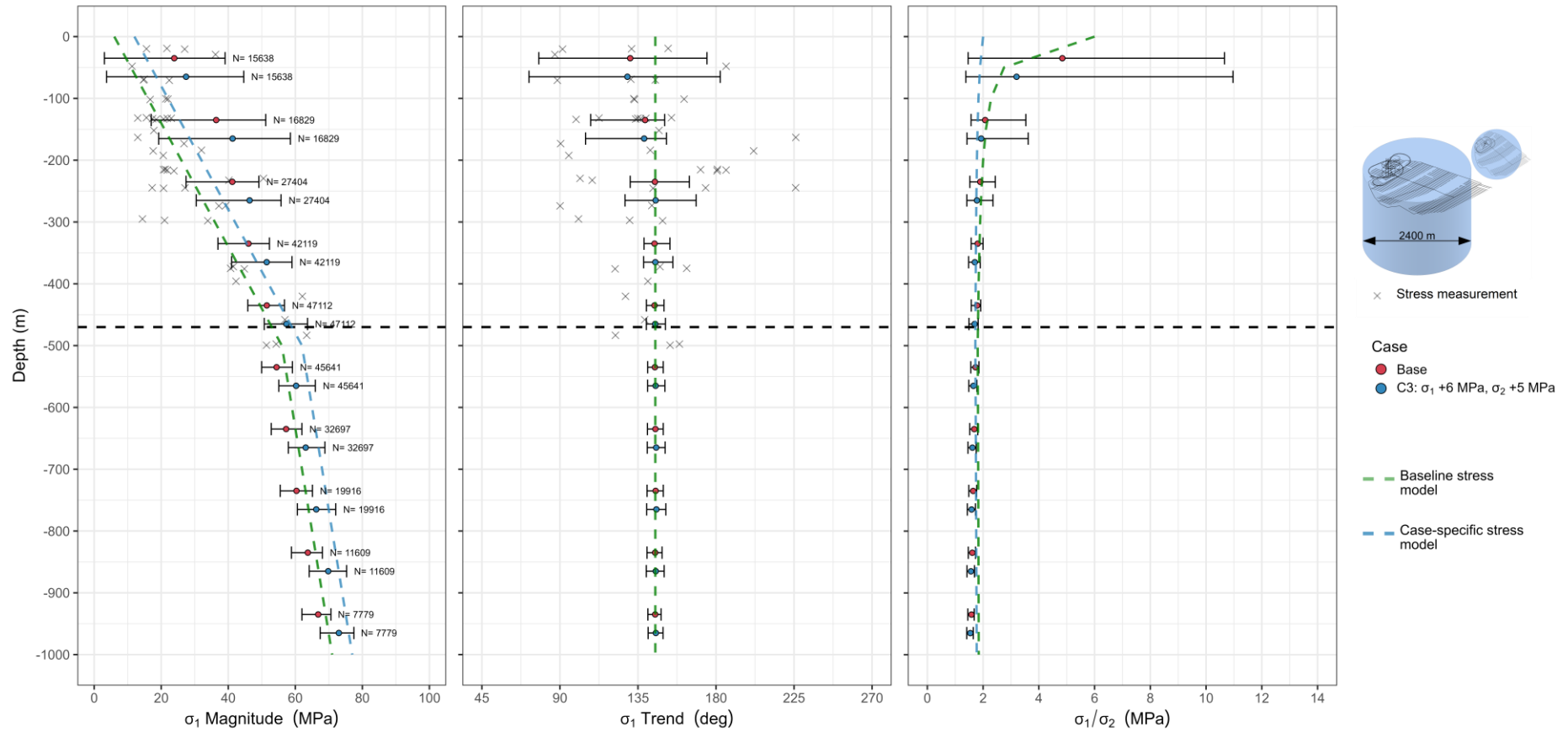


Figure 4-19. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and Case 3 after glaciation for a cylinder covering the repository footprint (in blue in top right inset). The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “x” markers.

Cylinder data: Post-Glacial

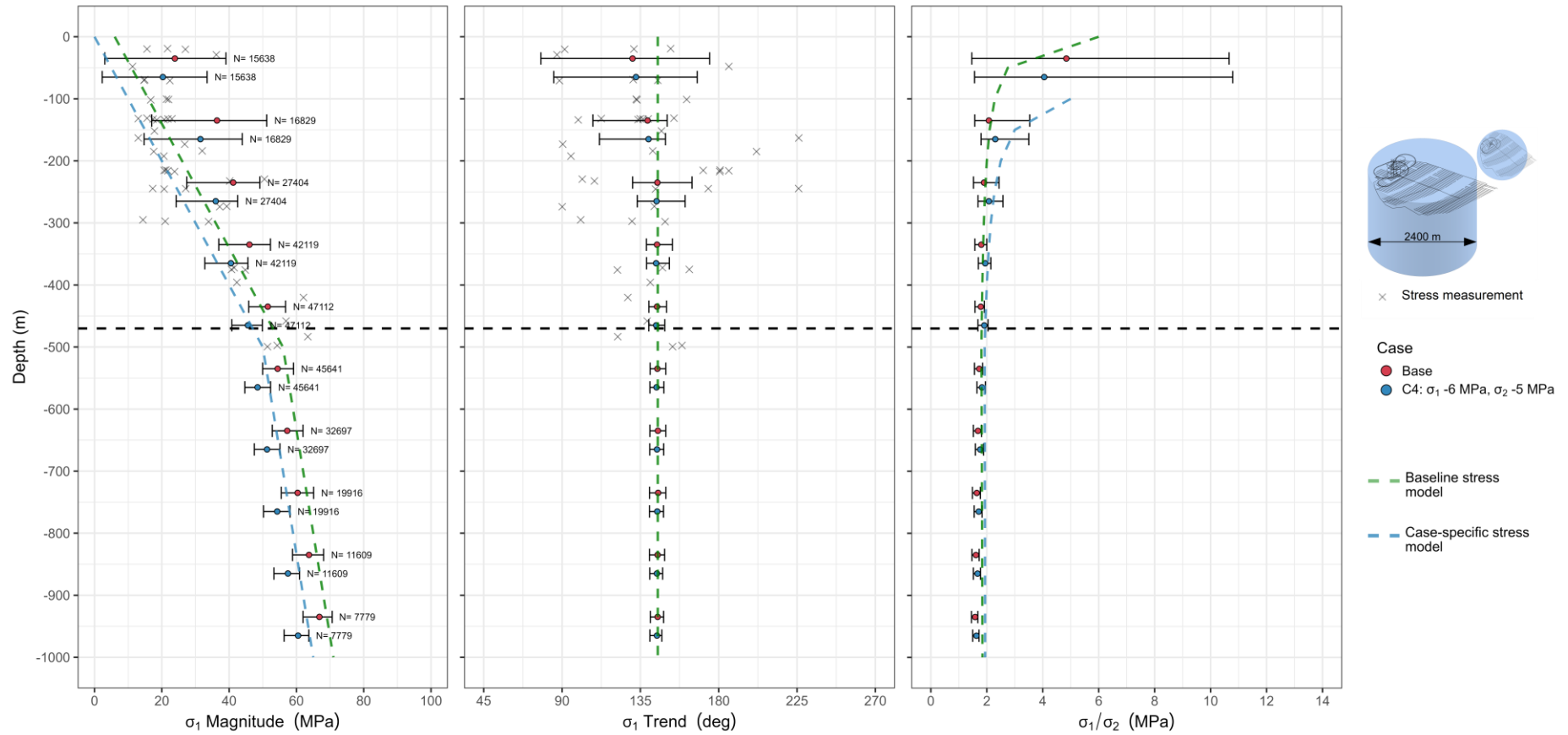
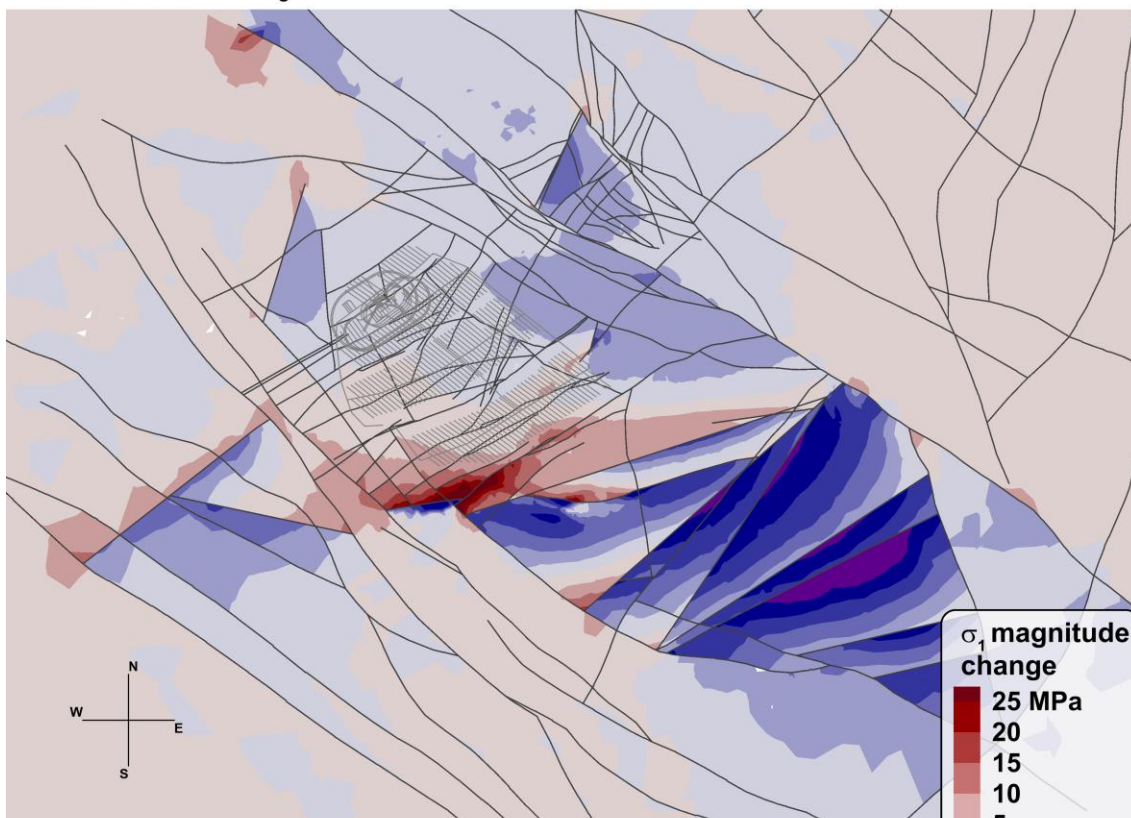


Figure 4-20. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and Case 4 *after* glaciation for a cylinder covering the repository footprint (in blue in top right inset). The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “x” markers.

Forsmark S-G Base Post-glacial



Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Post-glacial

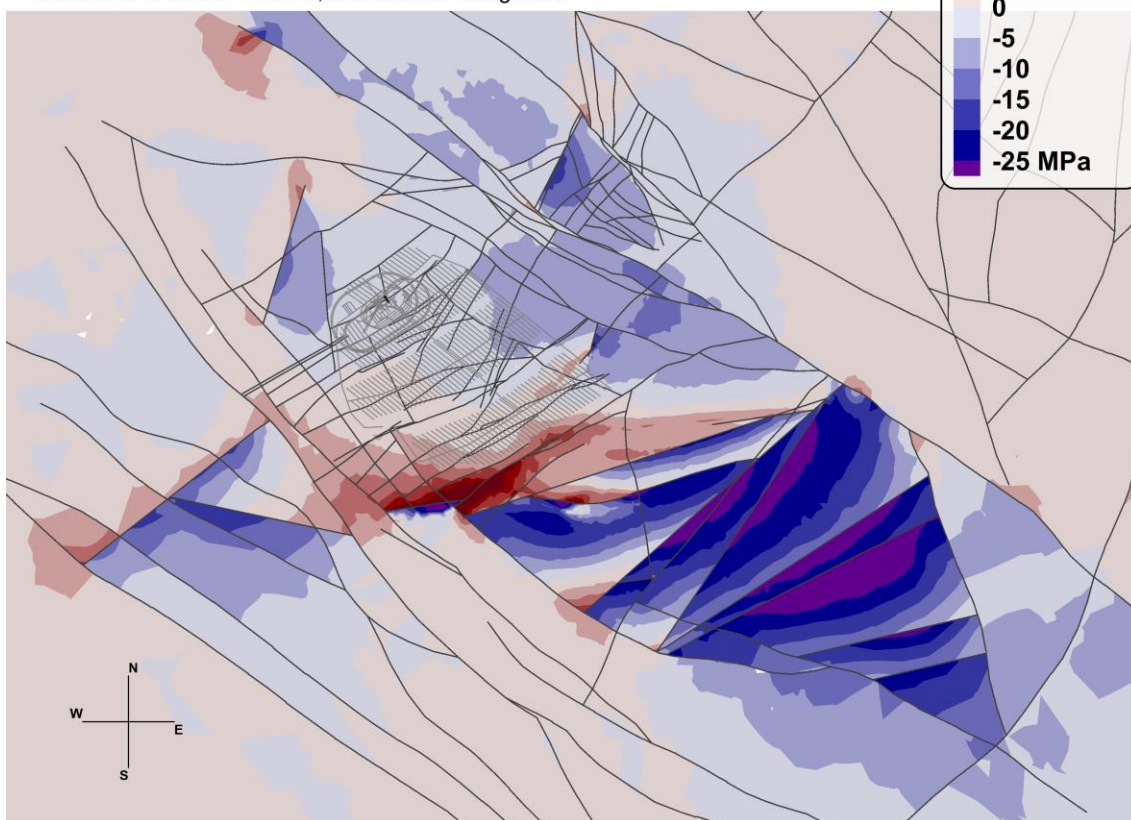
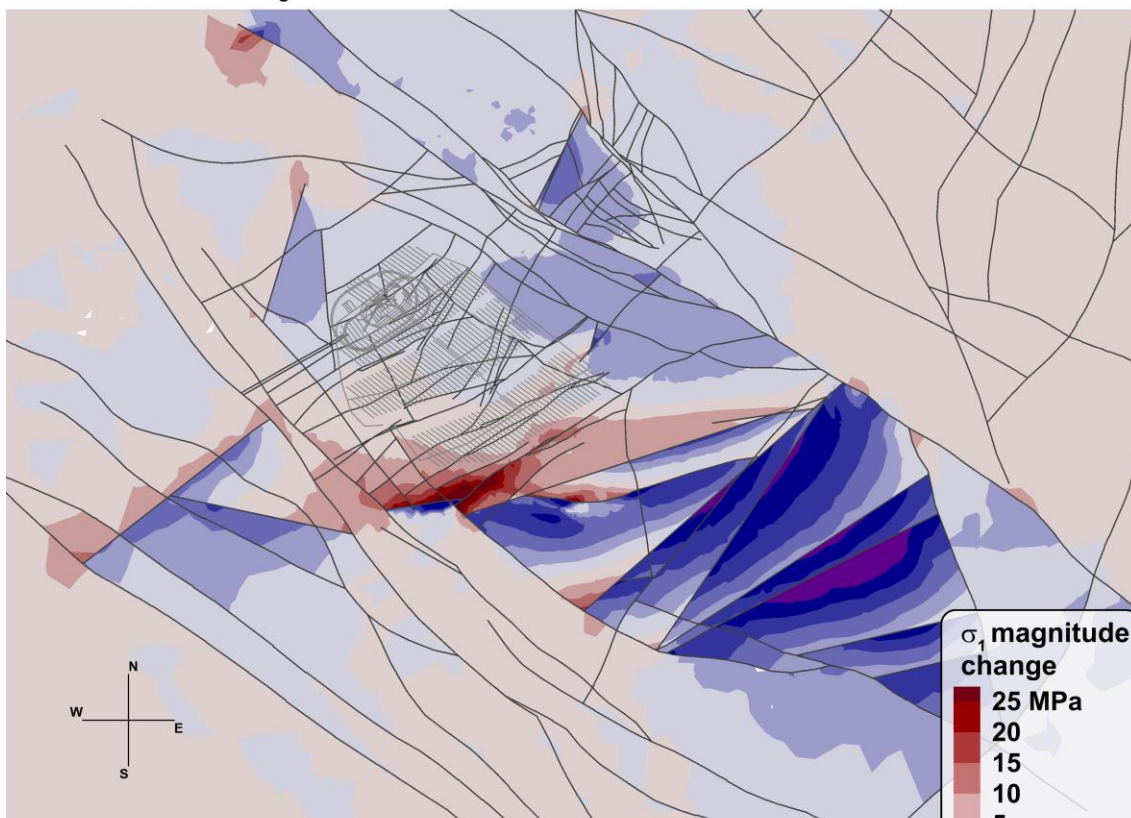


Figure 4-21. The change in σ_1 magnitude *after* glaciation for the Base case and Case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial



Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Post-glacial

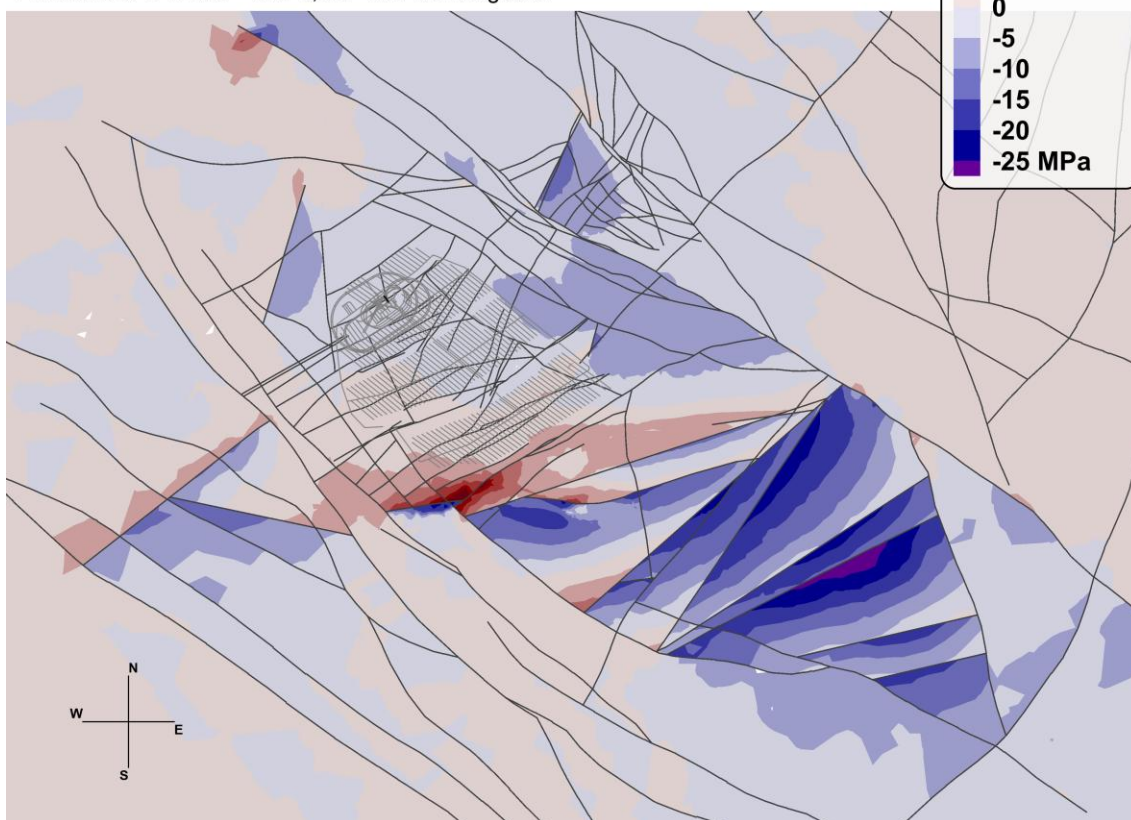
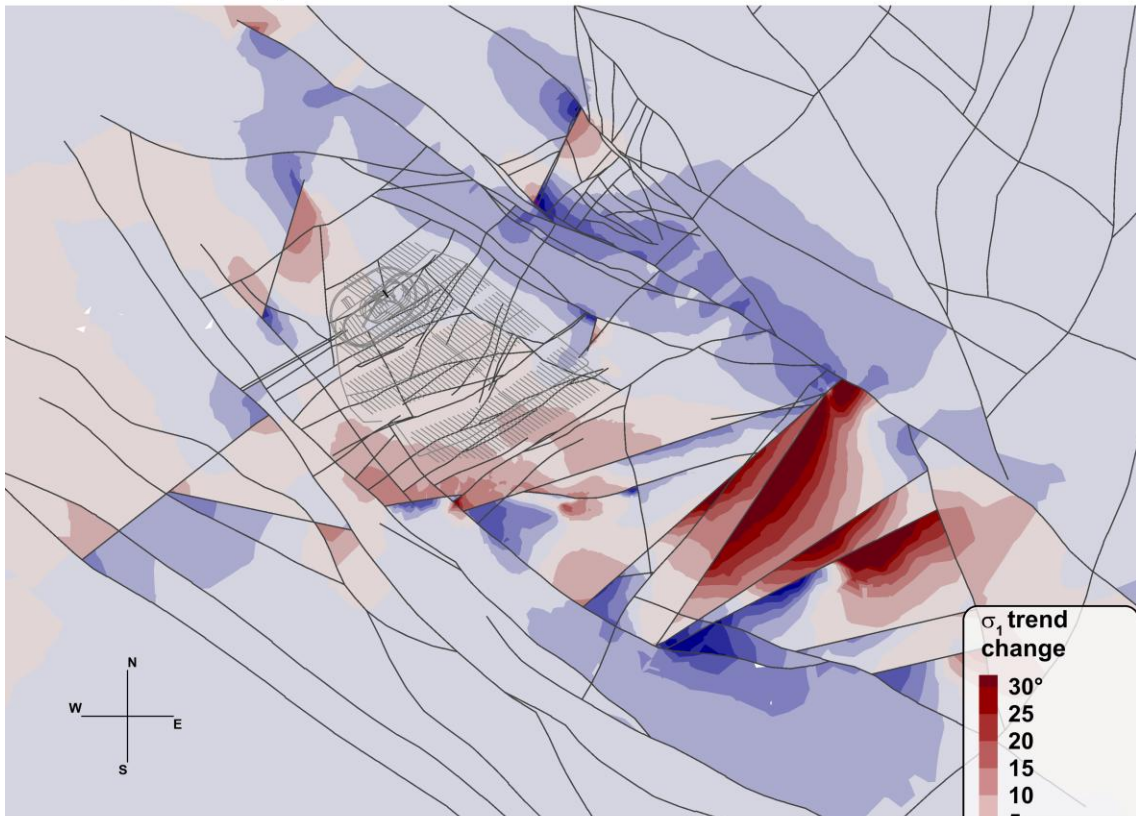


Figure 4-22. The change in σ_1 magnitude *after* glaciation for the Base case and Case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial



Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Post-glacial

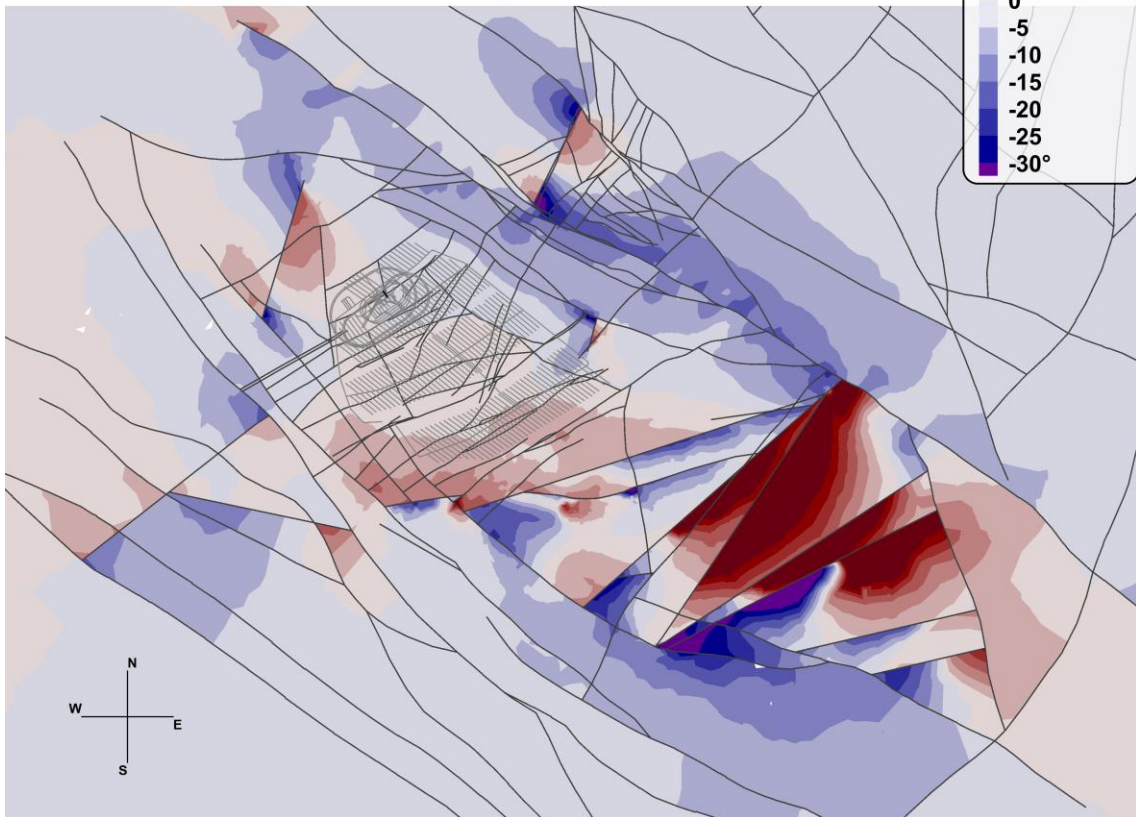
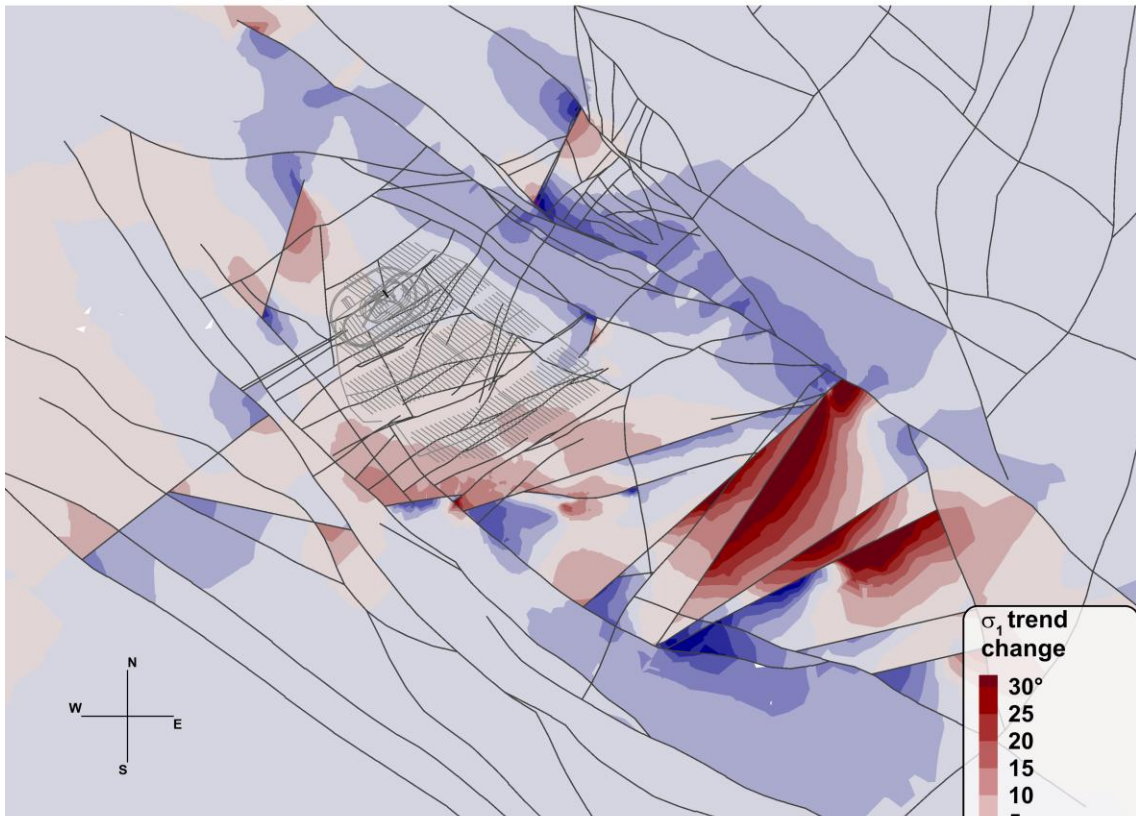


Figure 4-23. The change in σ_1 trend after glaciation for the Base case and Case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial



Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Post-glacial

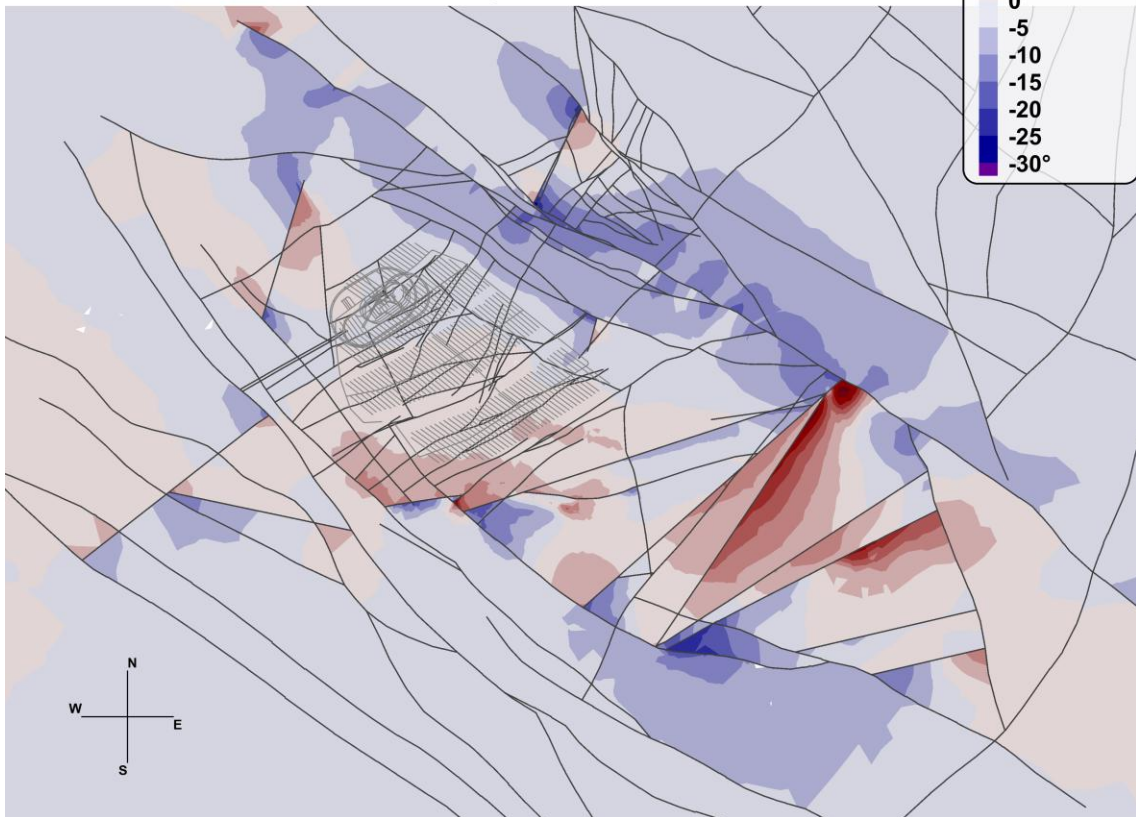


Figure 4-24. The change in σ_1 trend after glaciation for the Base case and Case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

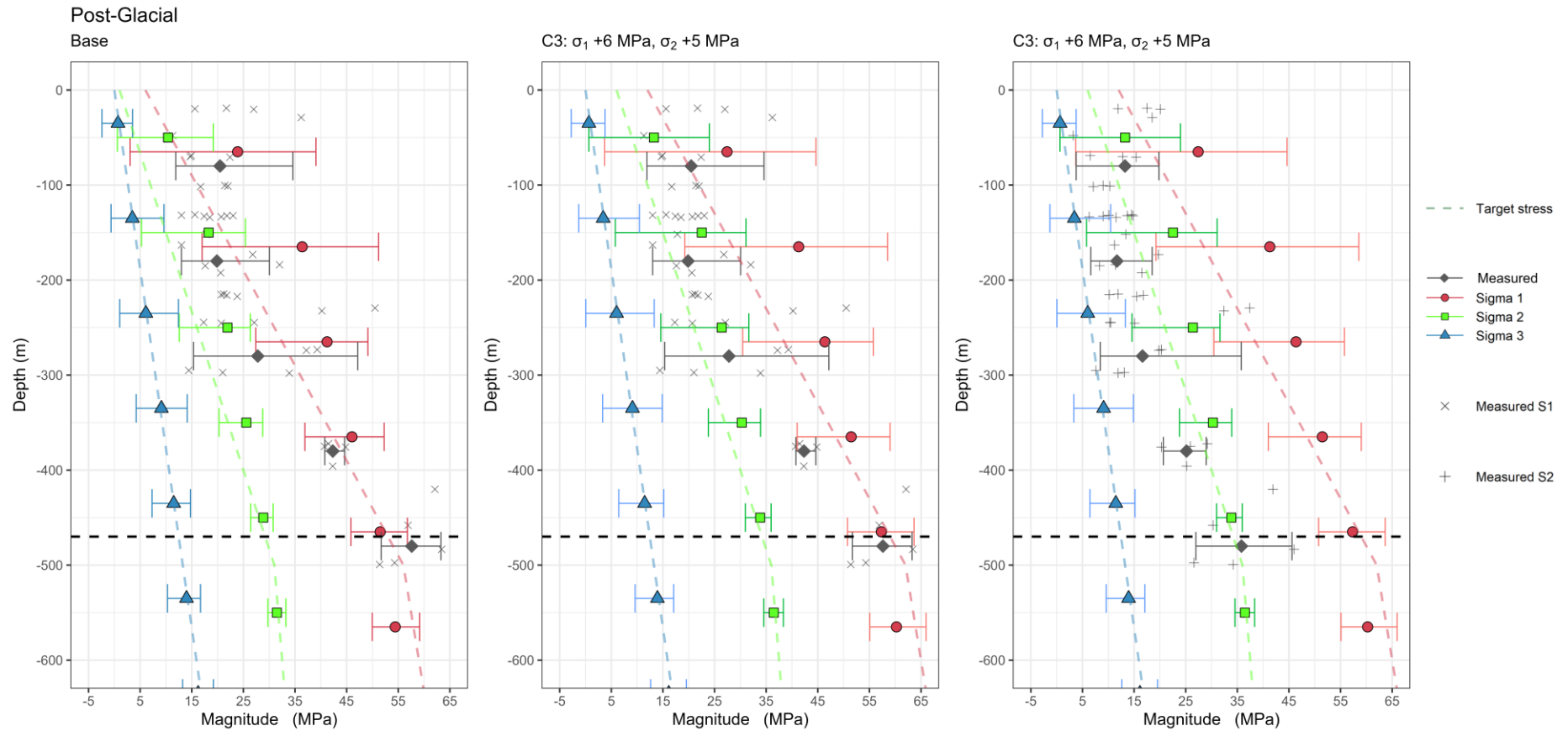


Figure 4-25. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and Case 3 simulations *after* glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

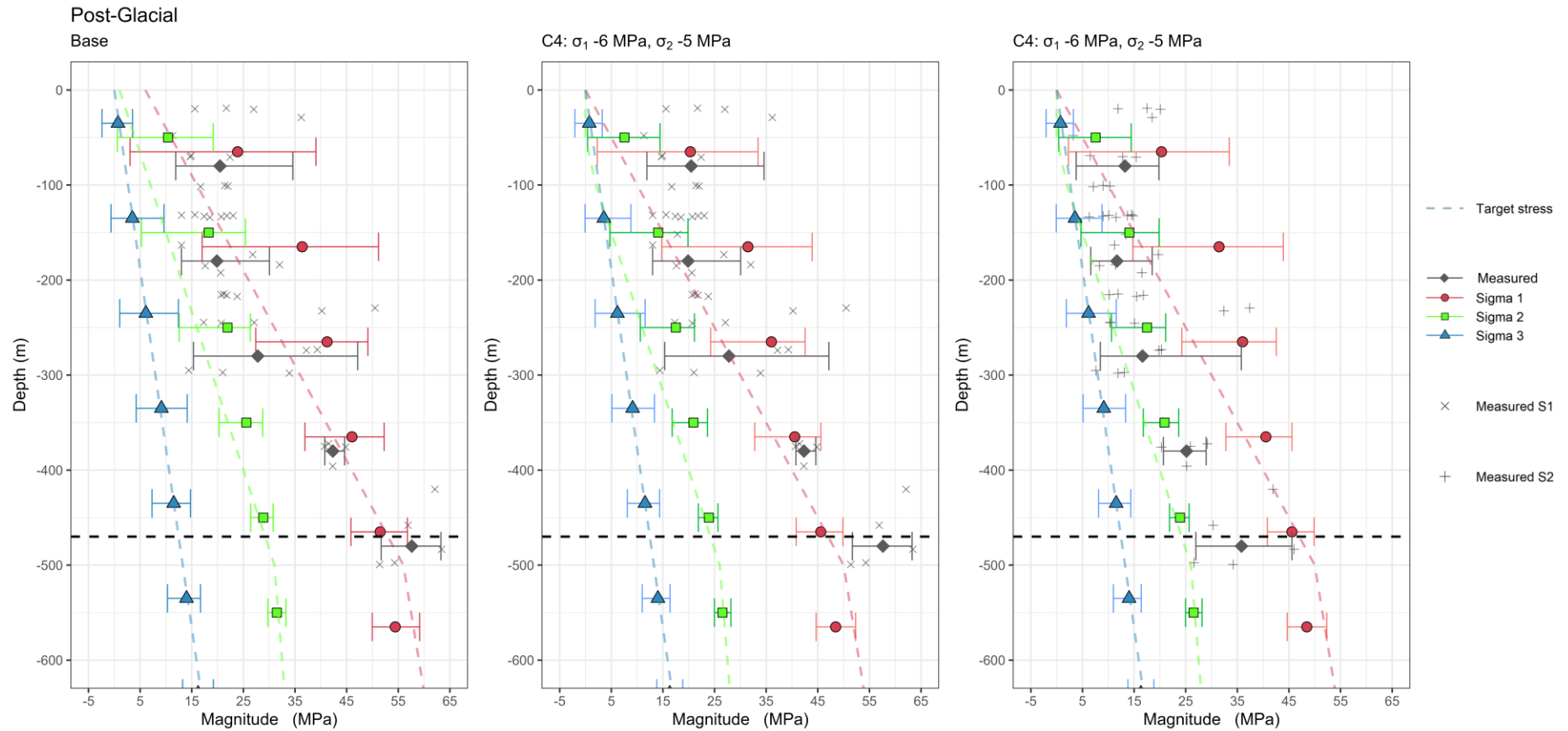


Figure 4-26. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and Case 4 simulations after glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey "+" or "x" symbols, with the mean and 95% variation interval also in grey.

4.5 Case 5: Overcoring stress measurement at KFM24

Case 5 is defined based on two overcoring stress measurements obtained at a location from a depth of about 560 m (Section 3.7). Its stress tensor differs markedly from that of the base case: σ_1 and σ_2 are roughly 50 % lower in magnitude, and the σ_1 trend is rotated by -24° . These differences make direct comparison with the base case difficult, as the resulting fault shear behaviour and stress distribution lie on different scales. Accordingly, results for Case 5 are shown with case-specific legends where appropriate. It is also important to note the results from these two measurements are excluded in Sjöberg et al. (2025) and are not within the 48 measurements ranked as “Good” or “Moderate”.

From the lower-hemisphere projection of fault shear, it is clear that Case 5 produces shear magnitudes of only about 20% of those seen in the other cases. No faults exceed 0.1 m of shear during the pre-glacial thrust, and only 11 faults exceed this threshold following glaciation (Figure 4-27).

The scatter in the simulated principal stress components is very small prior to glaciation, and remains minor for the σ_1 magnitude down to a depth of 300 m. The stress gradients are fairly uniform across all depths and fall toward the lower end of the measured stress range (Figure 4-28 and Figure 4-29). The target stresses at the KFM24 overcoring measurement location were achieved both before and after glaciation. The maximum, intermediate and minimum principal stresses at the location of the KFM24 overcoring measurement after glaciation in the Base case are 55.2, 31.7 and 14.2 MPa, respectively. The dip directions of the maximum and intermediate principal stresses are 144° and 54° .

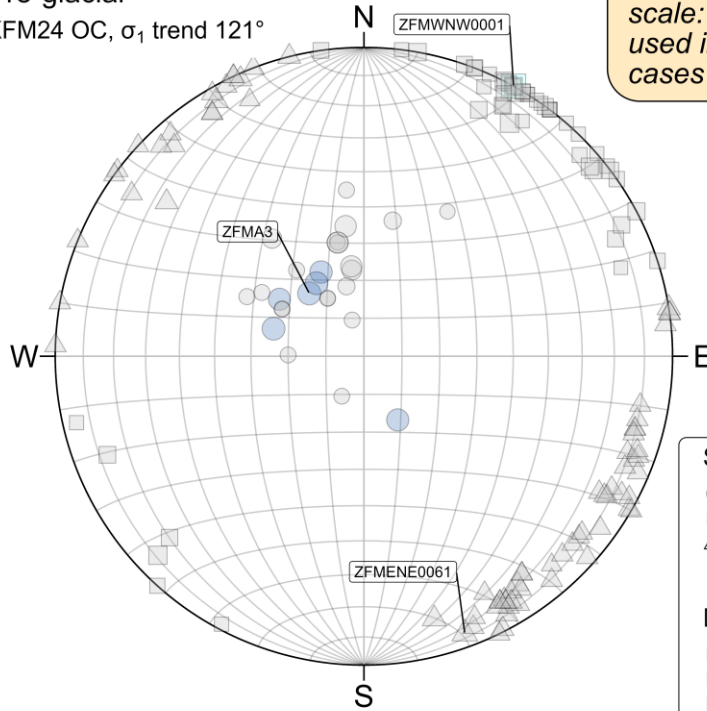
Glaciation increases the plastic shear in Set 1 down to a depth of 400 m, in Set 2 down to 300 m, and in Set 3 down to 100 m. However, these shear increments represent only about 10 % of the cumulative shear magnitudes observed in the other cases (Figure 4-30).

Fault shear LHP

C5 Pre-glacial

C5: KFM24 OC, σ_1 trend 121°

Note different displacement legend scale: 20% of the one used in the remaining cases



Set 1: Dip <50°, DD 0-360°

Set 2: Dip 50-90°, DD 170-260° & 350-080°

Set 3: Dip 50-90°, DD 080-170° & 260-350°

Set

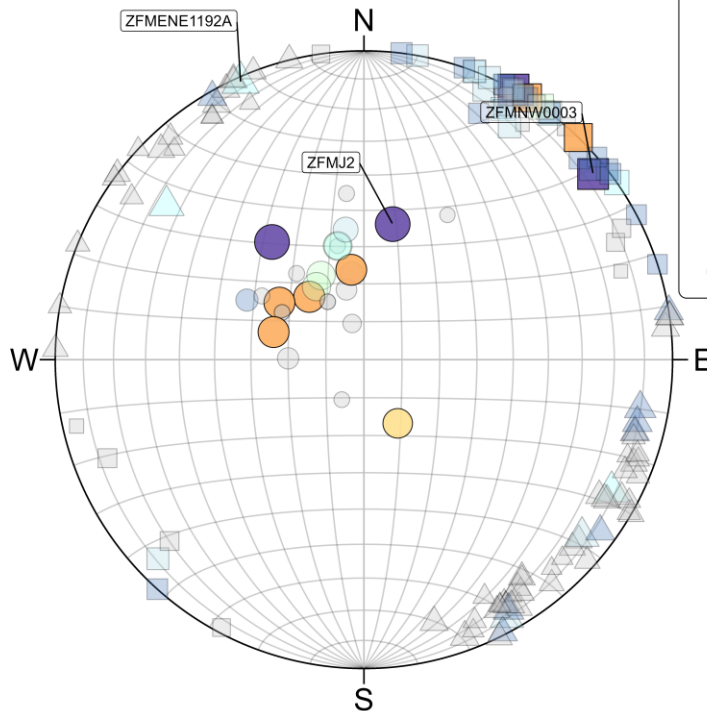
- Set 1
- Set 2
- △ Set 3

Displacement (m)

- [0,0.02]
- [0.02,0.04]
- [0.04,0.06]
- [0.06,0.08]
- [0.08,0.10]
- [0.10,0.12]
- [0.12,0.14]
- [0.14,0.16]
- [>0.16]

C5 Post-glacial

C5: KFM24 OC, σ_1 trend 121°



Displacement (m)

- 0.02 m
- 0.04 m
- 0.06 m
- 0.08 m
- 0.10 m
- 0.12 m
- 0.14 m
- 0.16 m

Figure 4-27. Deformation zone shear before and after glaciation by set group on an equal area lower hemisphere projection (LHP) for Case 5. Both symbol size and colour indicate displacement magnitude in metres.

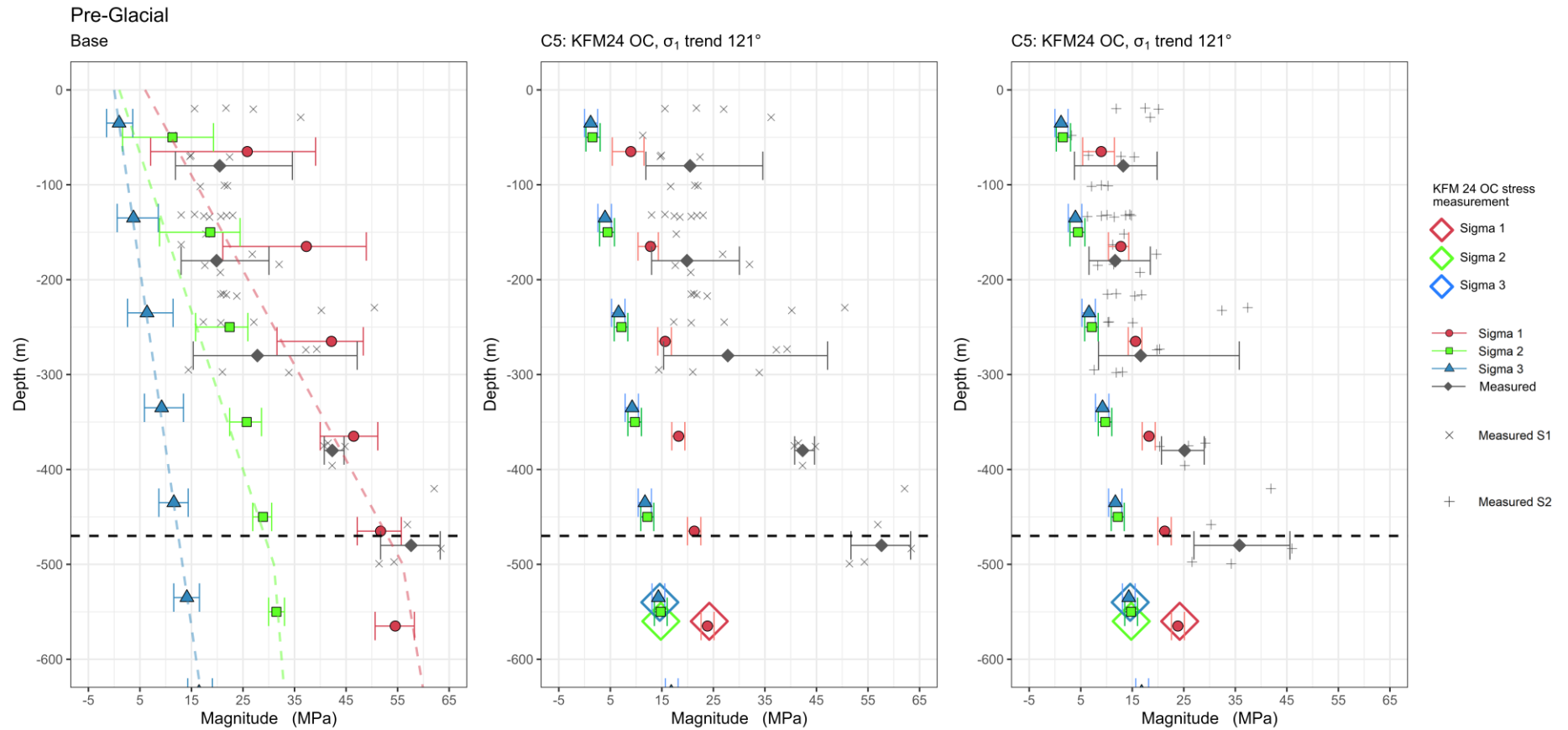


Figure 4-28. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and Case 5 simulations *before* glaciation from a cylinder covering the repository. The Baseline stress model is indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

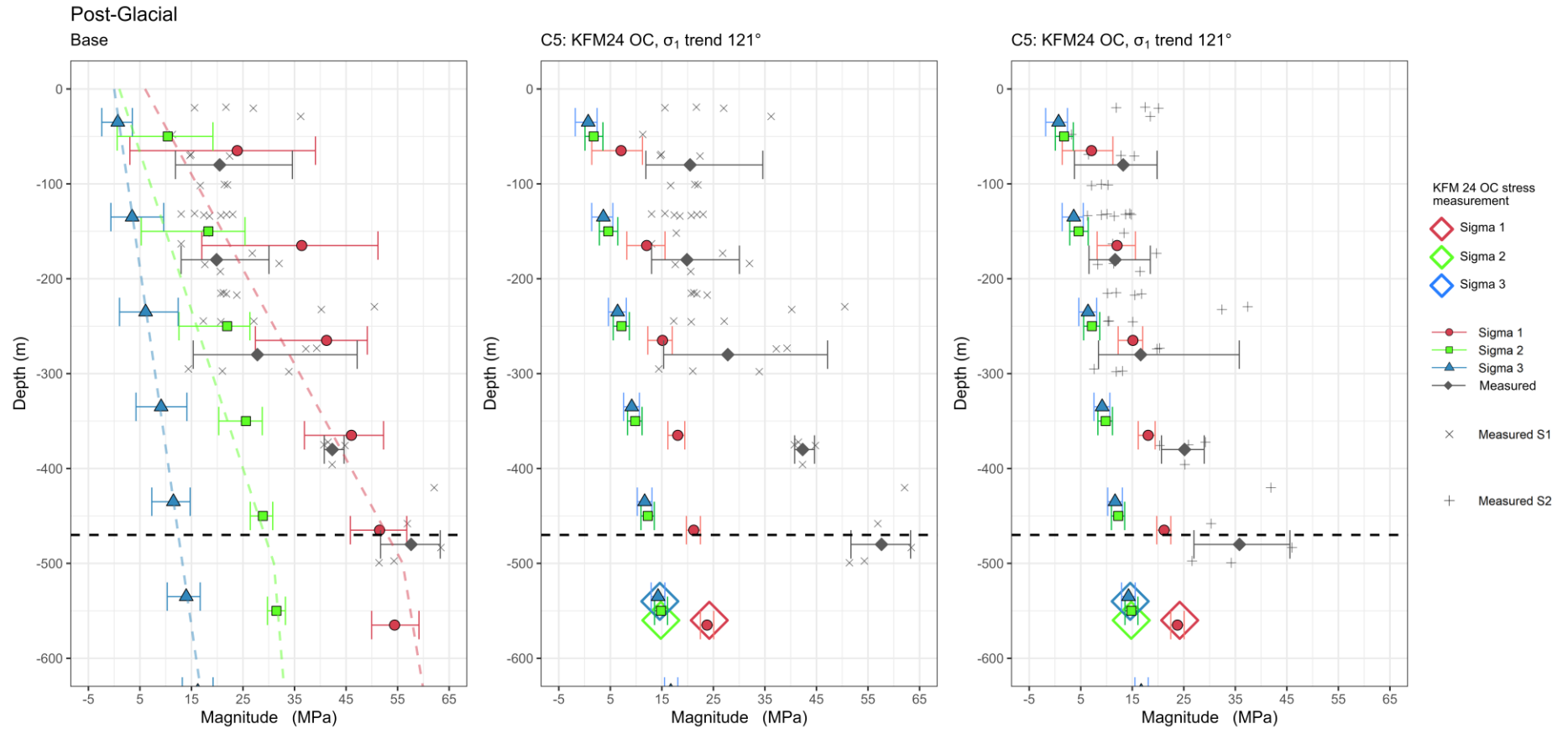


Figure 4-29. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and Case 5 simulations *after* glaciation from a cylinder covering the repository. The Baseline stress model is indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey "+" or "x" symbols, with the mean and 95% variation interval also in grey.

C5: KFM24 OC, σ_1 trend 121°

Pre-Glacial vs Post-Glacial

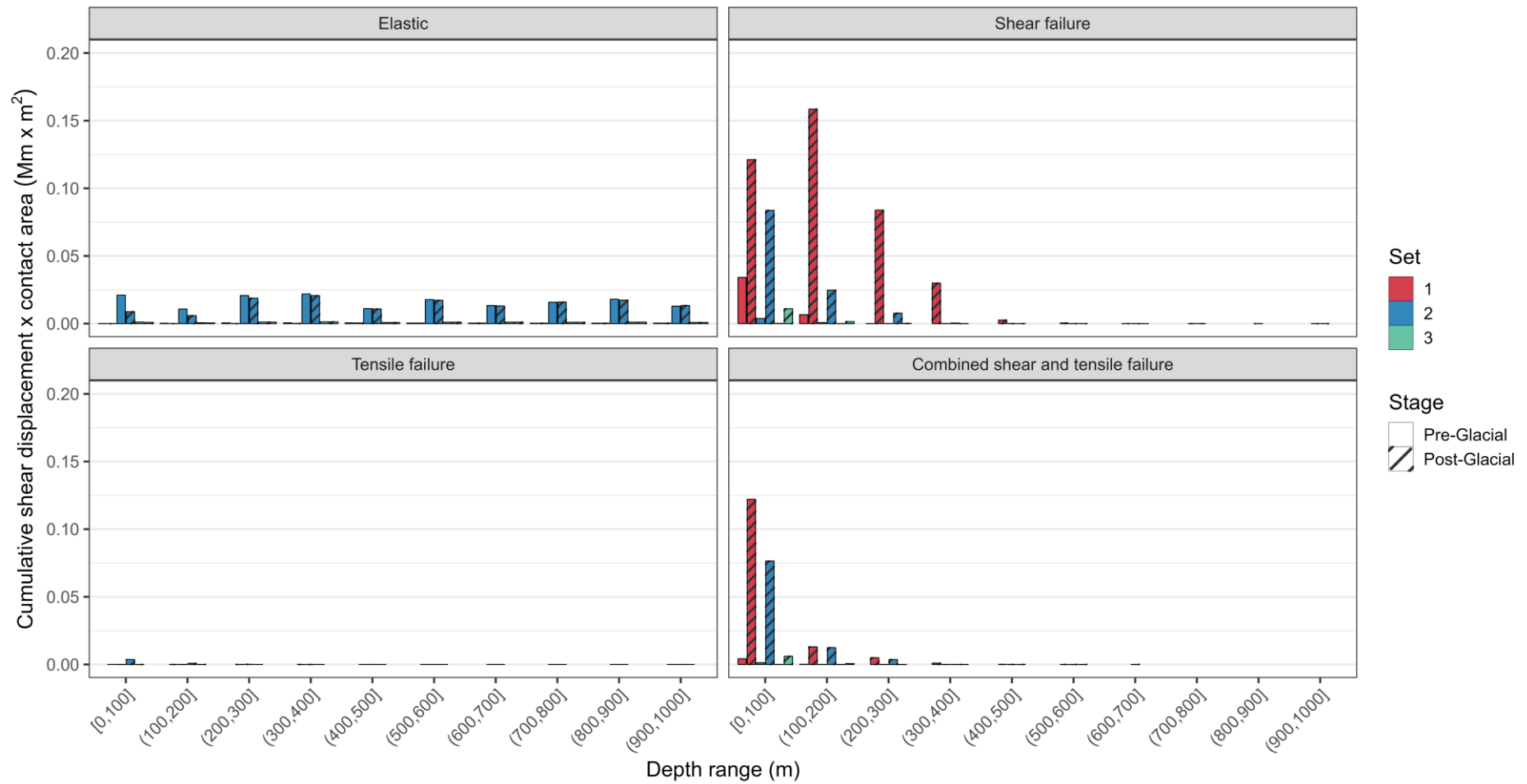


Figure 4-30. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Case 5 before and after glaciation

5 Concluding discussion and recommendations

Higher stress magnitudes systematically lead to greater post-glacial shear and more extensive plastic deformation, particularly in the gently dipping zones of Set 1 or the Singö fault, which respond most sensitively to stress changes. Under the Base case or cases with more elevated stresses, post-glacial maximum shear displacement close to the ground surface reaches approximately 0.8 m. Cases 1 and 3 exhibit increased DZ shear compared to Base case, with little difference in Case 2. Lower stress magnitudes such as in Cases 4 and 5 suppress DZ activity across all sets, reducing shear by up to 80% in the lowest-stress scenario and confining plasticity to limited DZ's; in these cases, the Singö fault and the Set 3 zones are only weakly activated with a maximum shear of 0.1 m. DZ shear of Case 5 is approximately 10% of Base case shear. Changing the trend of the maximum principal stress produces a similar directional effect: clockwise rotation increases shear and deepens plasticity, while counter-clockwise rotation reduces both.

Relative to the Base case in Valli et al. (2023), post-glacial DZ shear is approximately 30% higher at the surface with more pronounced plasticity within Set 1 zones due to +32% higher major and +30 % higher intermediate principal stresses at repository depth.

The direction of the maximum compressive stress relative to the orientation of the low-dipping faults is the primary cause of the rotation of σ_1 after glaciation. In all scenarios, σ_1 rotates more than 5° in the shallow subsurface, though the depth to which this persists varies with stress magnitude and typically ranges between about 50 and 150 m (Figure 5-1). At repository depth and within the repository footprint, deviations of the simulated σ_1 trend from the target orientation generally fall within $5 - 10^\circ$. These departures are most pronounced in the southernmost area of the repository layout (Appendix 11).

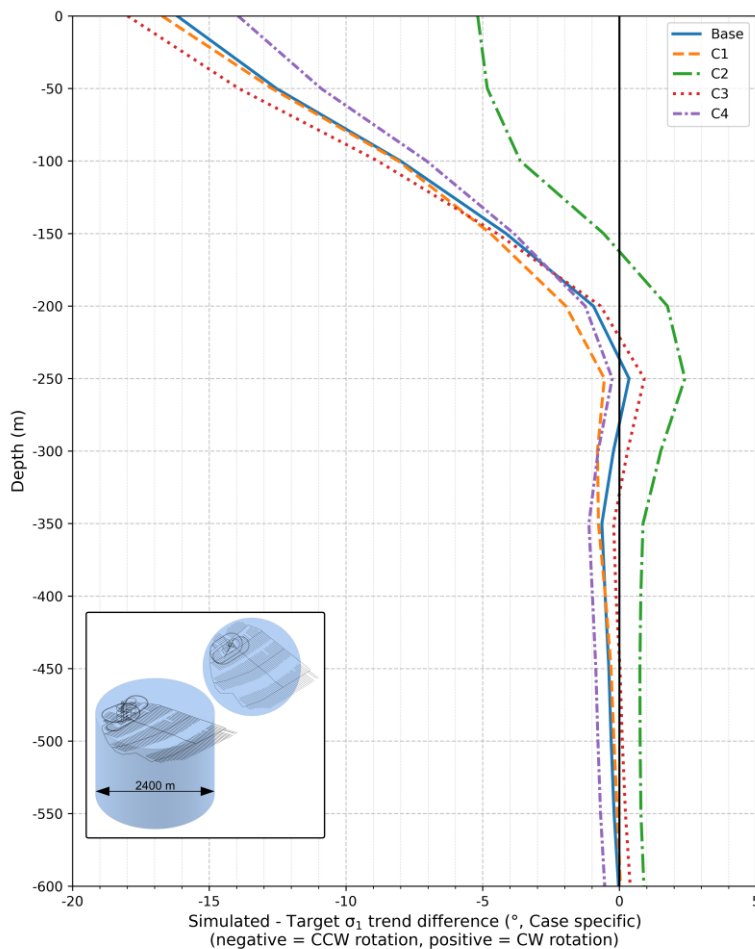


Figure 5-1. Difference between post-glacial simulated and target σ_1 stress trend at 50m intervals from a cylinder covering the repository footprint.

Across the full depth range, the simulated major principal stresses exhibit a consistent pattern: above 150 m level they exceed the baseline target by over 15 MPa (Figure 5-2), reducing to zero almost linearly with depth up to a depth of about 475 m. Below this depth the difference to the baseline is about 2 MPa. Case 5 is excluded from Figure 5-2 since it is defined based on a single target stress at 560 m depth and not a stress gradient as the rest of the cases: therefore, a comparison of simulated and target stress as a function of depth cannot be performed.

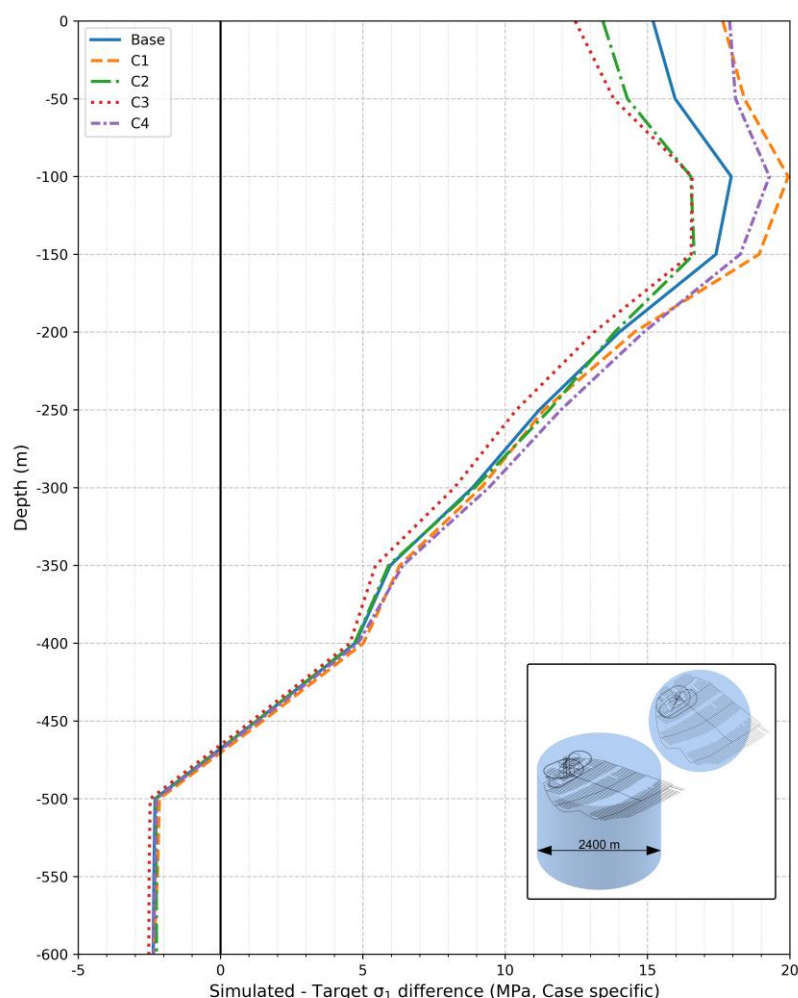


Figure 5-2. The difference between the post-glacial simulated and target σ_1 magnitude based on data from the cylinder in Figure 4-1.

A comparison of the simulated major principal stress magnitudes from a cylinder encompassing the repository to the mean of the stress measurements at 50 m depth intervals also partly illustrates a similar phenomenon (Figure 5-3). Assuming the stress measurements ranked “Good” and “Moderate” in Sjöberg et al. (2025) are reliable, this systematic overprediction of stresses in the shallow subsurface aligns with the observed mechanical responses, namely, overstated near-surface shear displacement. This suggests that the rock mass deformation moduli or the DZ stiffnesses in the upper part of the model may be too high, leading to unrealistic stress concentrations and increased deformation near the ground surface. It is important to note that the modelling assumes a constant normal and shear stiffness as well as friction angle and cohesion for the deformation zones, and also a constant modulus and Poisson’s ratio for the rock mass at each geological domain (Table 3-1, Table 3-2). The latter assumes a constant fracture normal and shear stiffness implicitly within the rock mass that is unrealistic: fracture normal and shear stiffness typically increase with increasing normal stress.

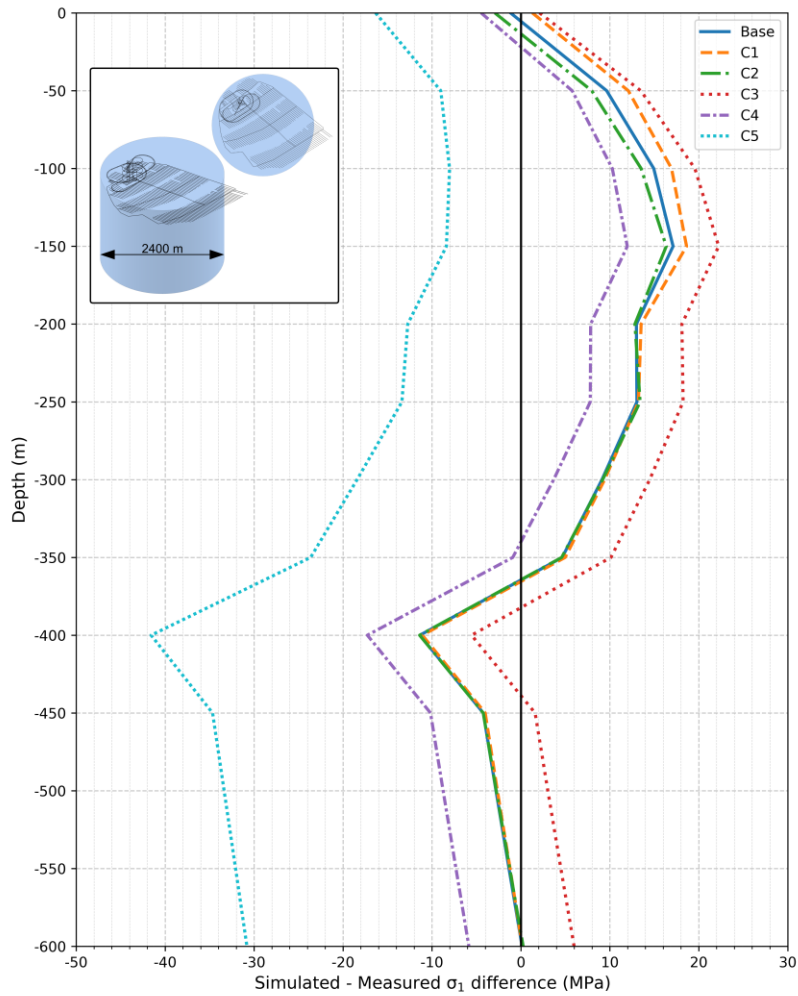


Figure 5-3. The difference between the post-glacial simulated and measured σ_1 magnitude based on data from the cylinder in Figure 4-1.

For future simulations it is strongly recommended that the stiffness model of the rock mass and the deformation zones are re-evaluated. A stress dependent rock mass modulus or a normal stress dependent DZ normal and shear stiffness would be more realistic. The shallow parts of the deformation zones have undergone more shear deformation during past thrust and glaciation, resulting in a potentially lower shear strength as well.

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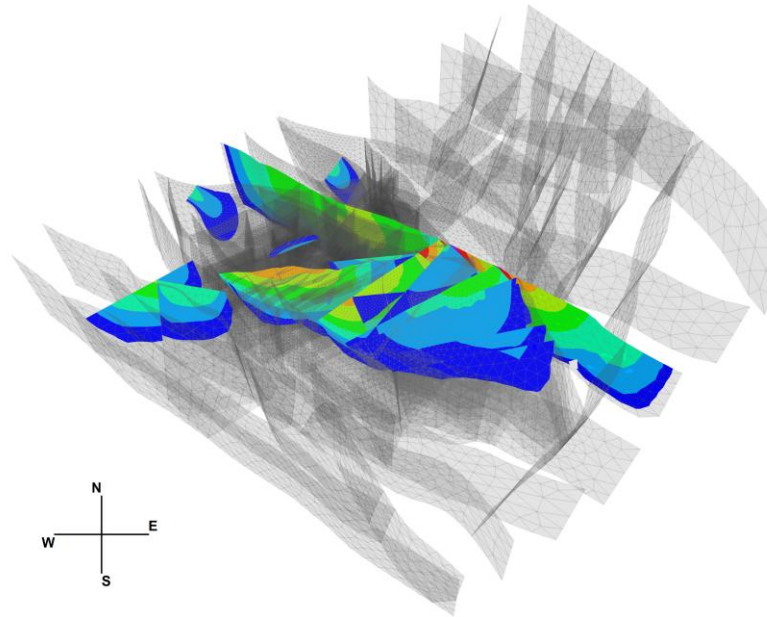
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Appendix 1. Deformation zone shear

Forsmark S-G Base Pre-glacial



Forsmark S-G C1: s1 trend -15° Pre-glacial

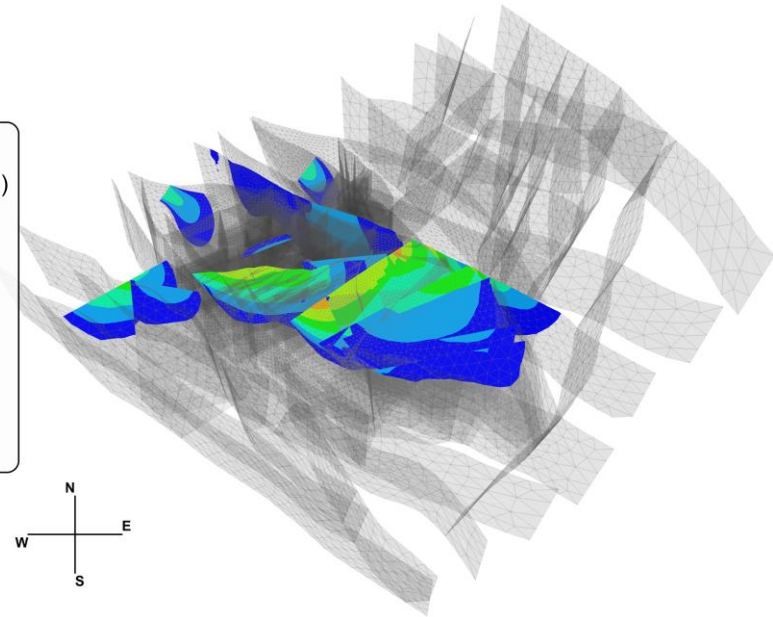
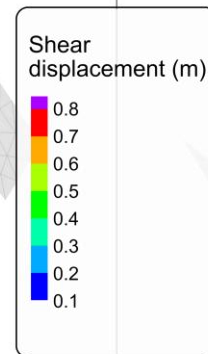
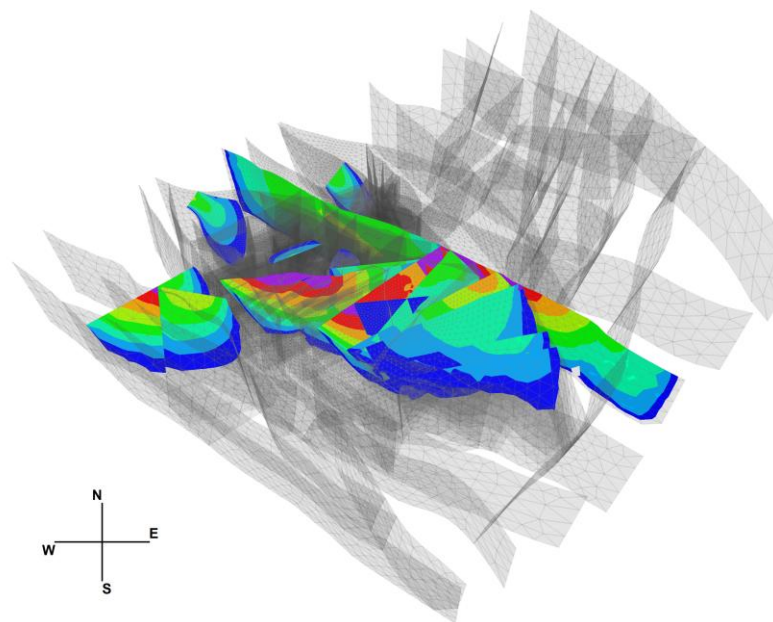


Figure A1- 1. Deformation zone shear contours before glaciation for the Base case and case 1.

Forsmark S-G Base Post-glacial



Forsmark S-G C1: s1 trend -15° Post-glacial

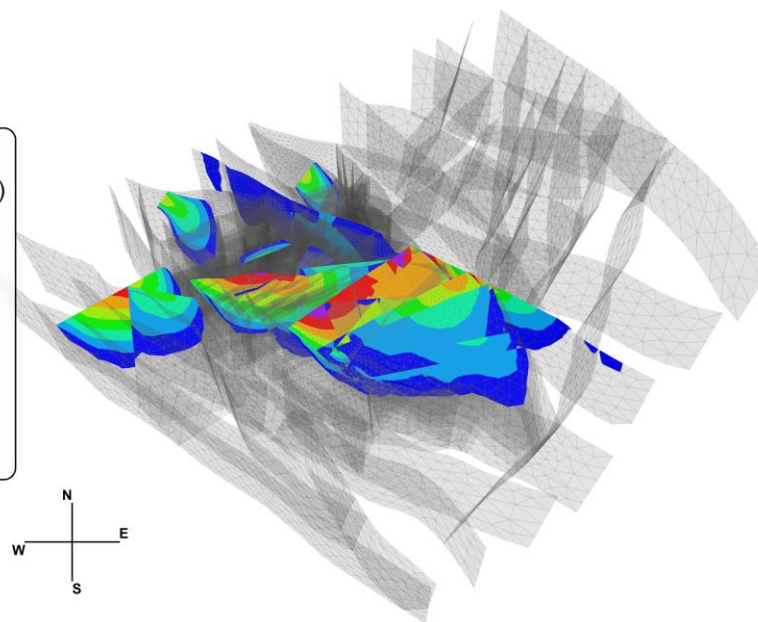
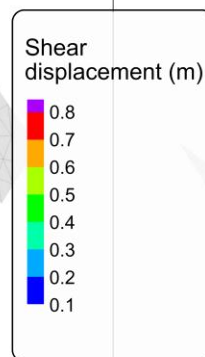
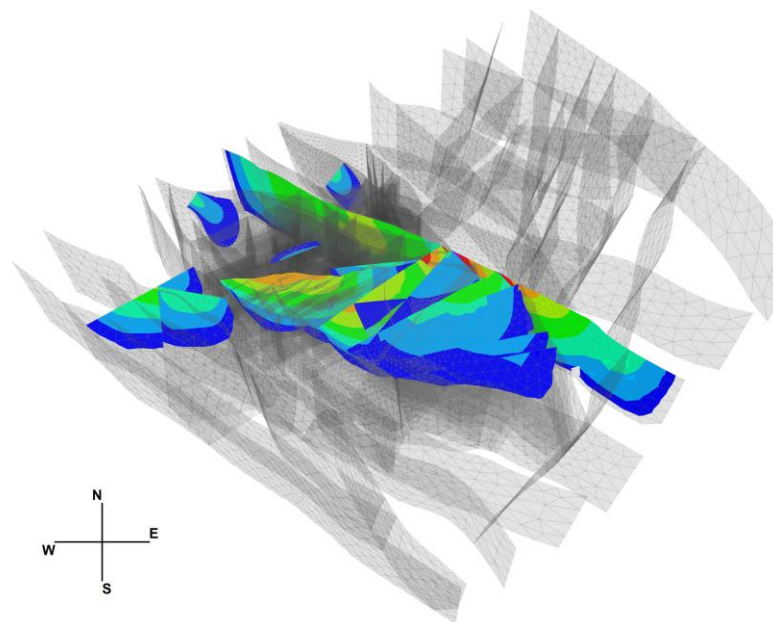


Figure A1- 2. Deformation zone shear contours after glaciation for the Base case and case 1.

Forsmark S-G Base Pre-glacial



Forsmark S-G C2: s1 trend +15° Pre-glacial

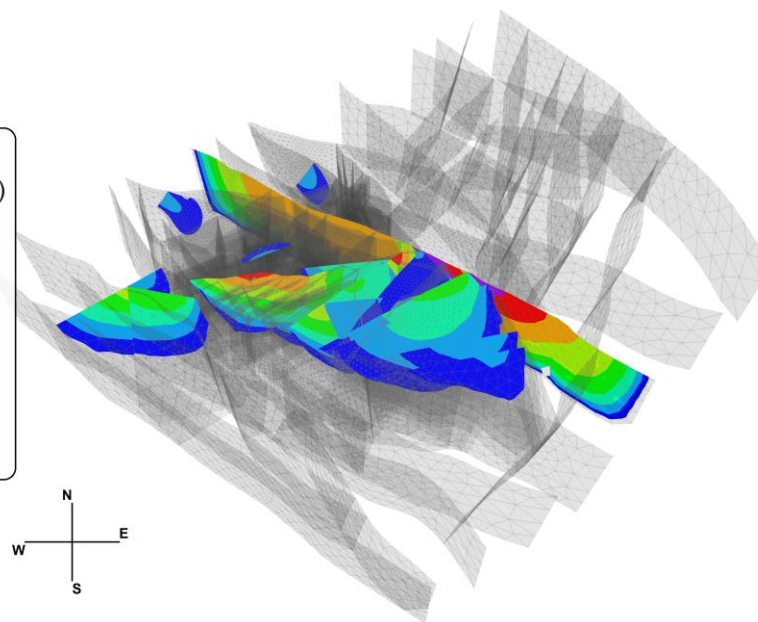
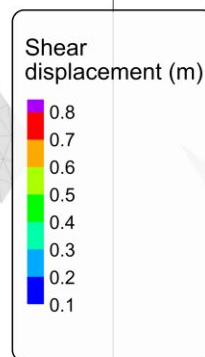


Figure A1- 3. Deformation zone shear contours before glaciation for the Base case and case 2.

Forsmark S-G Base Post-glacial

Forsmark S-G C2: s1 trend +15° Post-glacial

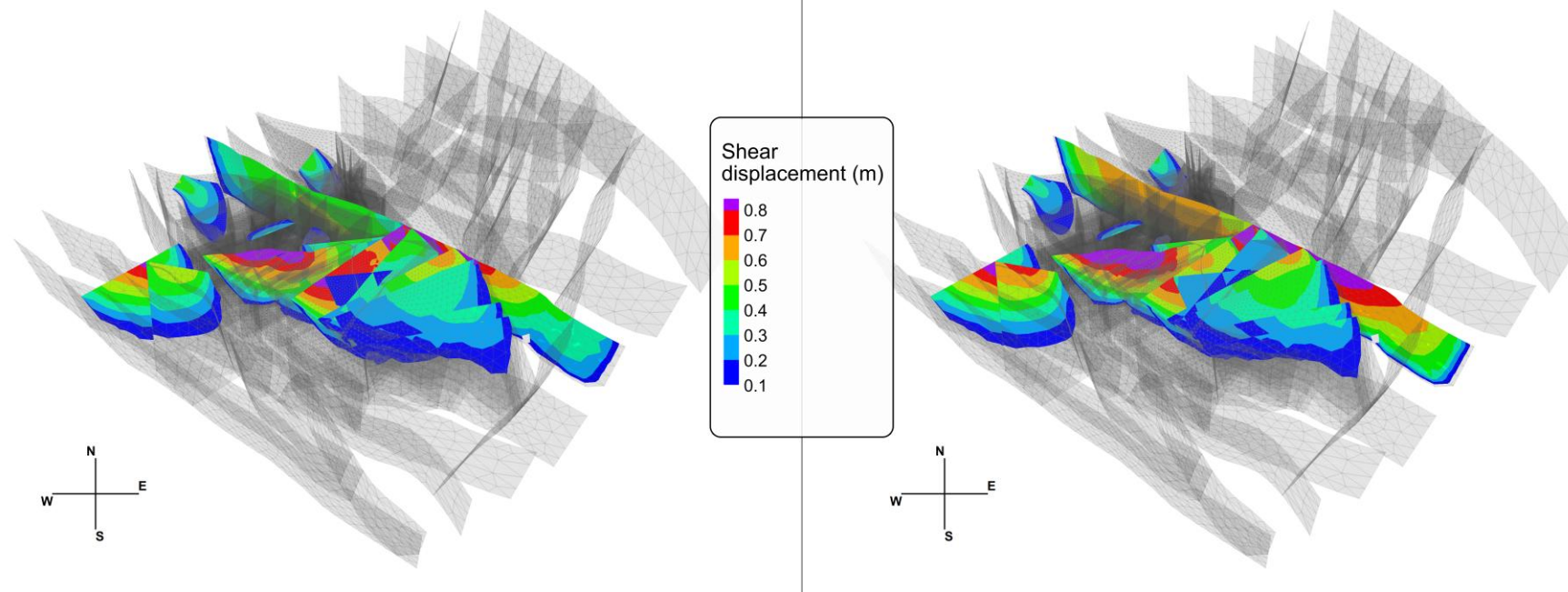
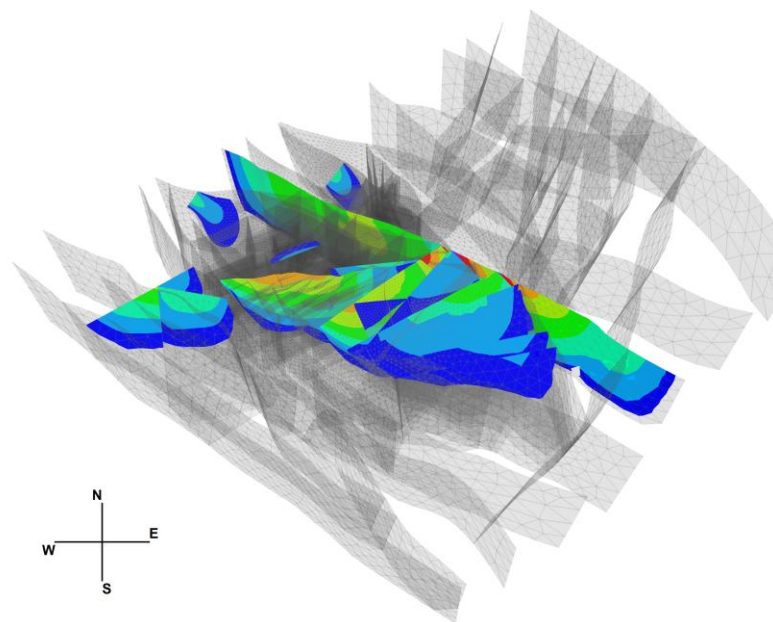


Figure A1- 4. Deformation zone shear contours after glaciation for the Base case and case 2.

Forsmark S-G Base Pre-glacial



Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Pre-glacial

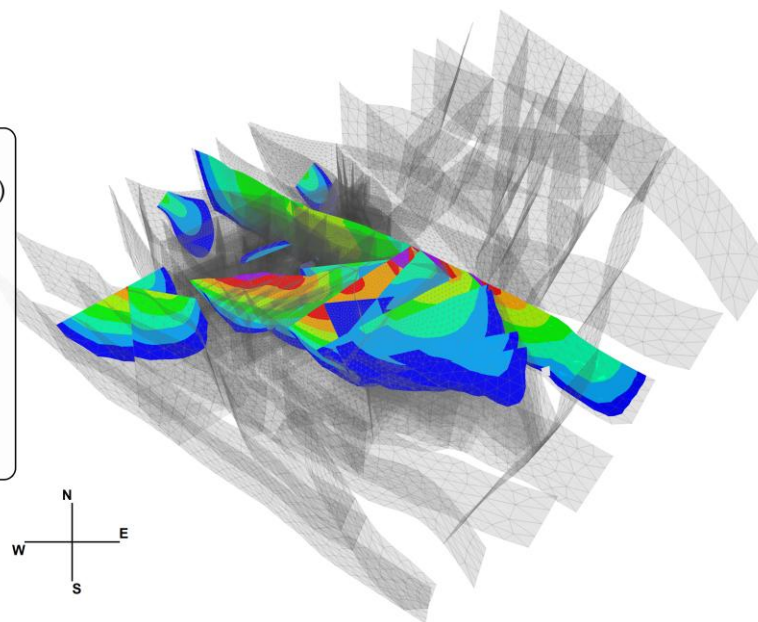
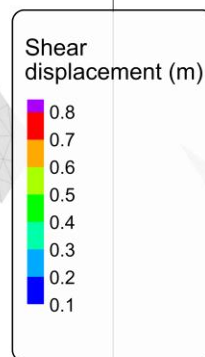
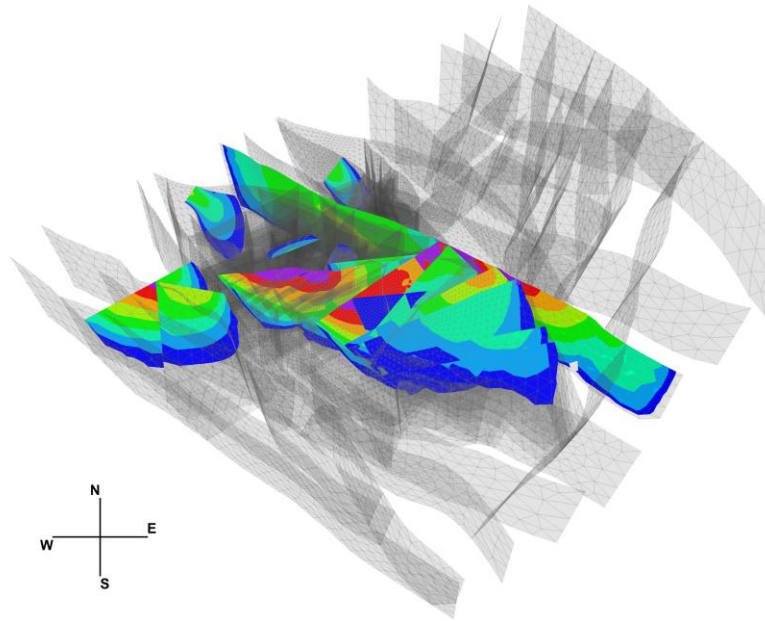


Figure A1- 5. Deformation zone shear contours before glaciation for the Base case and case 3.

Forsmark S-G Base Post-glacial



Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Post-glacial

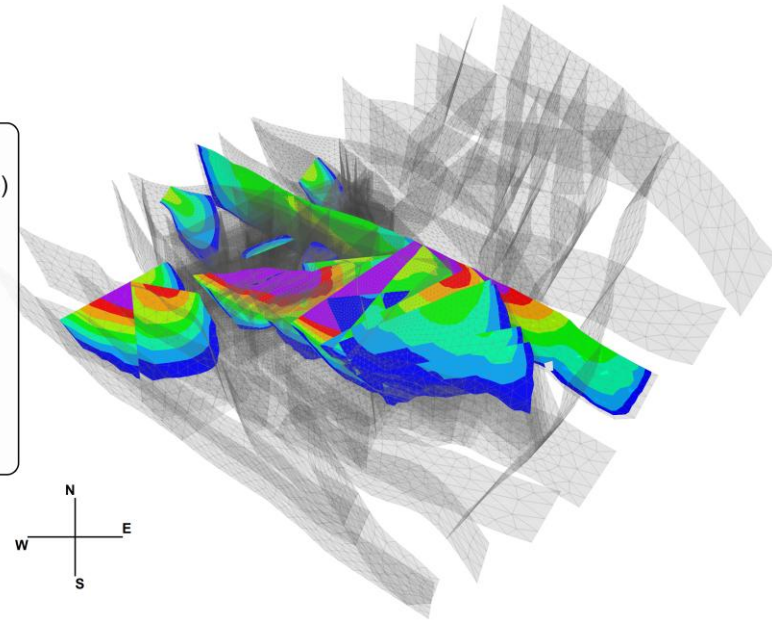
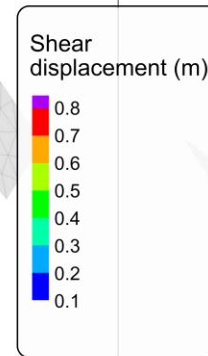
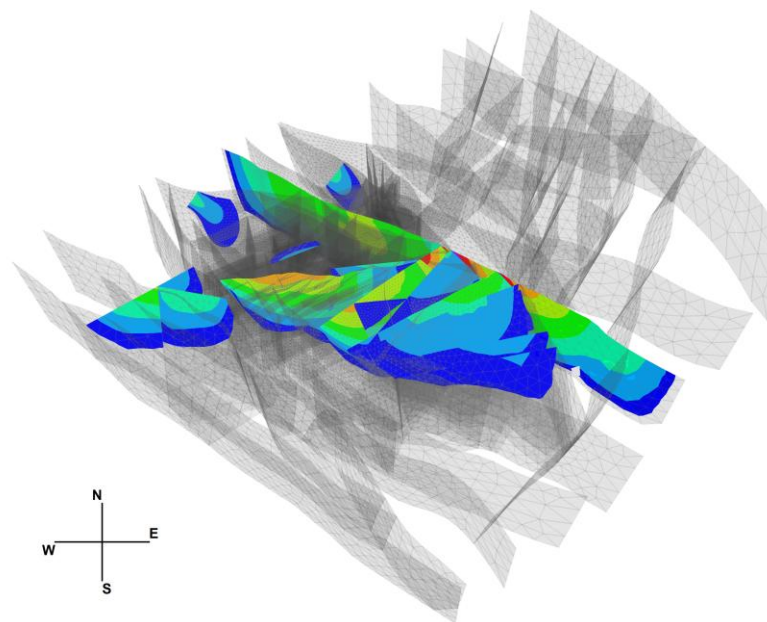


Figure A1- 6. Deformation zone shear contours after glaciation for the Base case and case 3.

Forsmark S-G Base Pre-glacial



Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Pre-glacial

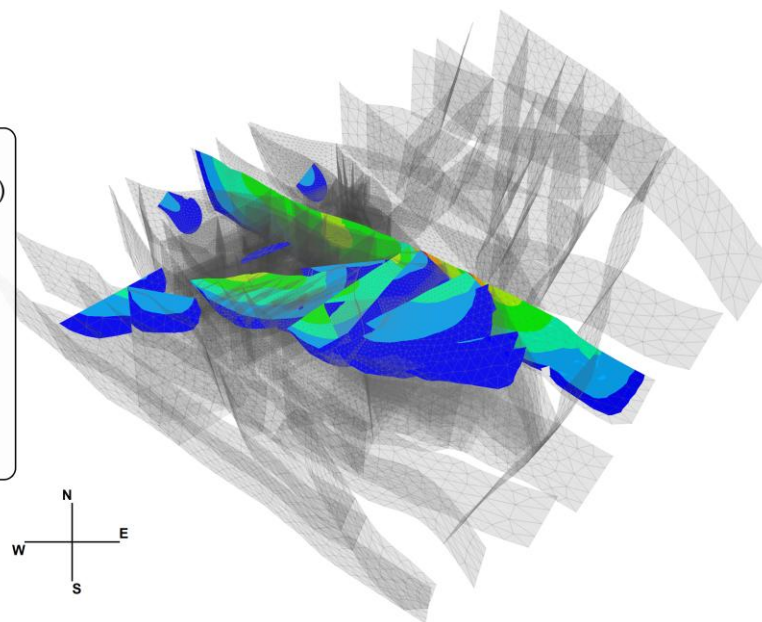
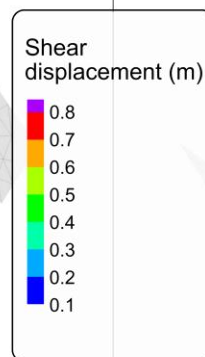


Figure A1- 7. Deformation zone shear contours before glaciation for the Base case and case 4.

Forsmark S-G Base Post-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Post-glacial

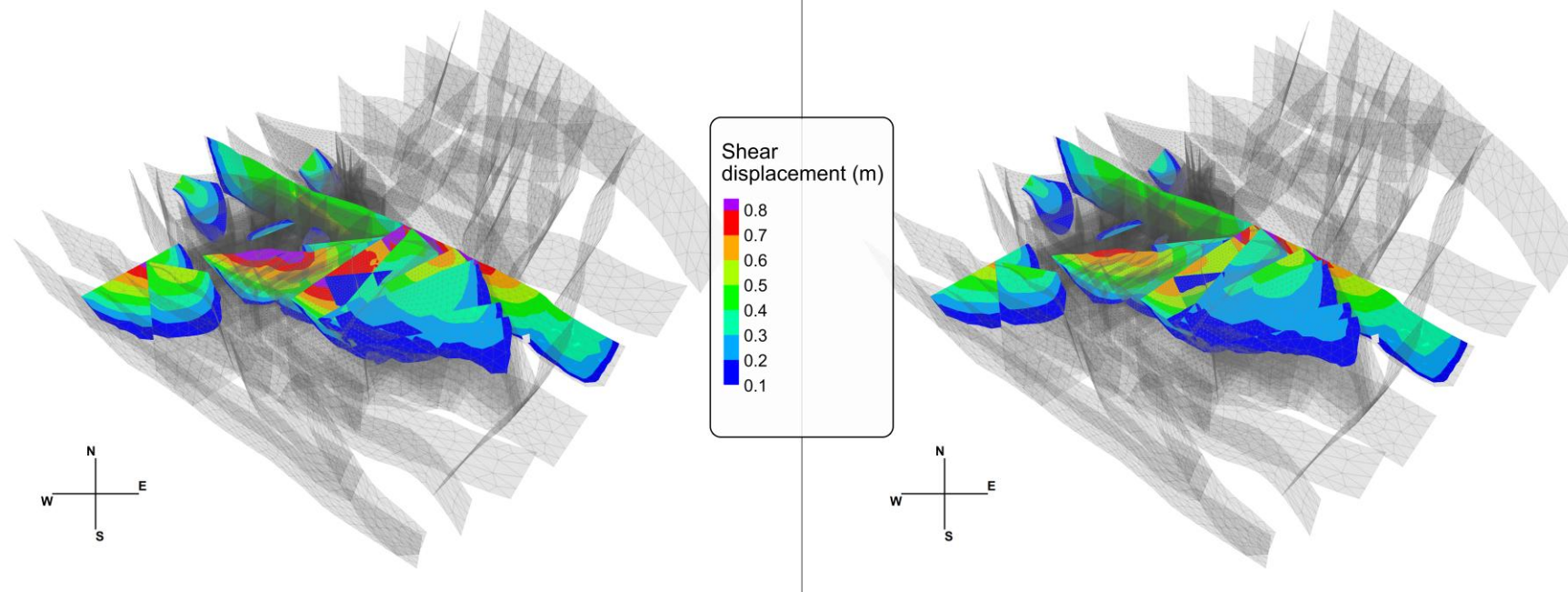
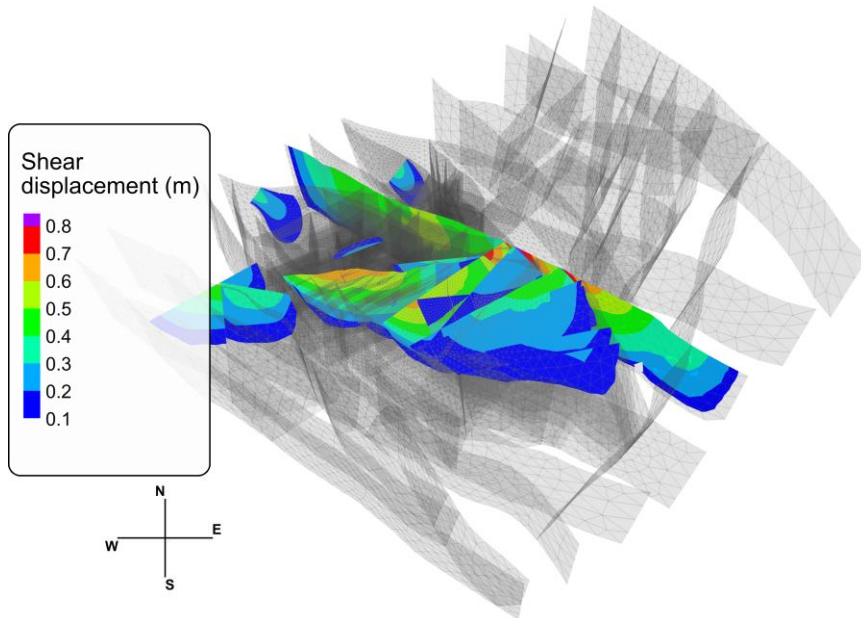


Figure A1- 8. Deformation zone shear contours after glaciation for the Base case and case 4.

Forsmark S-G Base Pre-glacial



Forsmark S-G C5: KFM24 OC, s1 trend 121° Pre-glacial

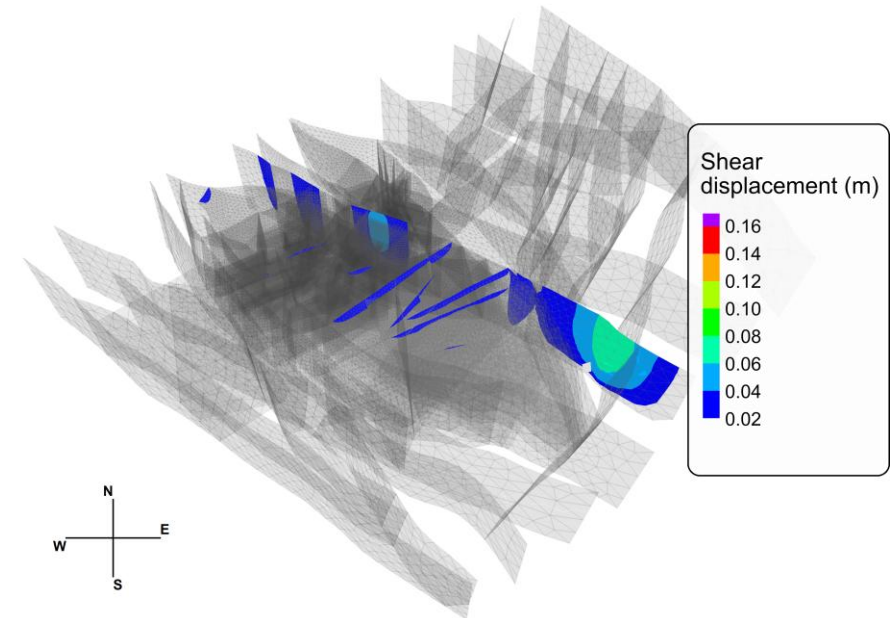
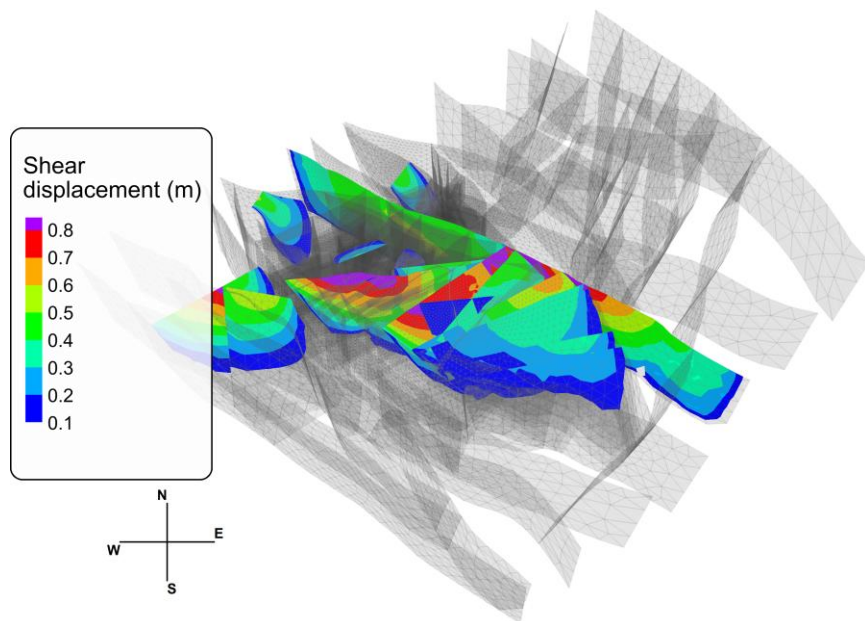


Figure A1- 9. Deformation zone shear contours before glaciation for the Base case and case 5. *Note the different legend for Case 5.*

Forsmark S-G Base Post-glacial



Forsmark S-G C5: KFM24 OC, s1 trend 121° Post-glacial

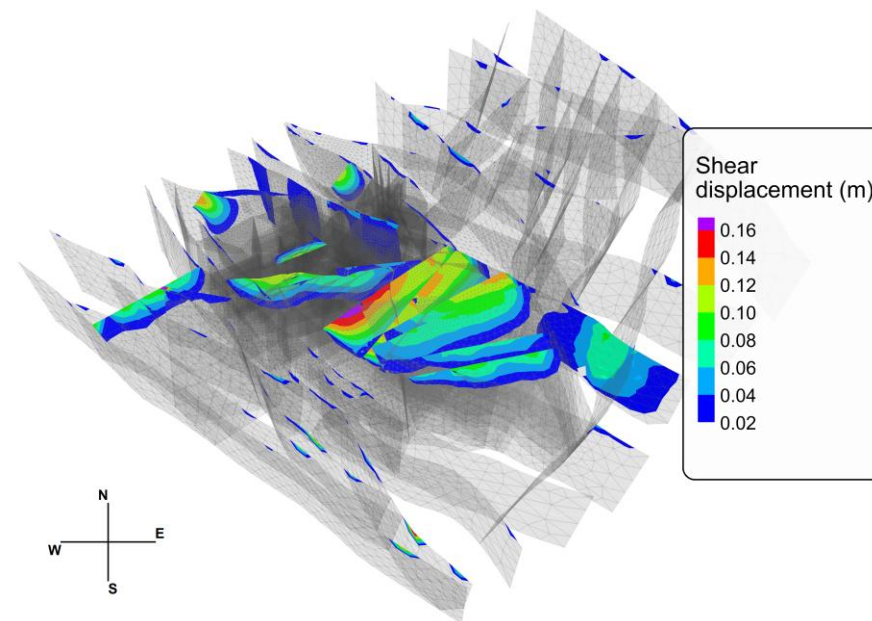
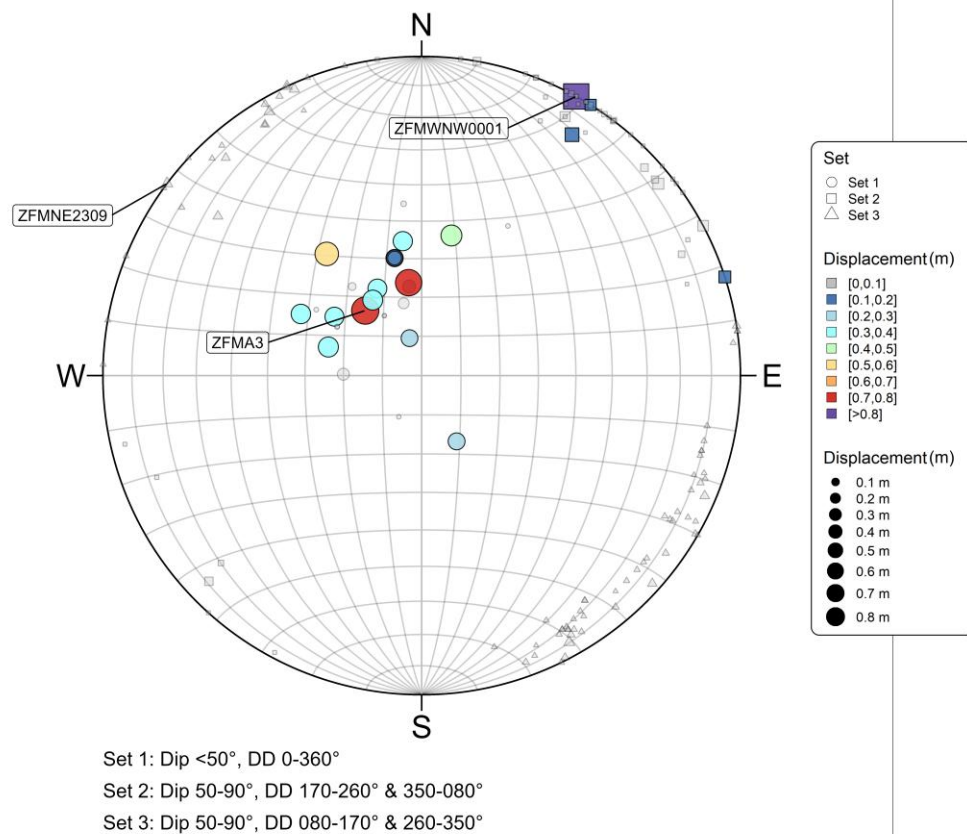


Figure A1- 10. Deformation zone shear contours after glaciation for the Base case and case 5. *Note the different legend for Case 5.*

Appendix 2. Deformation zone shear lower hemisphere projections

Base Pre-glacial
Base



C1 Pre-glacial
C1: σ_1 trend -15°

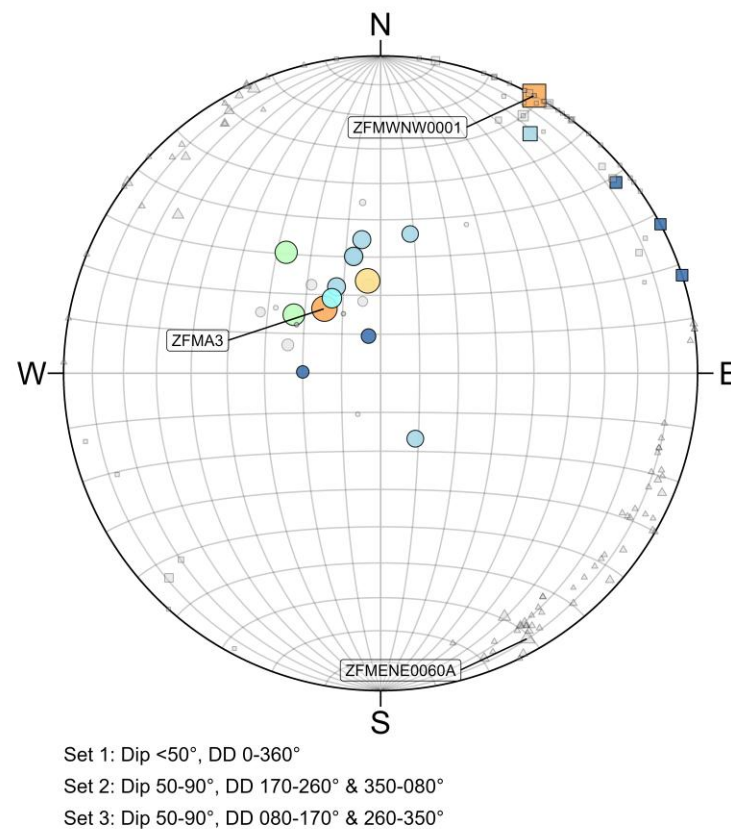
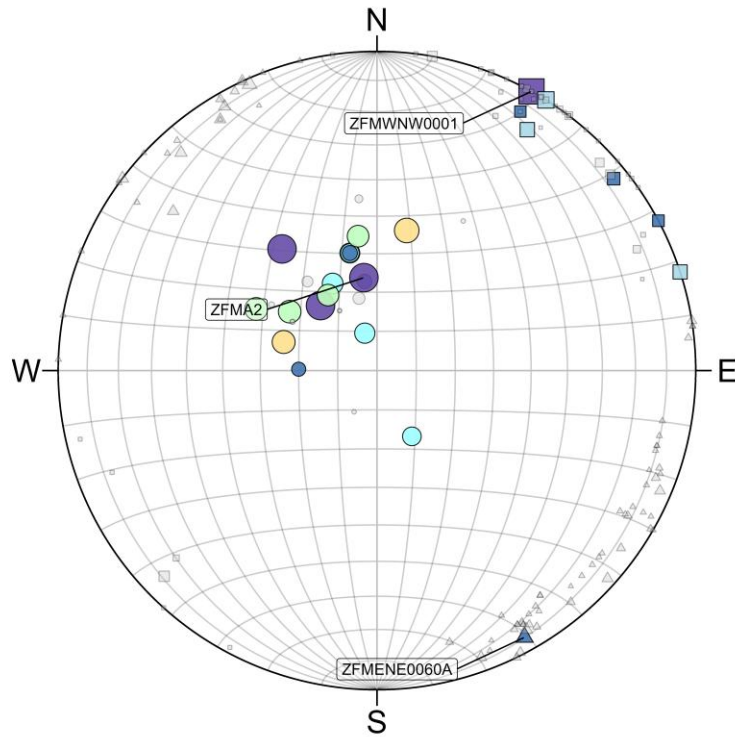


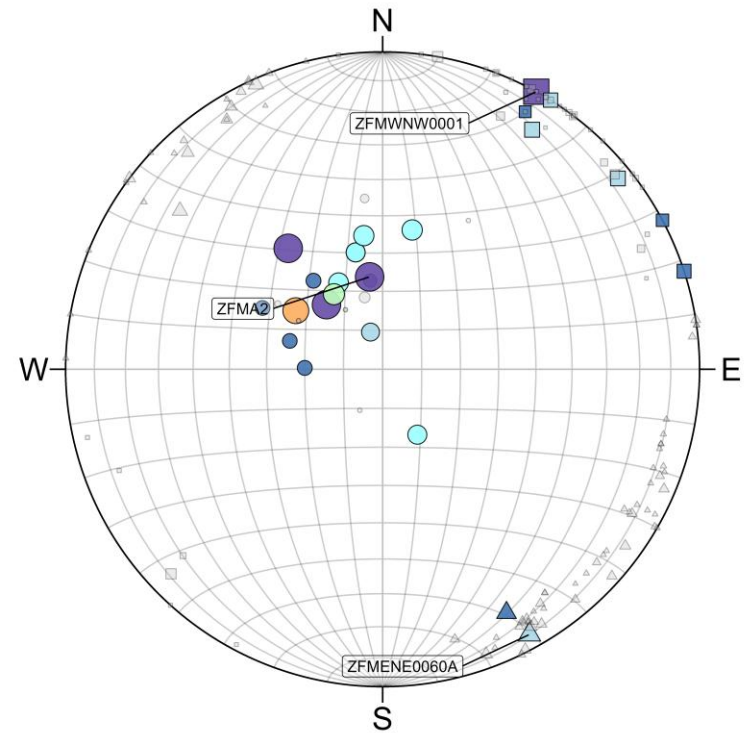
Figure A2- 1. Deformation zone shear before glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 1. Both symbol size and colour indicate displacement magnitude in metres.

Base Post-glacial
Base



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

C1 Post-glacial
C1: σ_1 trend -15°



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

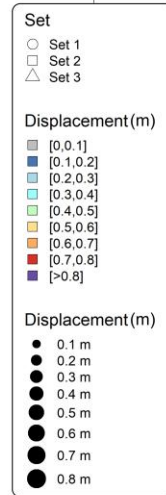
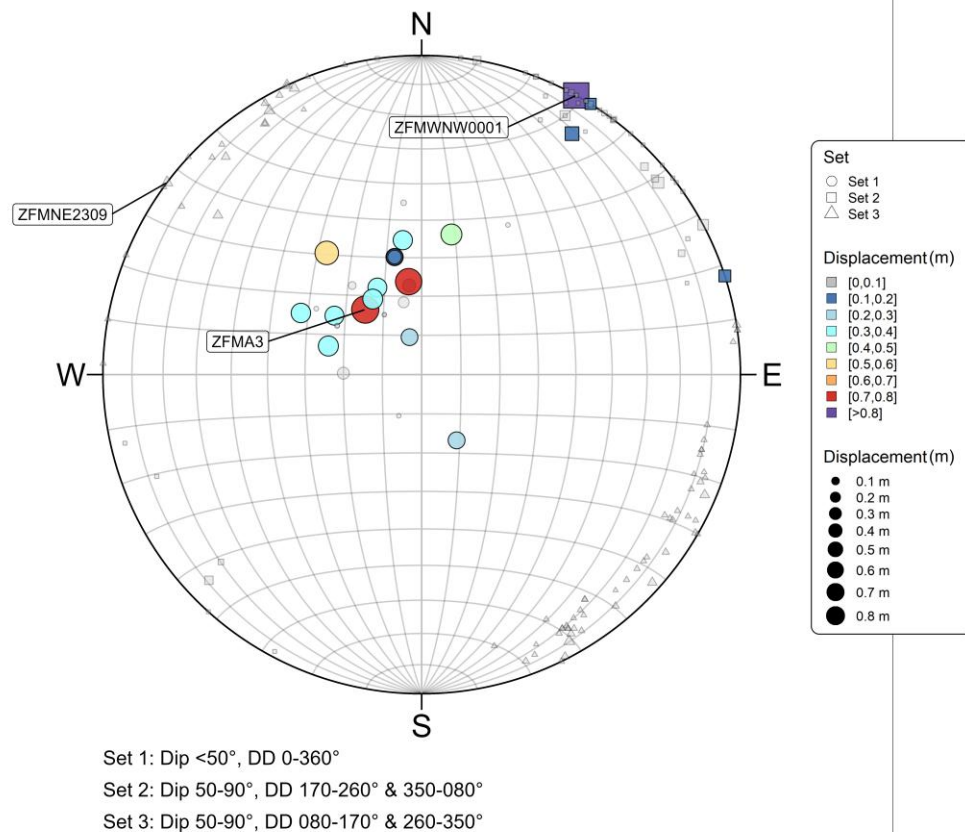


Figure A2- 2. Deformation zone shear after glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 1. Both symbol size and colour indicate displacement magnitude in metres.

Base Pre-glacial
Base



C2 Pre-glacial
C2: σ_1 trend +15°

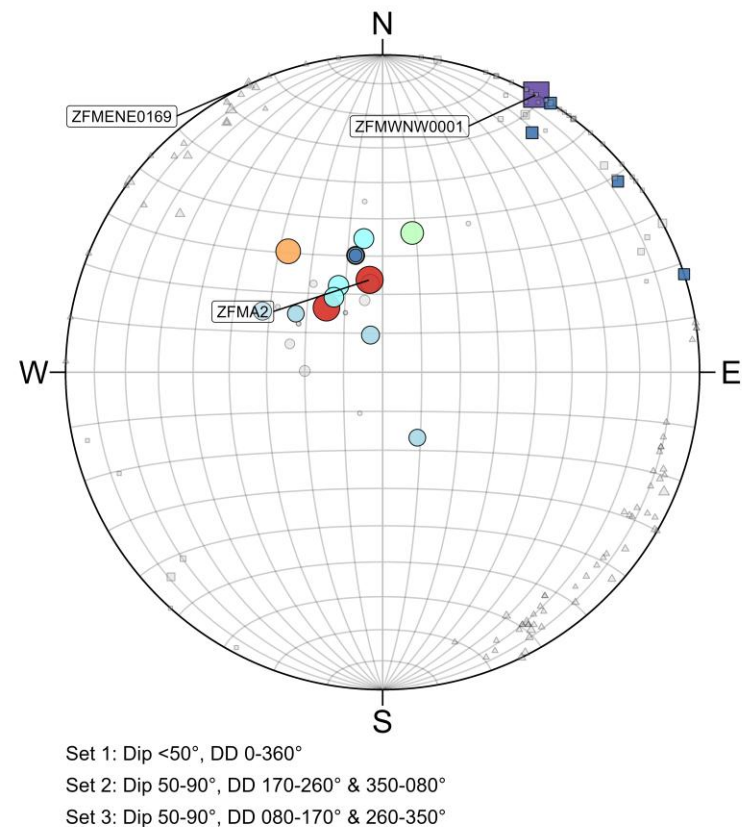
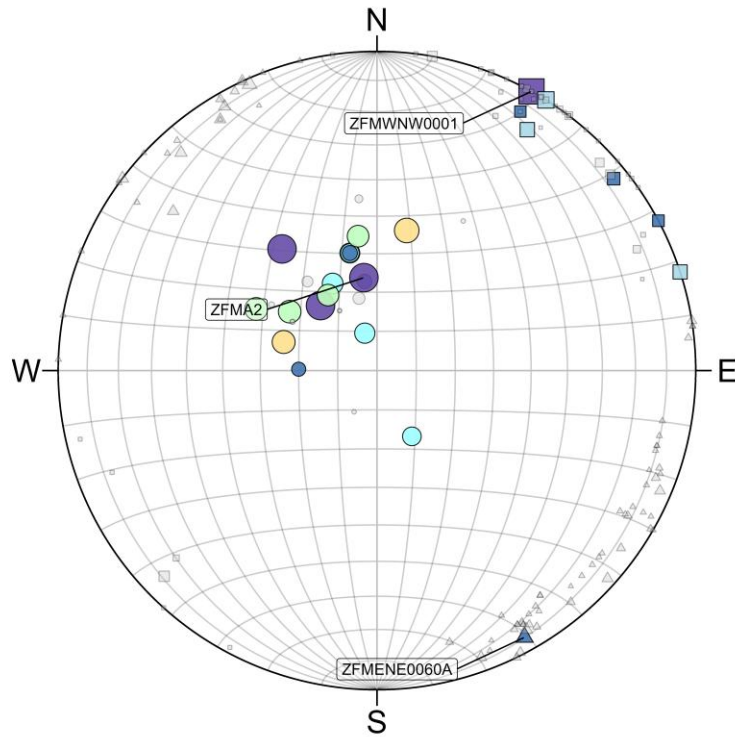


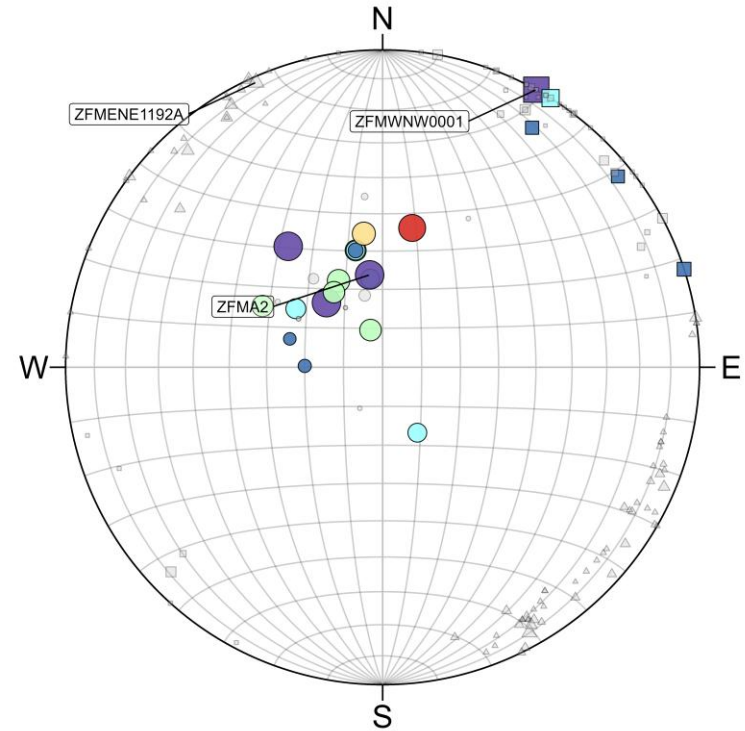
Figure A2- 3. Deformation zone shear before glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 2. Both symbol size and colour indicate displacement magnitude in metres.

Base Post-glacial
Base



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

C2 Post-glacial
C2: σ_1 trend +15°



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

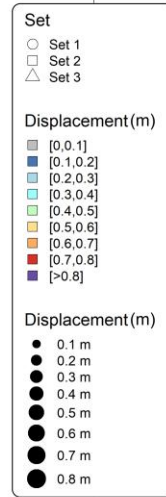
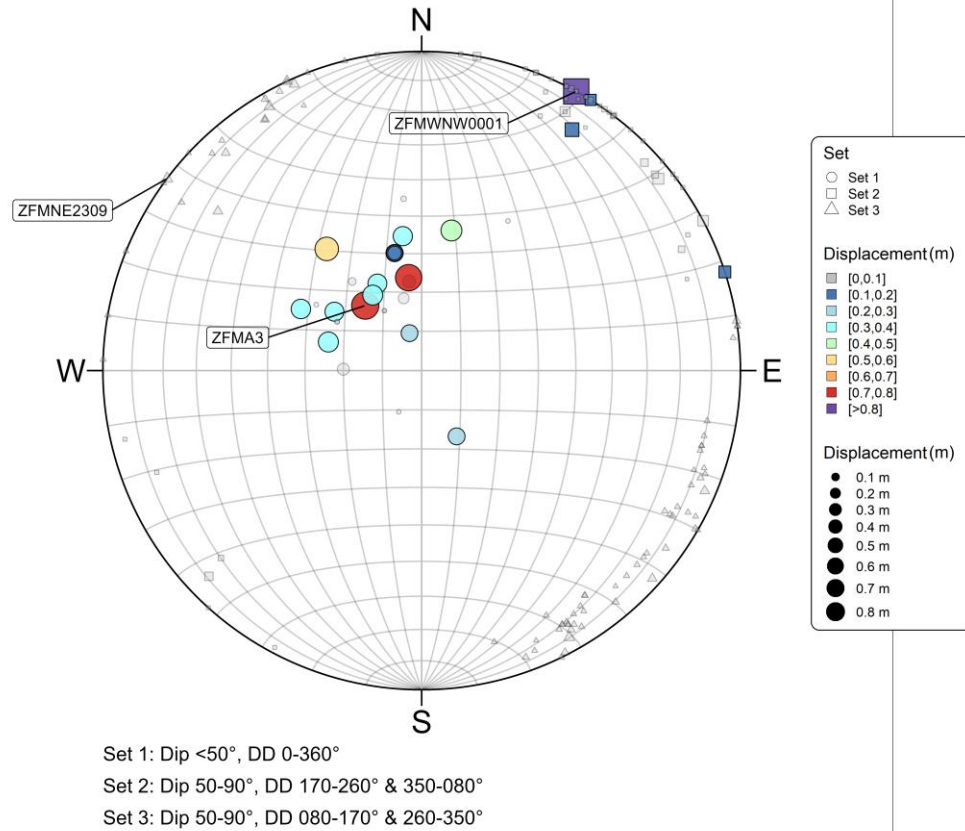


Figure A2- 4. Deformation zone shear after glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 2. Both symbol size and colour indicate displacement magnitude in metres.

Base Pre-glacial
Base



C3 Pre-glacial
C3: σ_1 +6 MPa, σ_2 +5 MPa

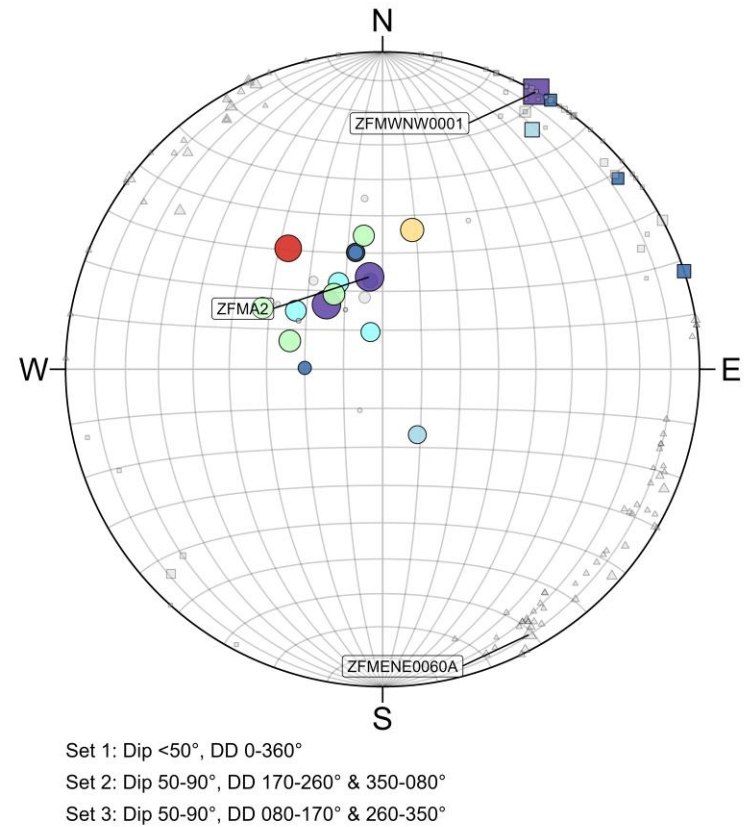
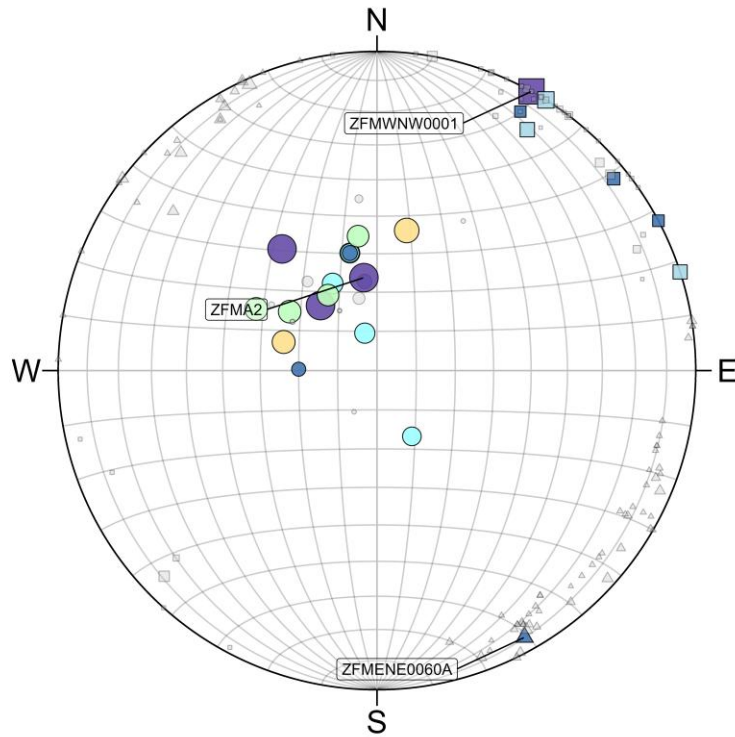


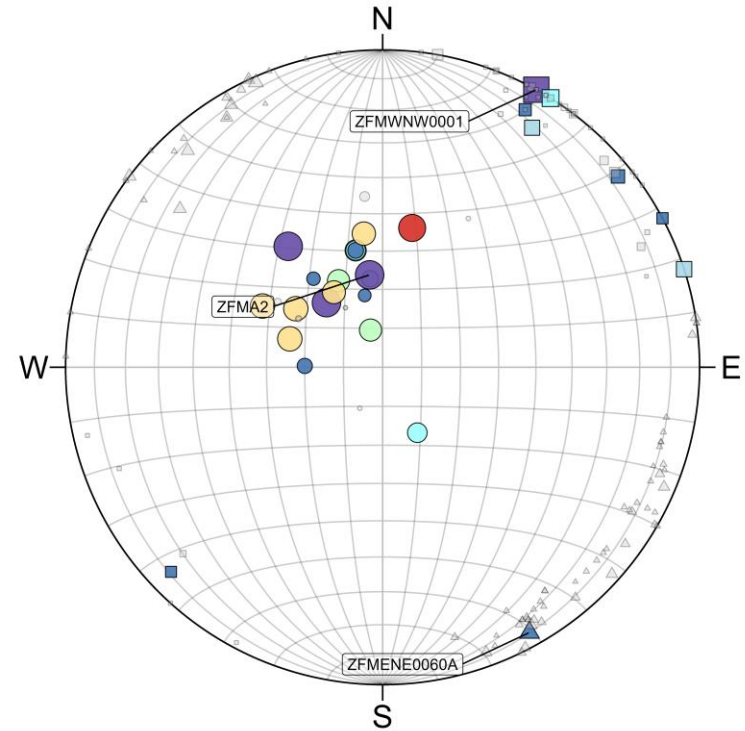
Figure A2- 5. Deformation zone shear before glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 3. Both symbol size and colour indicate displacement magnitude in metres.

Base Post-glacial
Base



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

C3 Post-glacial
C3: σ_1 +6 MPa, σ_2 +5 MPa



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

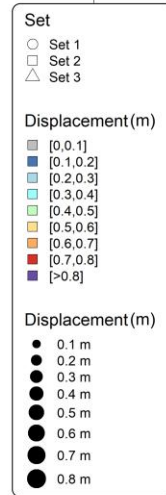
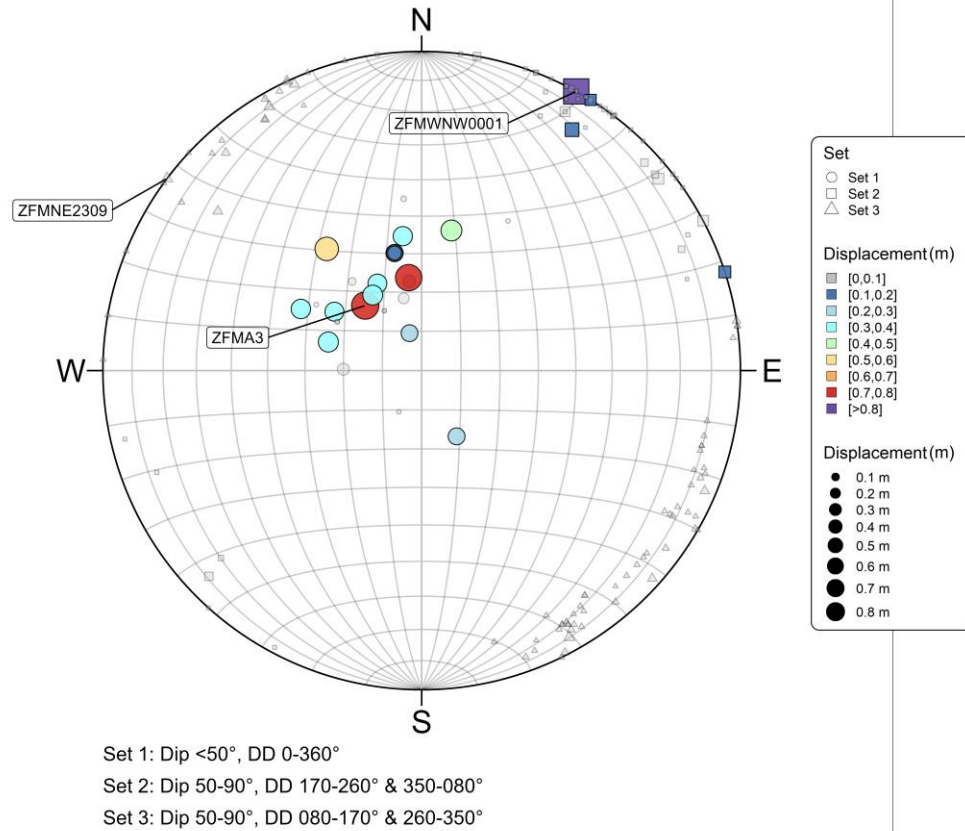


Figure A2- 6. Deformation zone shear after glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 3. Both symbol size and colour indicate displacement magnitude in metres.

Base Pre-glacial
Base



C4 Pre-glacial
C4: σ_1 -6 MPa, σ_2 -5 MPa

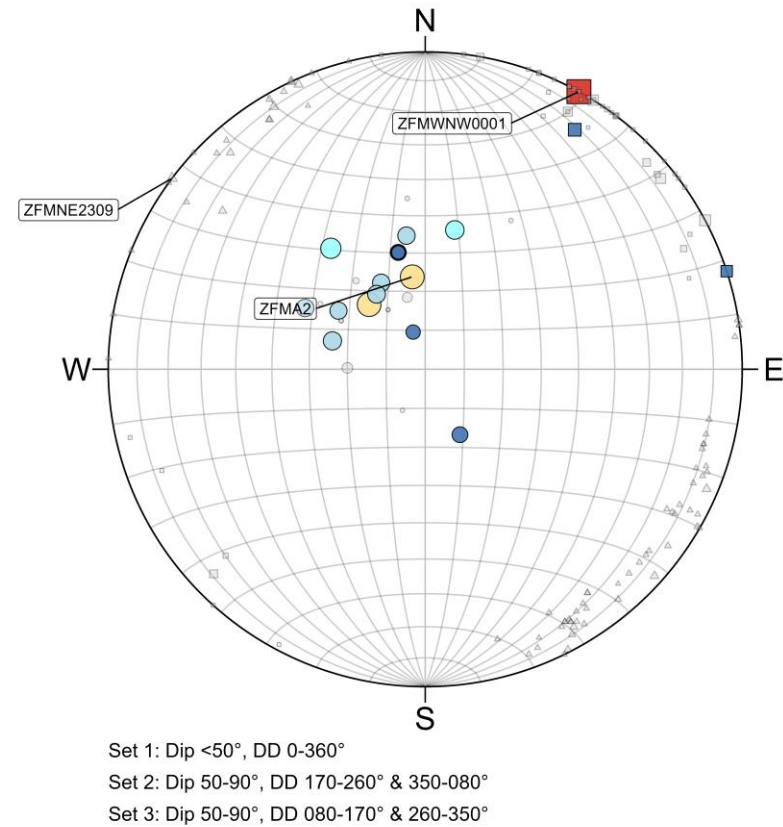
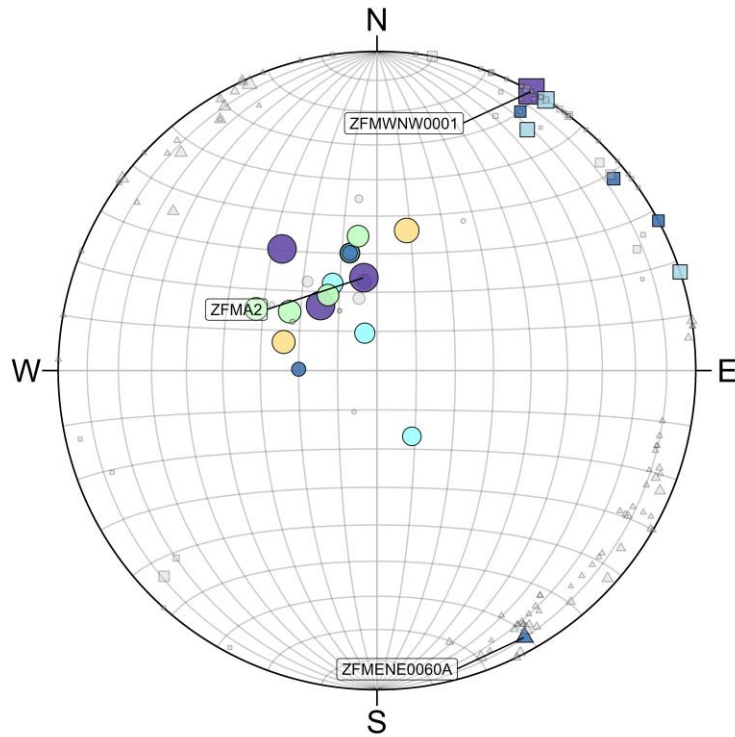


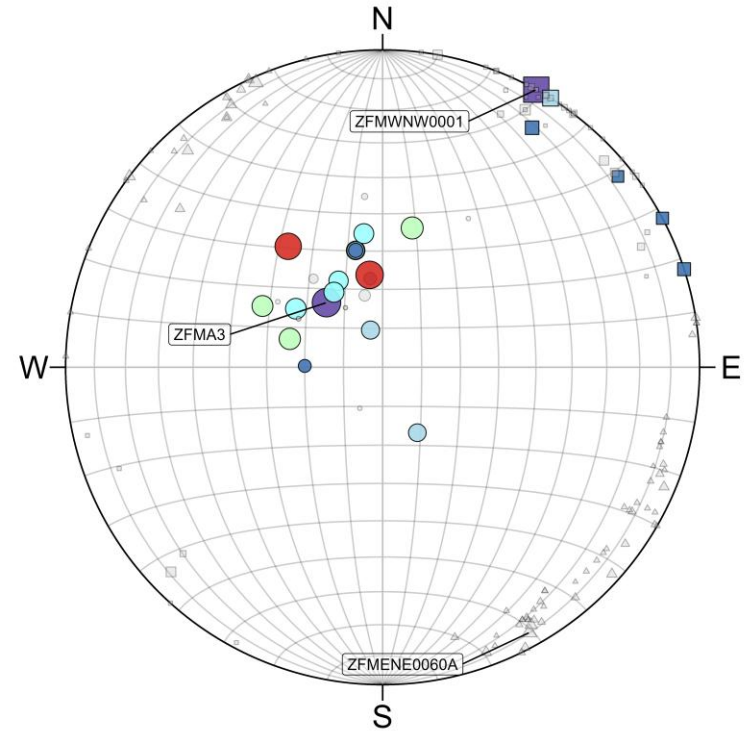
Figure A2- 7. Deformation zone shear before glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 4. Both symbol size and colour indicate displacement magnitude in metres.

Base Post-glacial
Base



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

C4 Post-glacial
C4: σ_1 -6 MPa, σ_2 -5 MPa



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

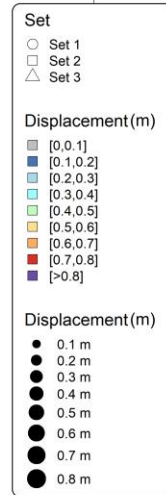
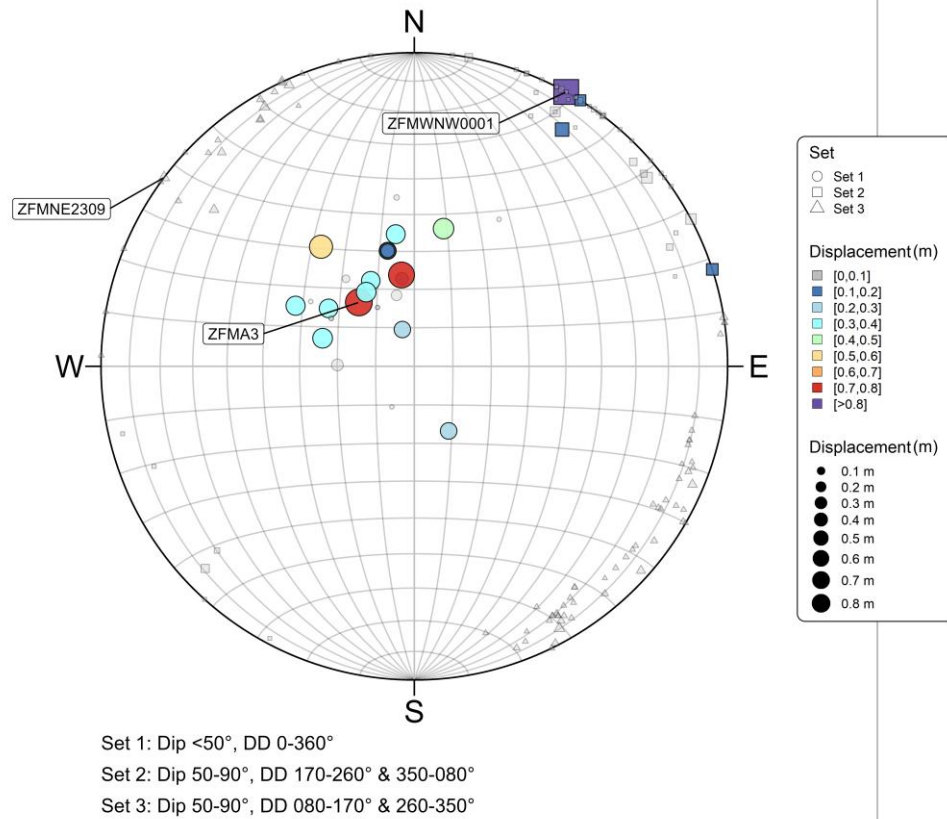


Figure A2- 8. Deformation zone shear after glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 4. Both symbol size and colour indicate displacement magnitude in metres.

Base Pre-glacial
Base



C5 Pre-glacial
C5: KFM24 OC, σ_1 trend 121°

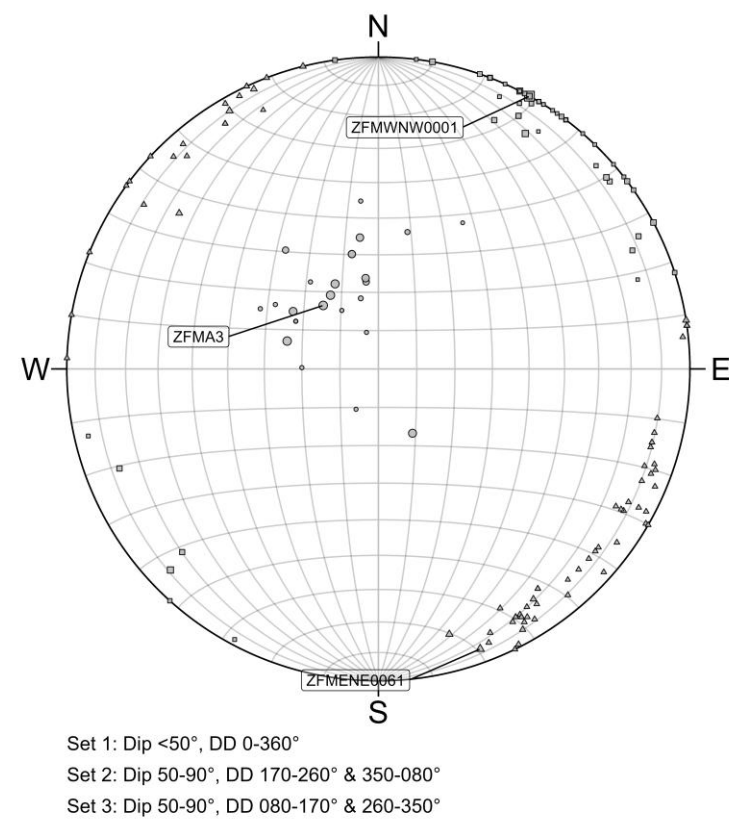
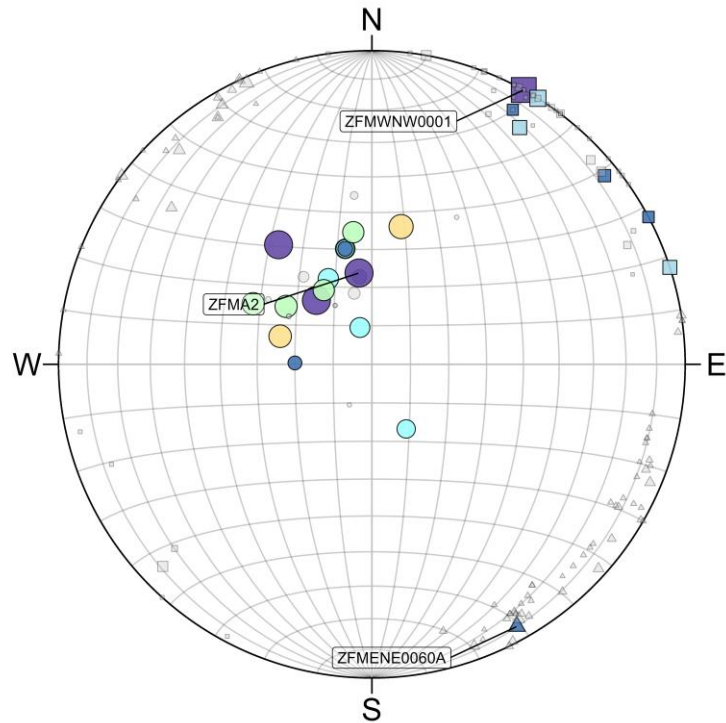


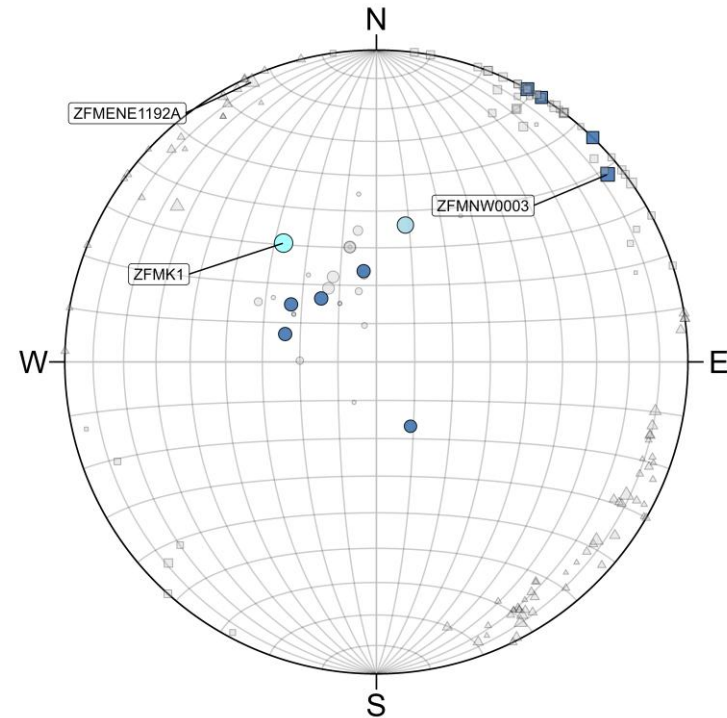
Figure A2- 9. Deformation zone shear before glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 5. Both symbol size and colour indicate displacement magnitude in metres.

Base Post-glacial
Base



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

C5 Post-glacial
C5: KFM24 OC, σ_1 trend 121°



Set 1: Dip <50°, DD 0-360°
Set 2: Dip 50-90°, DD 170-260° & 350-080°
Set 3: Dip 50-90°, DD 080-170° & 260-350°

Figure A2- 10. Deformation zone shear after glaciation by set group on an equal area lower hemisphere projection (LHP) for the Base case and case 5. Both symbol size and colour indicate displacement magnitude in metres.

Appendix 3. Deformation zone slip histograms

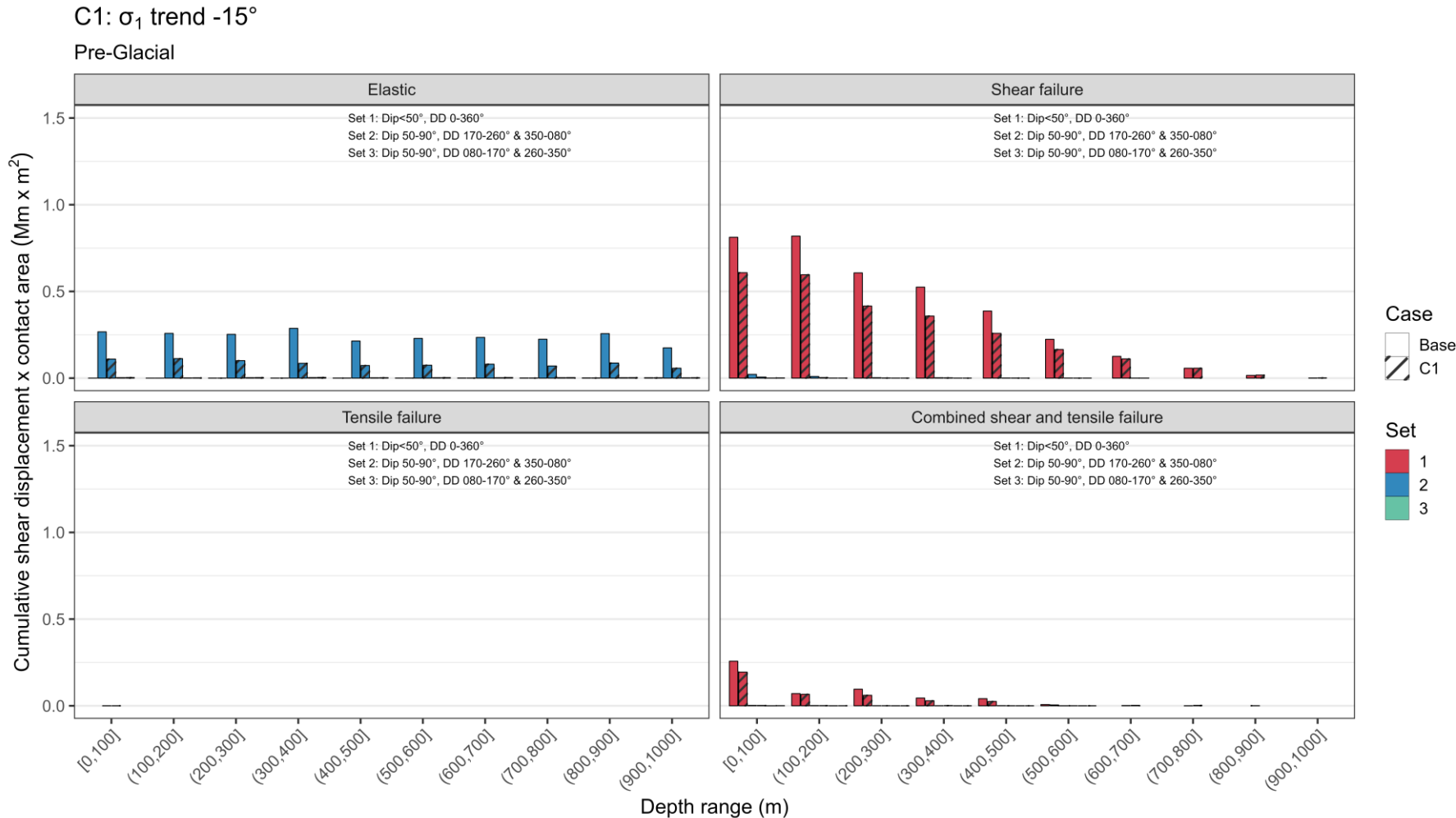


Figure A3- 1. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 1 before glaciation.

C1: σ_1 trend -15°

Post-Glacial

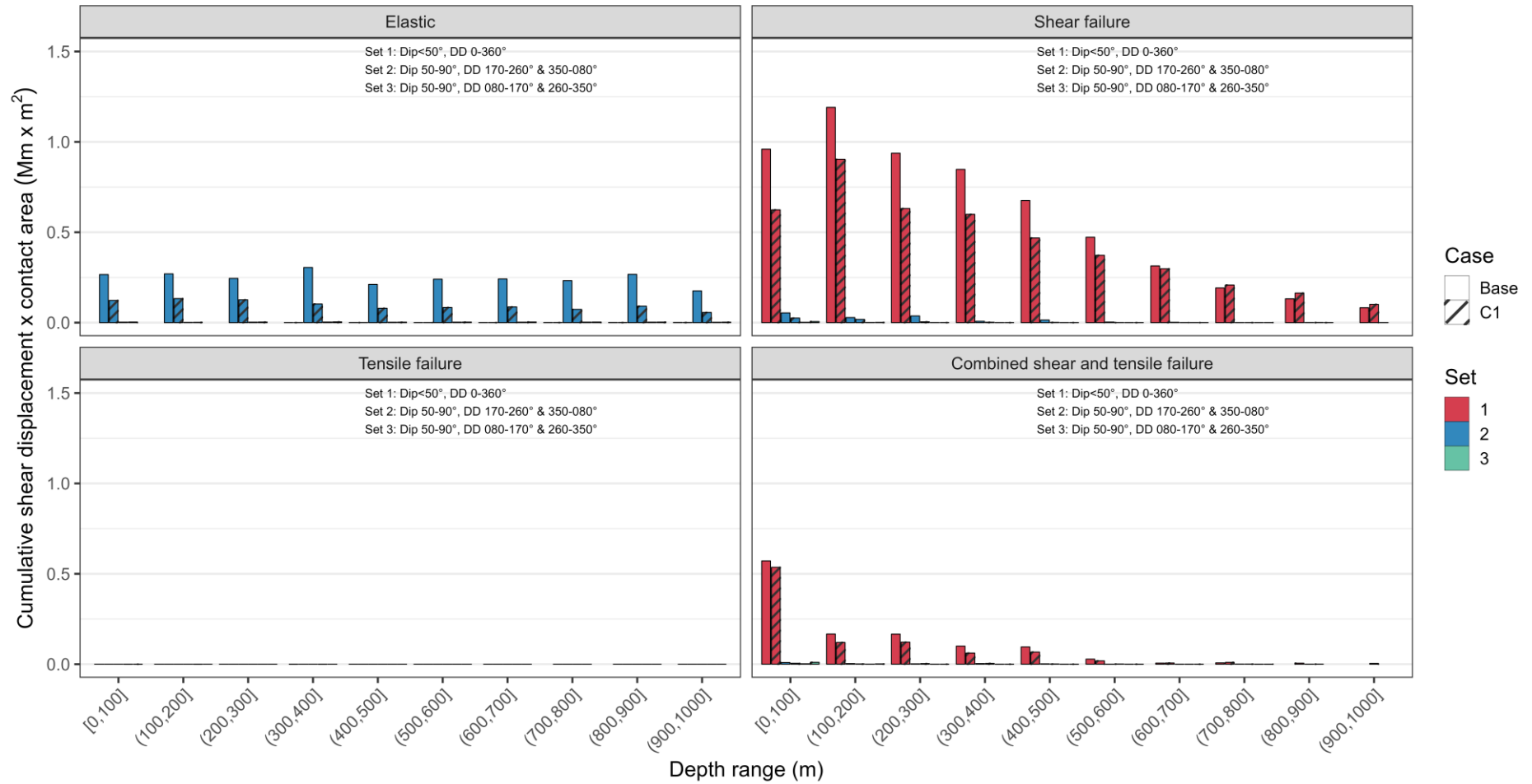


Figure A3- 2. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 1 after glaciation.

C2: σ_1 trend +15°

Pre-Glacial

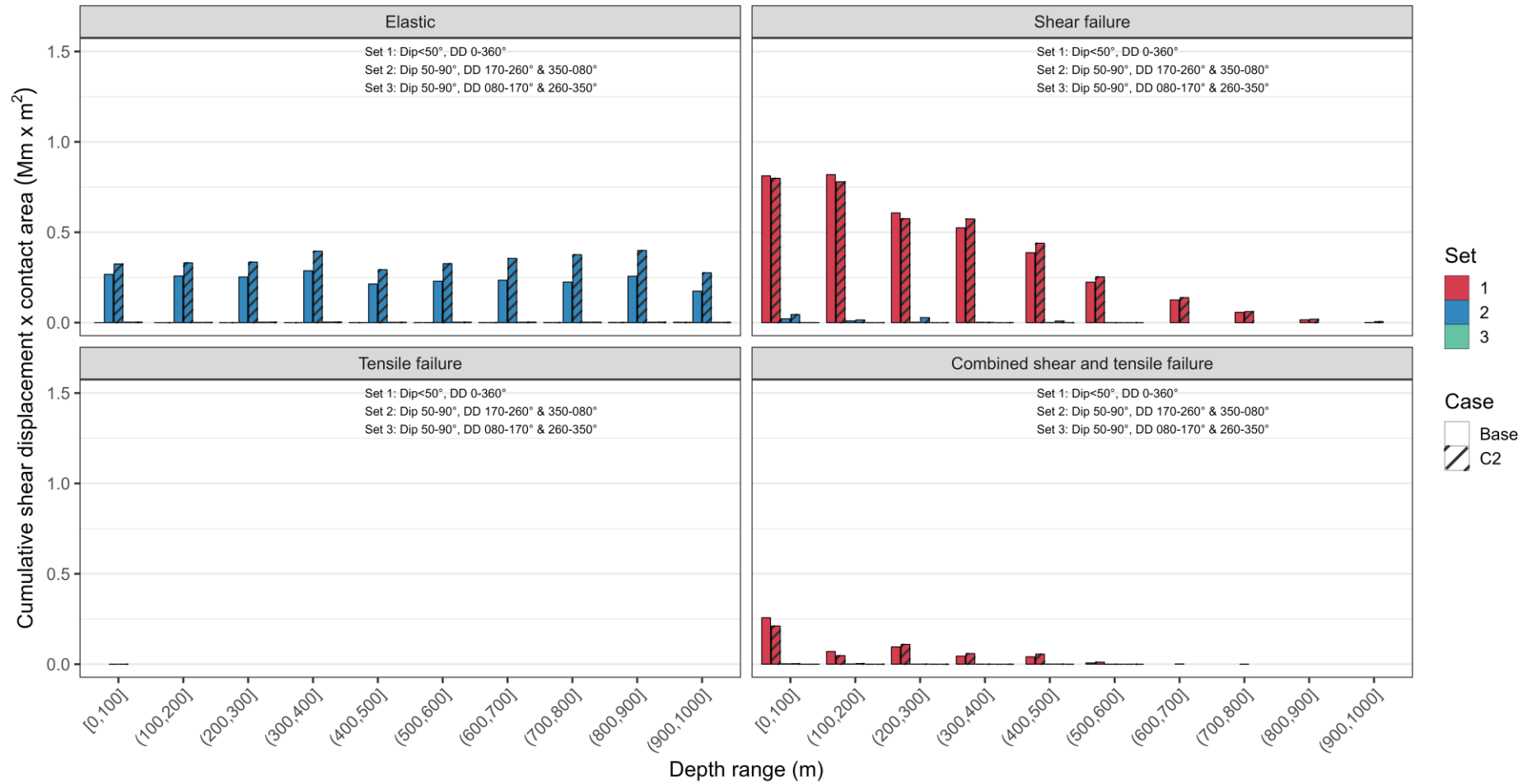


Figure A3- 3. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 2 before glaciation.

C2: σ_1 trend +15°

Post-Glacial

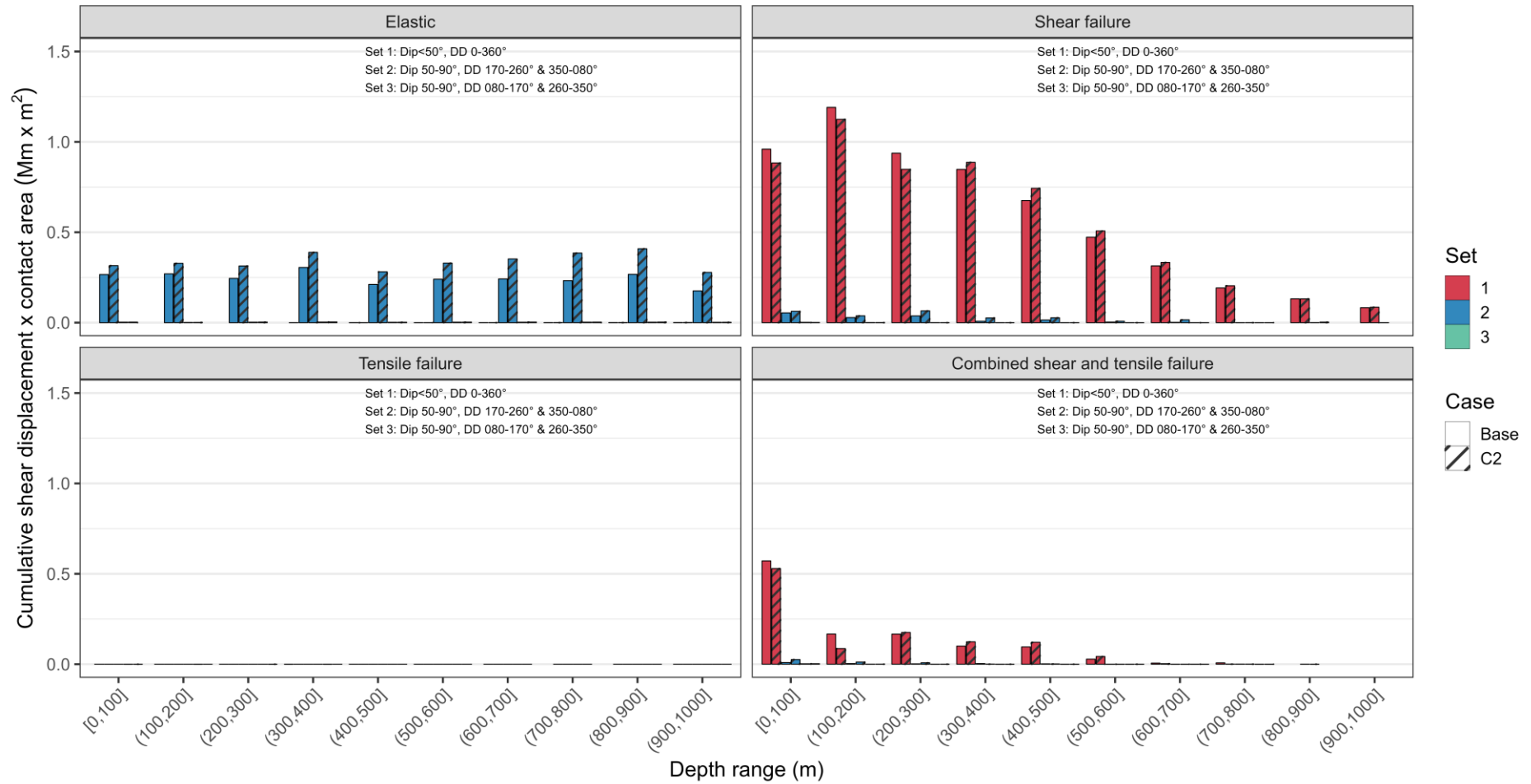


Figure A3- 4. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 2 after glaciation.

C3: σ_1 +6 MPa, σ_2 +5 MPa

Pre-Glacial

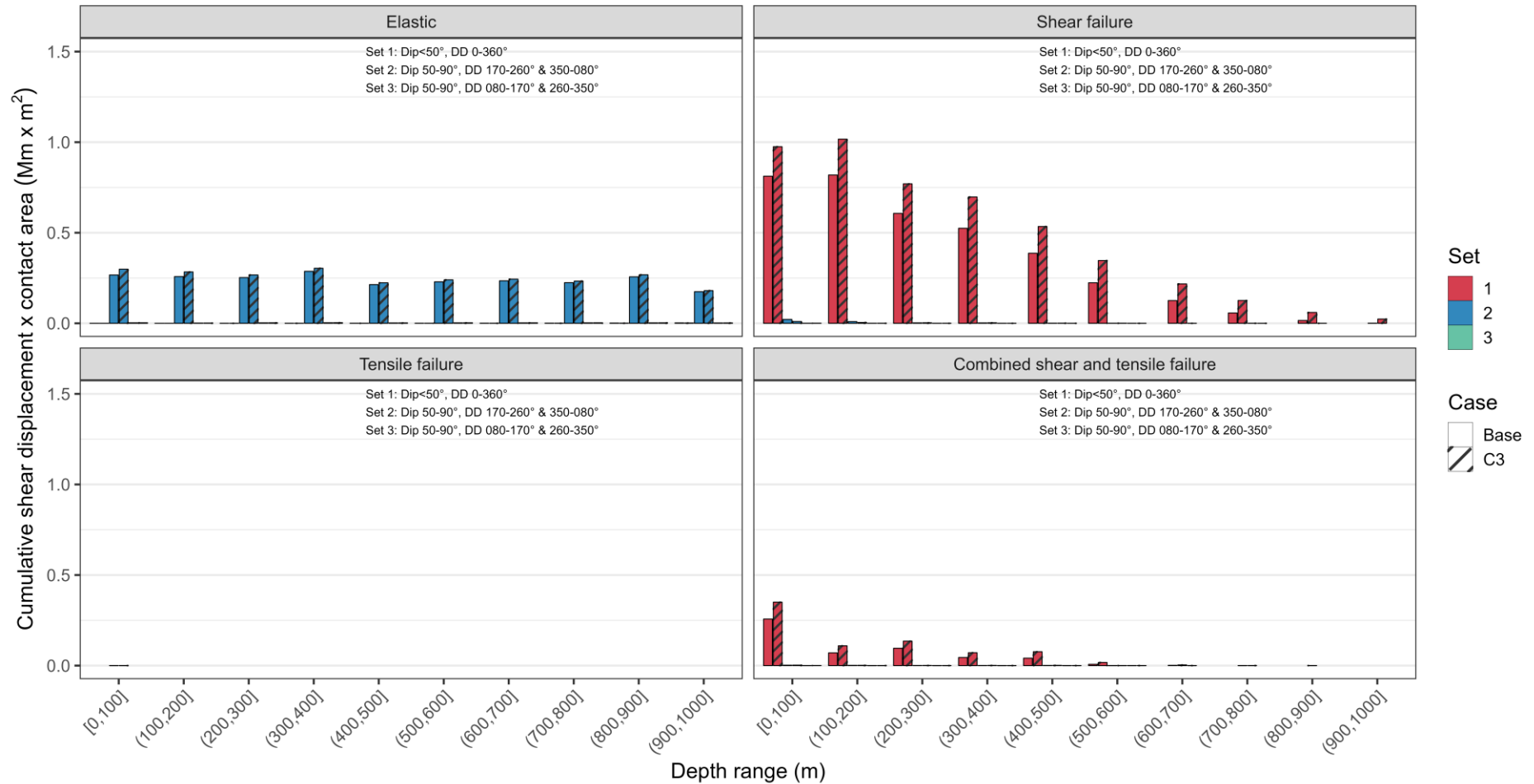


Figure A3- 5. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 3 before glaciation.

C3: σ_1 +6 MPa, σ_2 +5 MPa

Post-Glacial

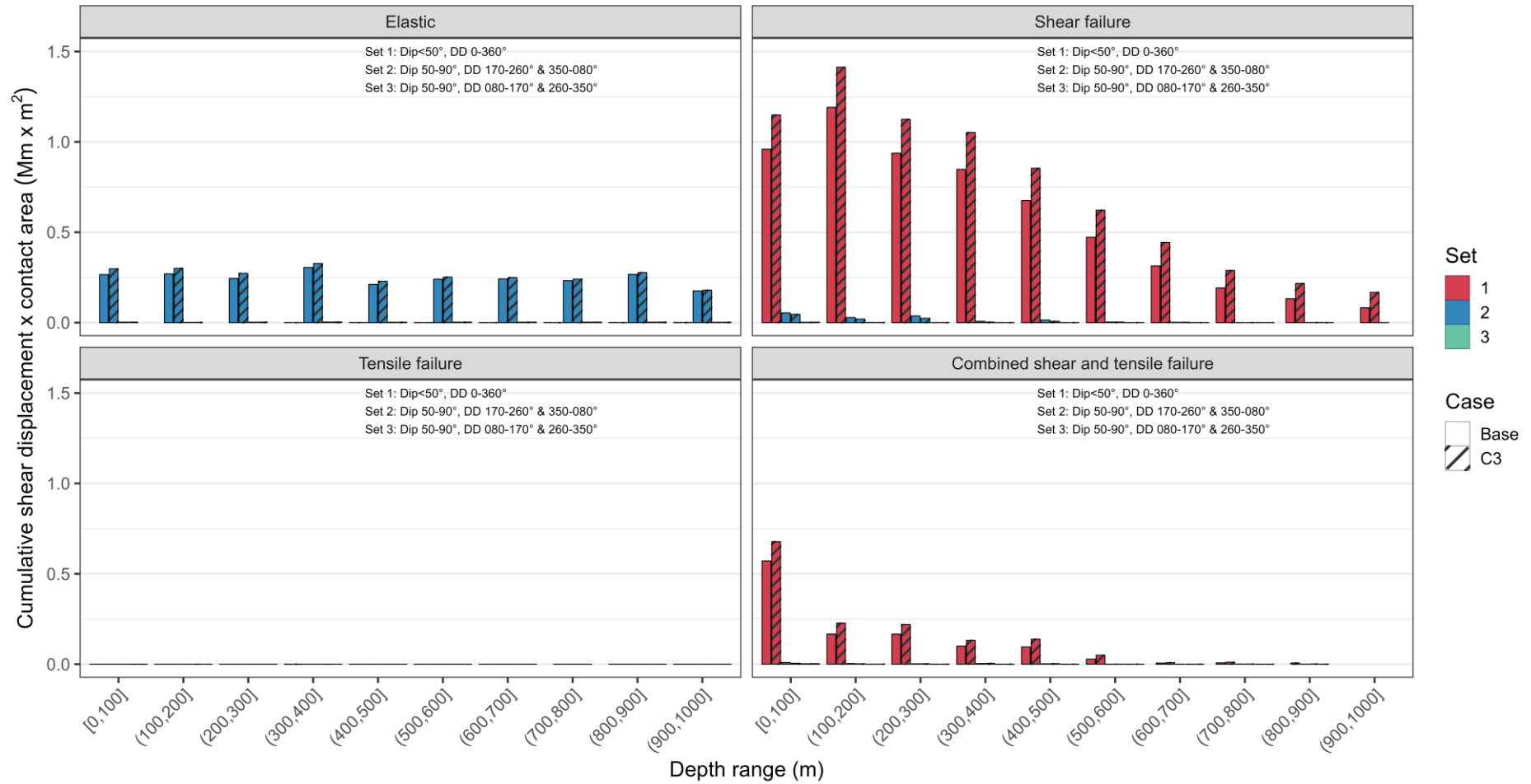


Figure A3- 6. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 3 after glaciation.

C4: σ_1 -6 MPa, σ_2 -5 MPa

Pre-Glacial

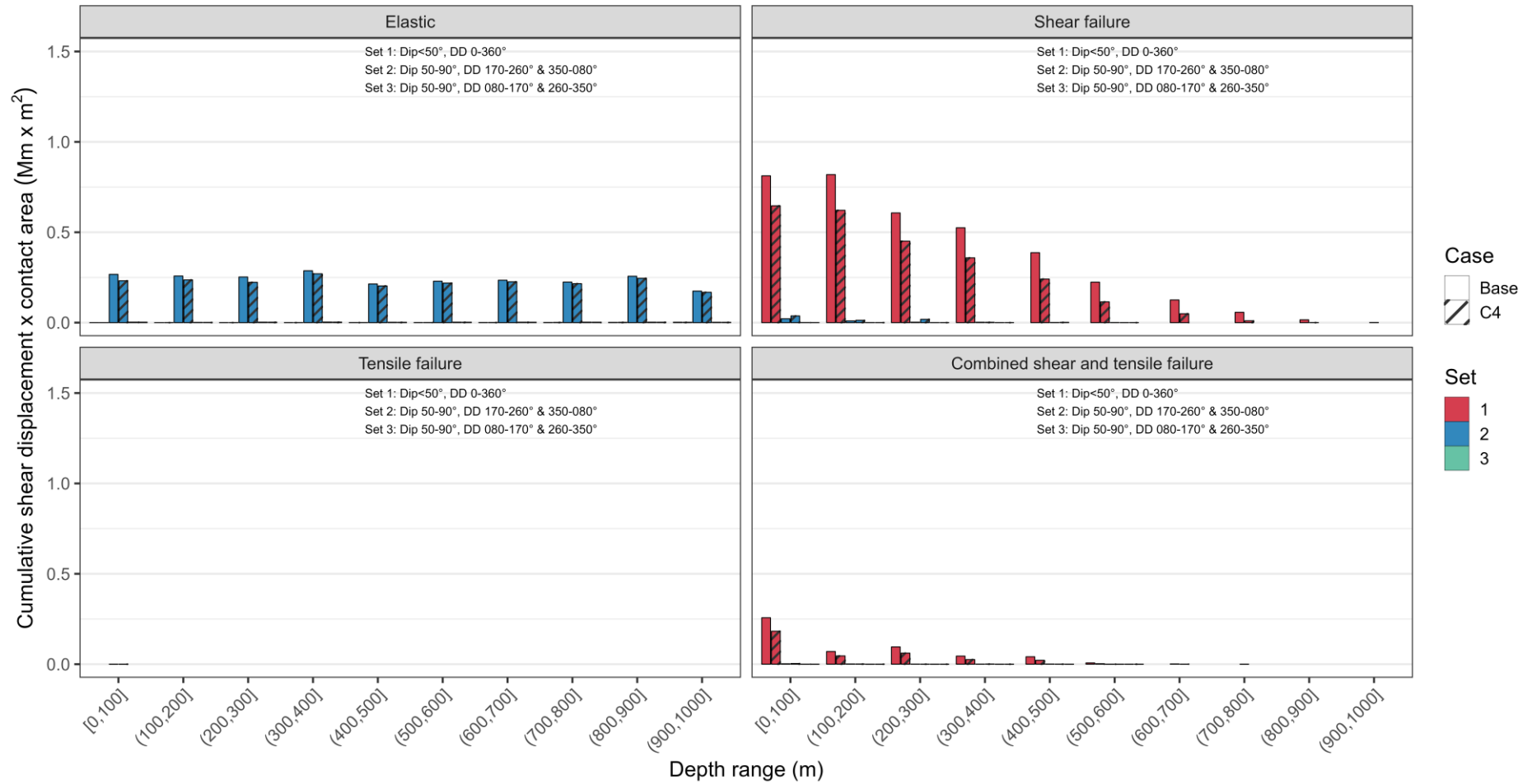


Figure A3- 7. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 4 before glaciation.

C4: σ_1 -6 MPa, σ_2 -5 MPa

Post-Glacial

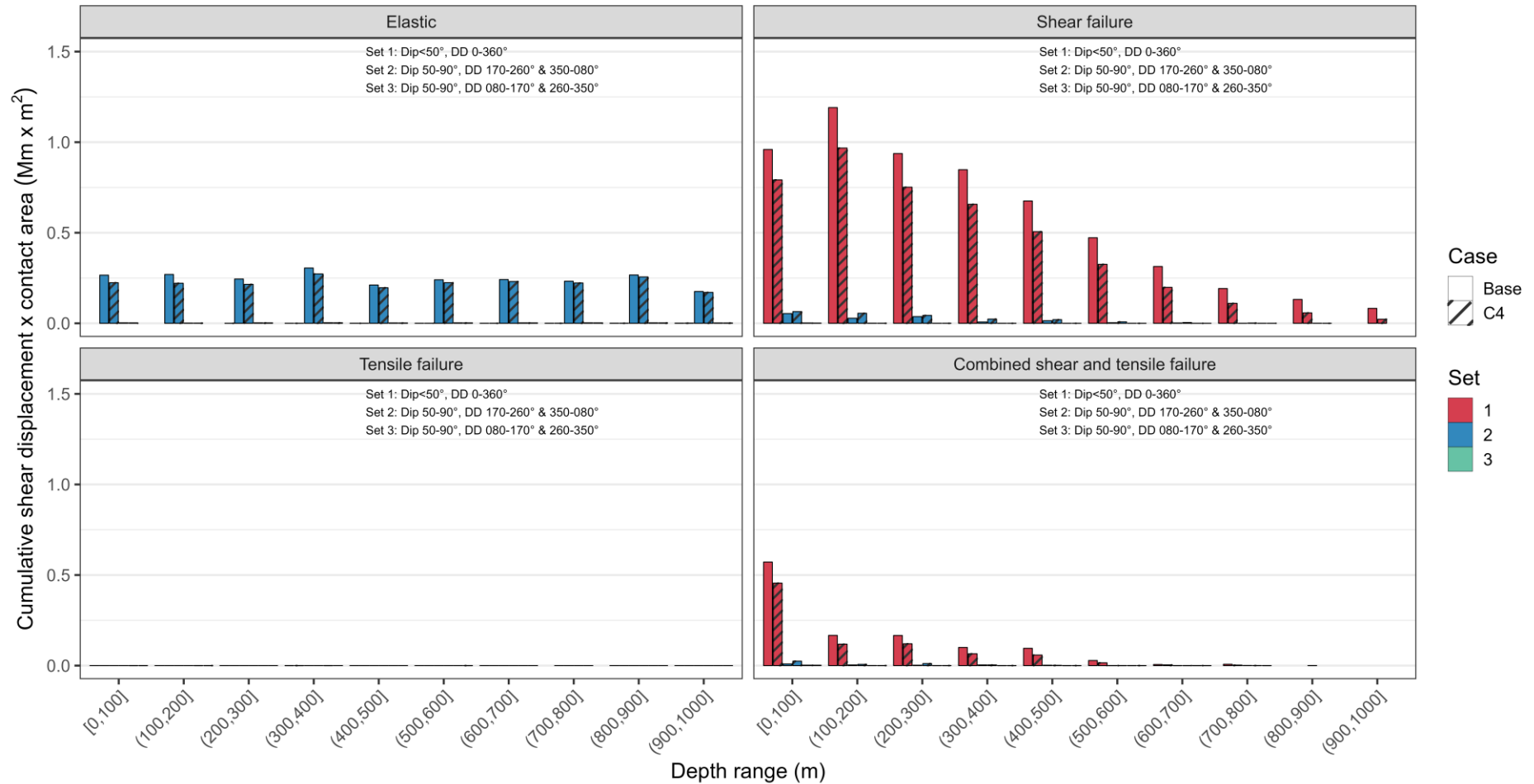


Figure A3- 8. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 4 after glaciation.

C5: KFM24 OC, σ_1 trend 121°

Pre-Glacial

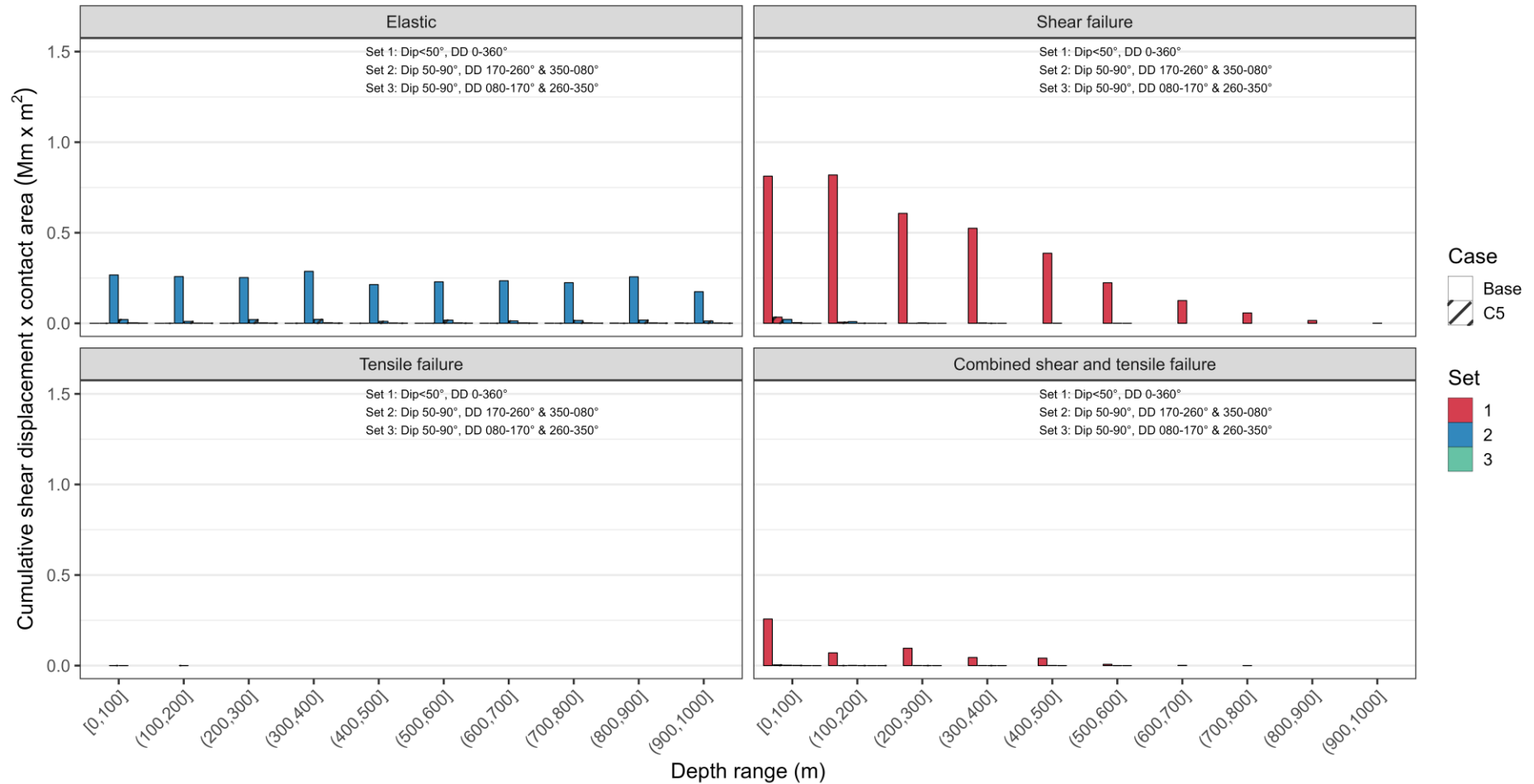


Figure A3- 9. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 5 before glaciation.

C5: KFM24 OC, σ_1 trend 121°

Post-Glacial

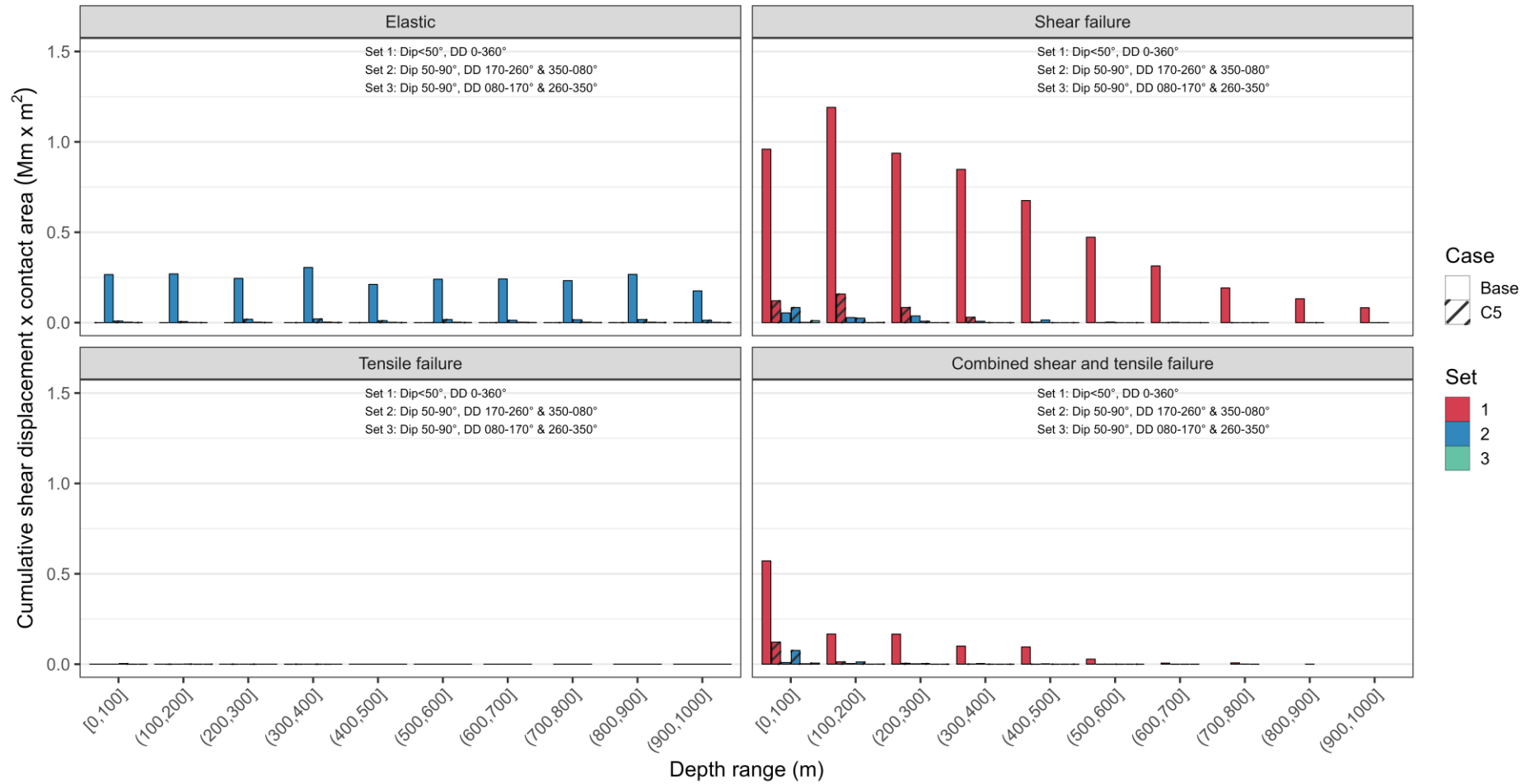


Figure A3- 10. Cumulative shear displacement multiplied by associated area versus depth for major orientation sets of DZ for the Base Case and case 5 after glaciation.

Appendix 4. Mean and variation of σ_1 magnitude, trend and σ_1/σ_2 ratio for hundred meter intervals (95 % variation interval)

Cylinder data: Pre-Glacial

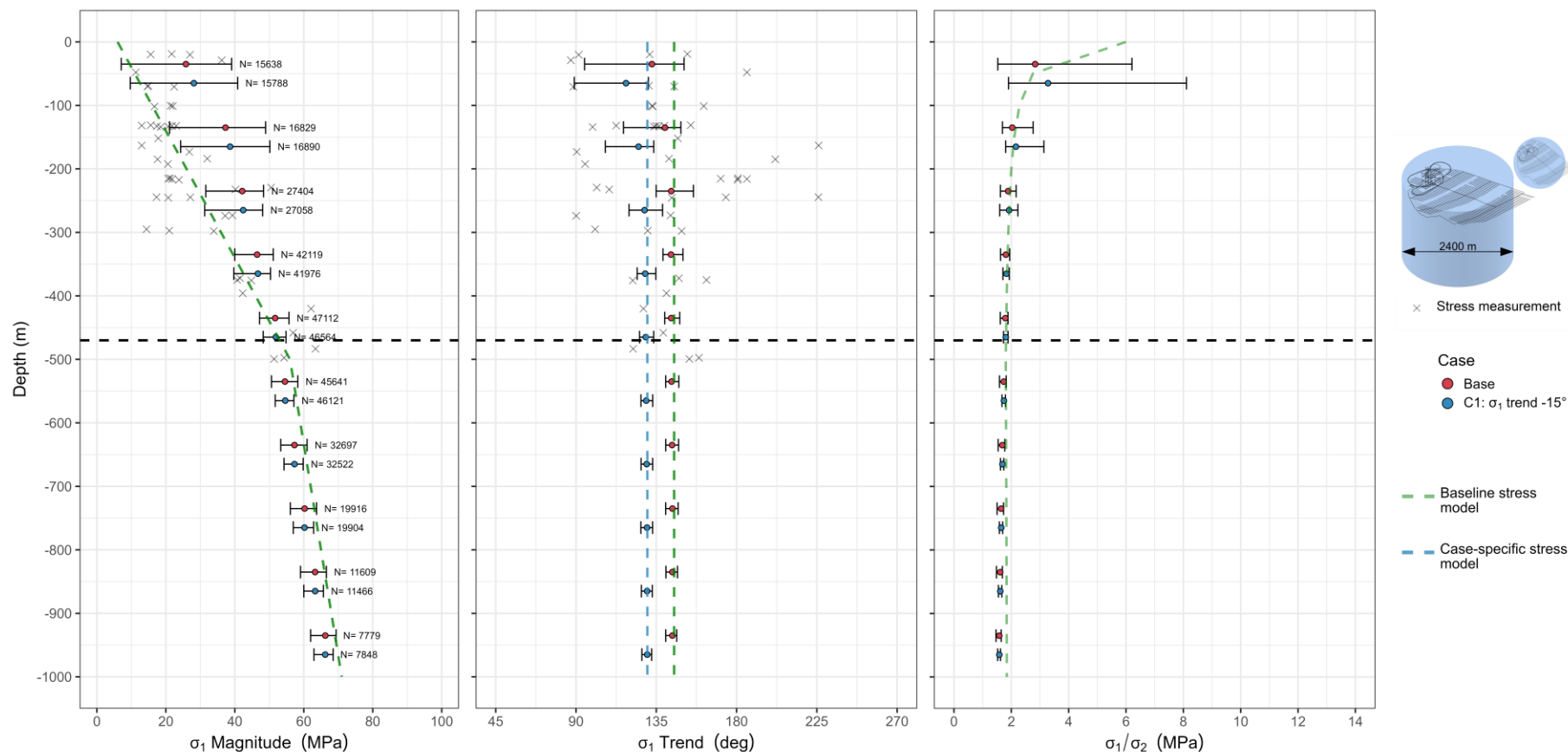


Figure A4- 1. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 1 before glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target trend of σ_1 for case 1. Field stress measurements indicated with grey “x” markers.

Cylinder data: Post-Glacial

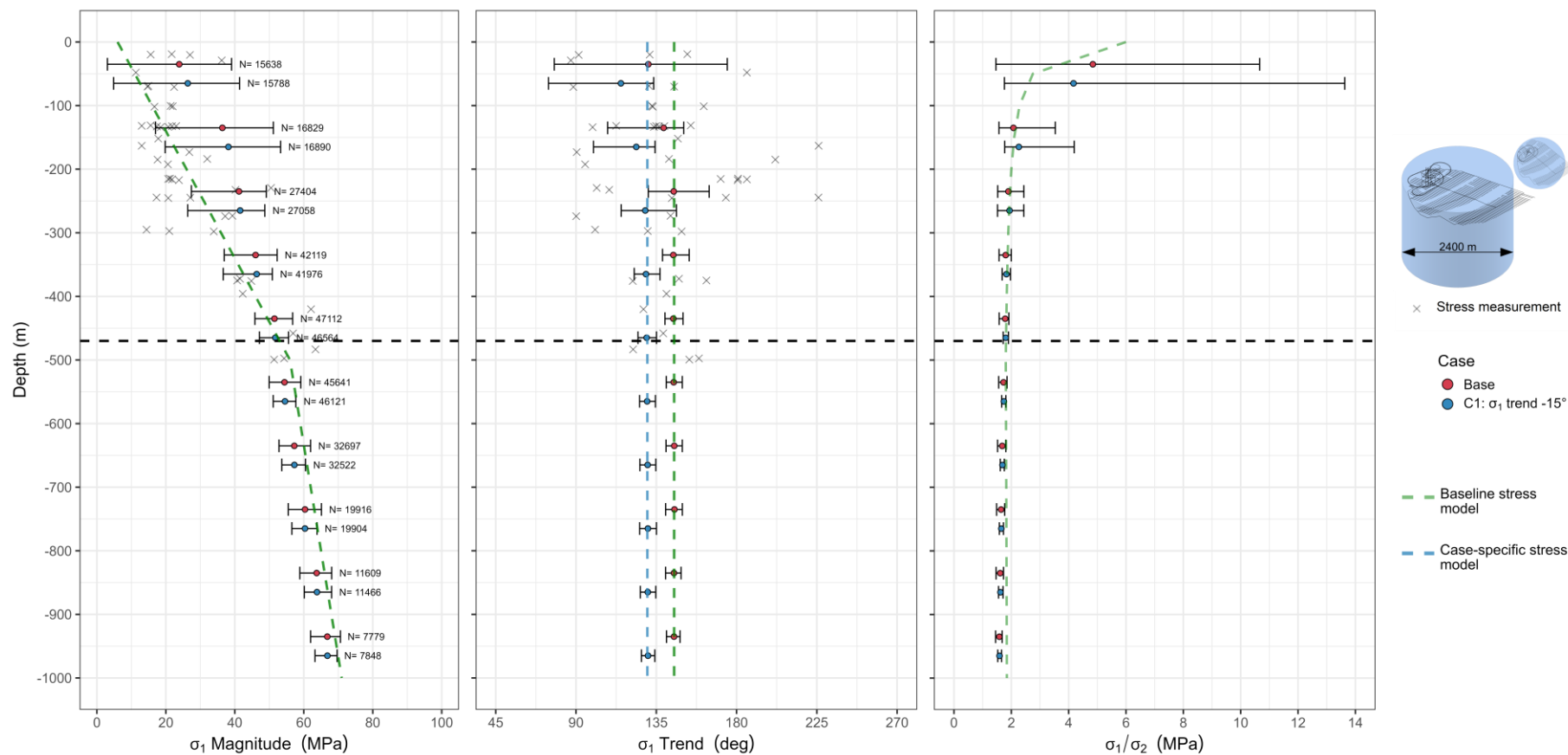


Figure A4- 2. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 1 after glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target trend of σ_1 for case 1. Field stress measurements indicated with grey “x” markers.

Cylinder data: Pre-Glacial

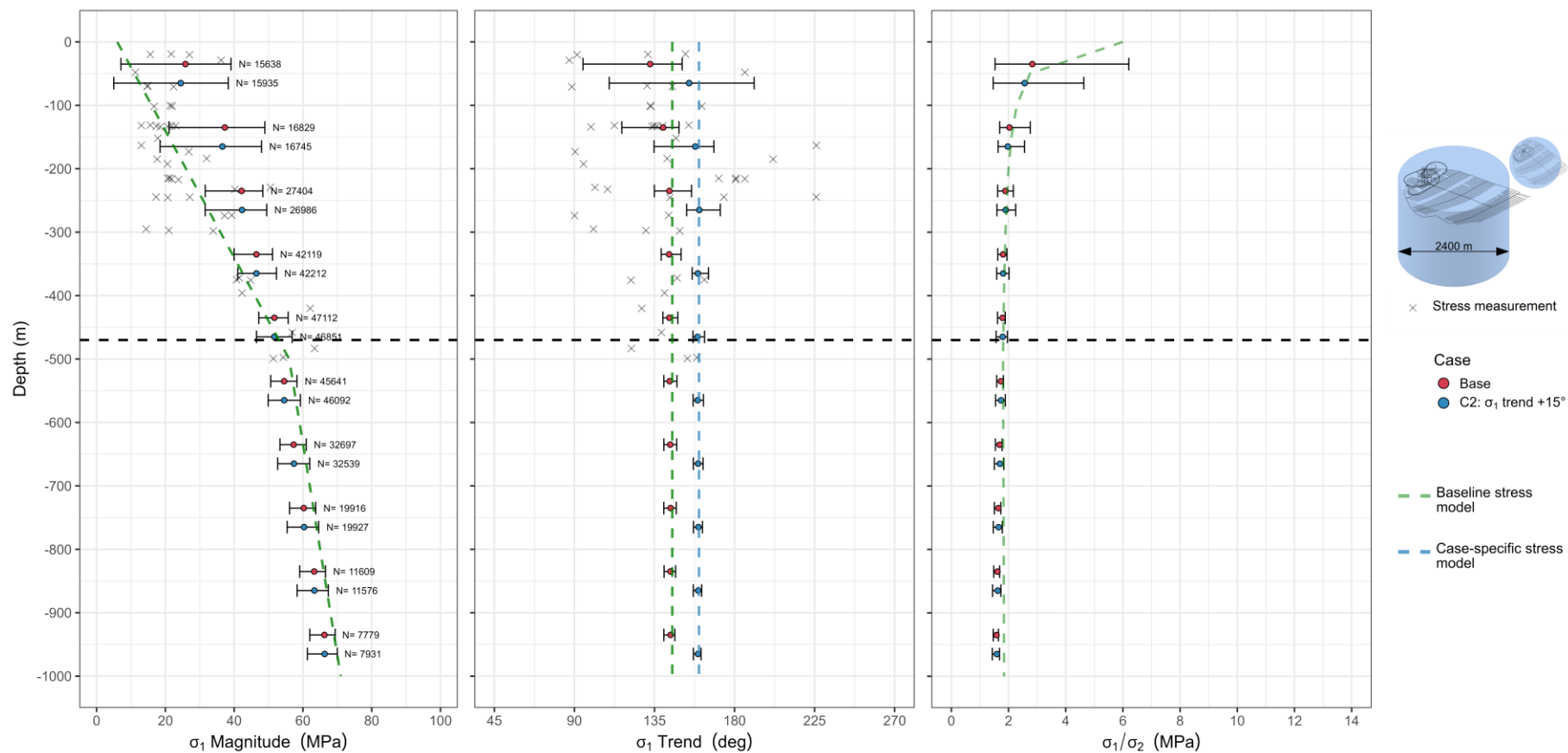


Figure A4- 3. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 2 before glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target trend of σ_1 for case 2. Field stress measurements indicated with grey “x” markers.

Cylinder data: Post-Glacial

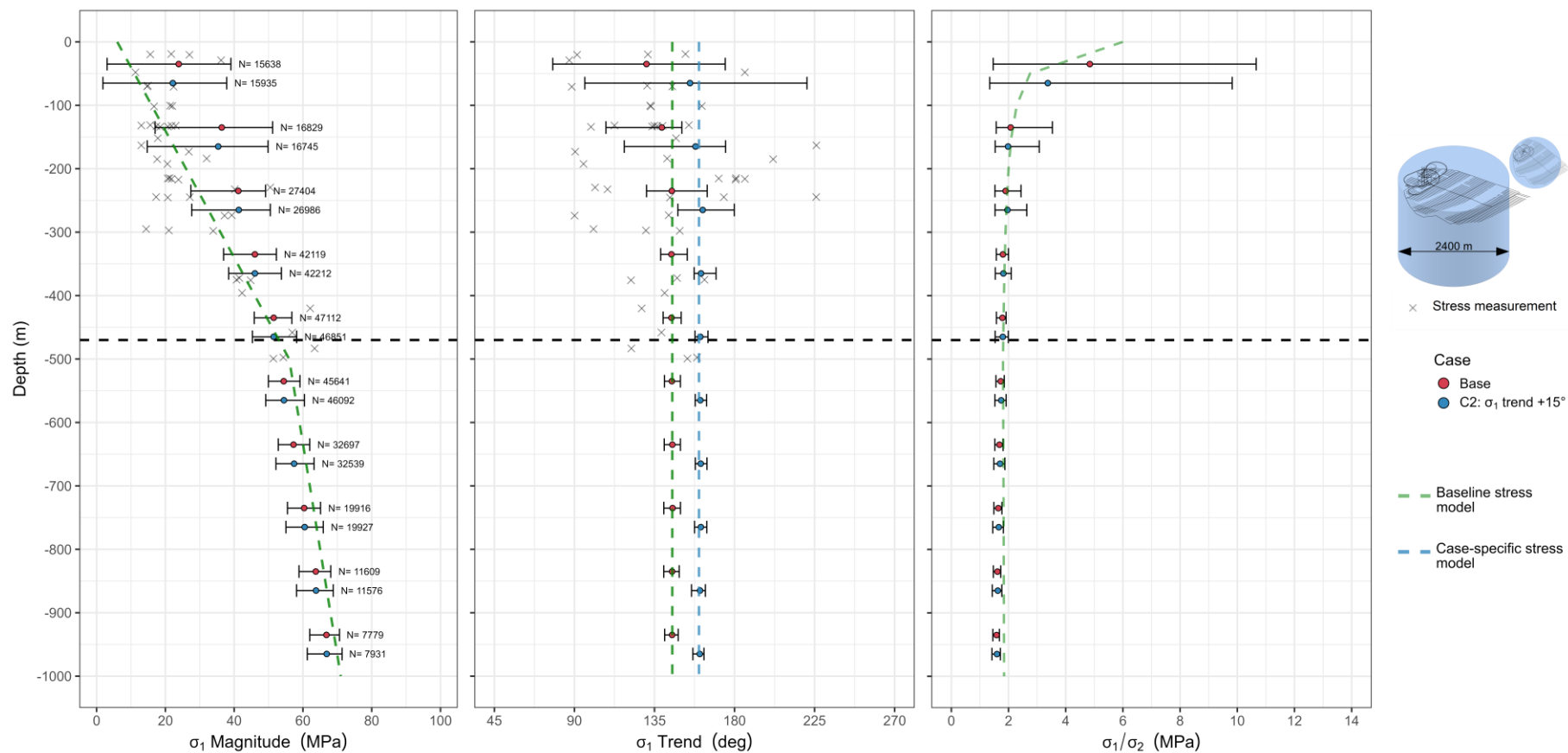


Figure A4- 4. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 2 after glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target trend of σ_1 for case 2. Field stress measurements indicated with grey “x” markers.

Cylinder data: Pre-Glacial

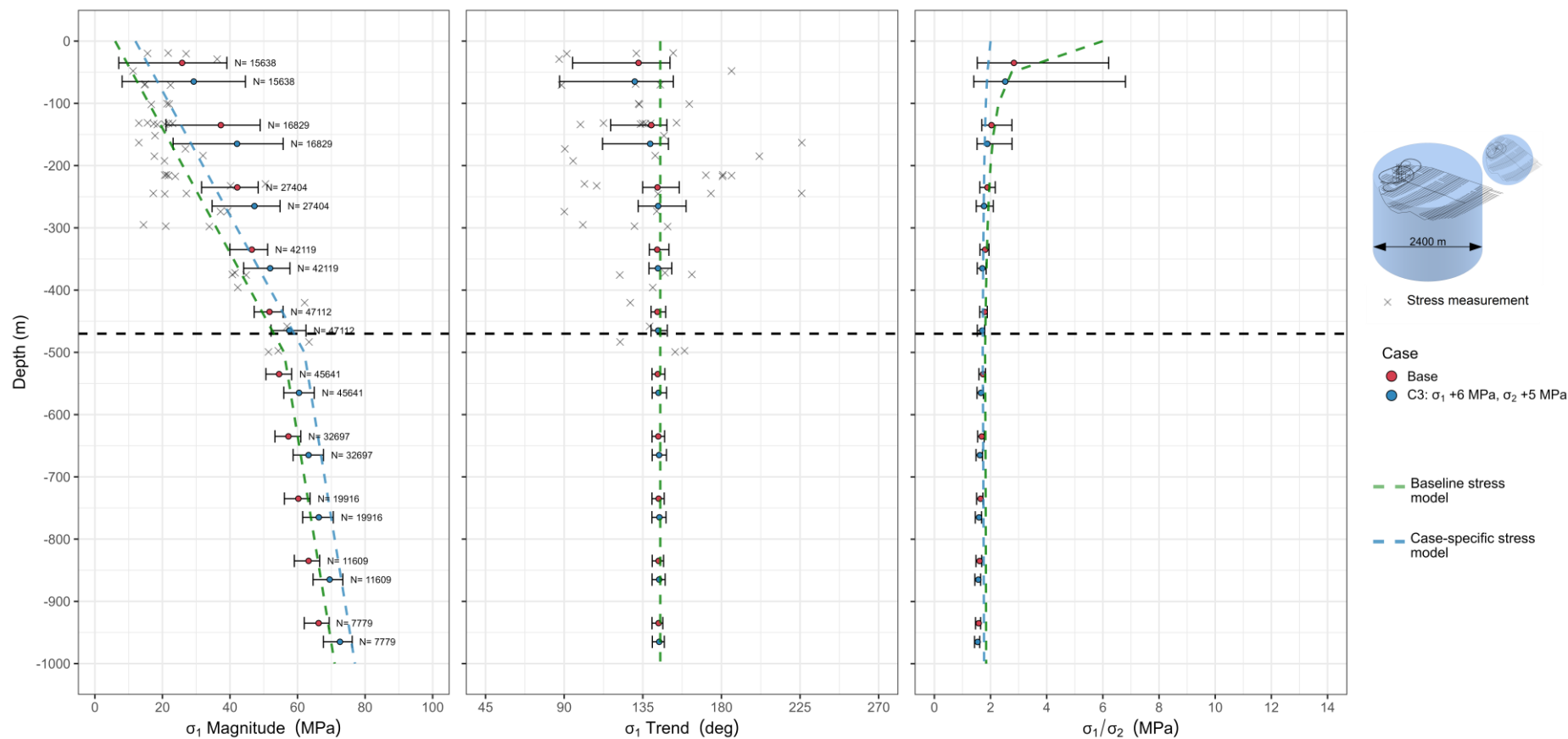


Figure A4- 5. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 3 before glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target ratio of σ_1/σ_2 for case 3. Field stress measurements indicated with grey "x" markers.

Cylinder data: Post-Glacial

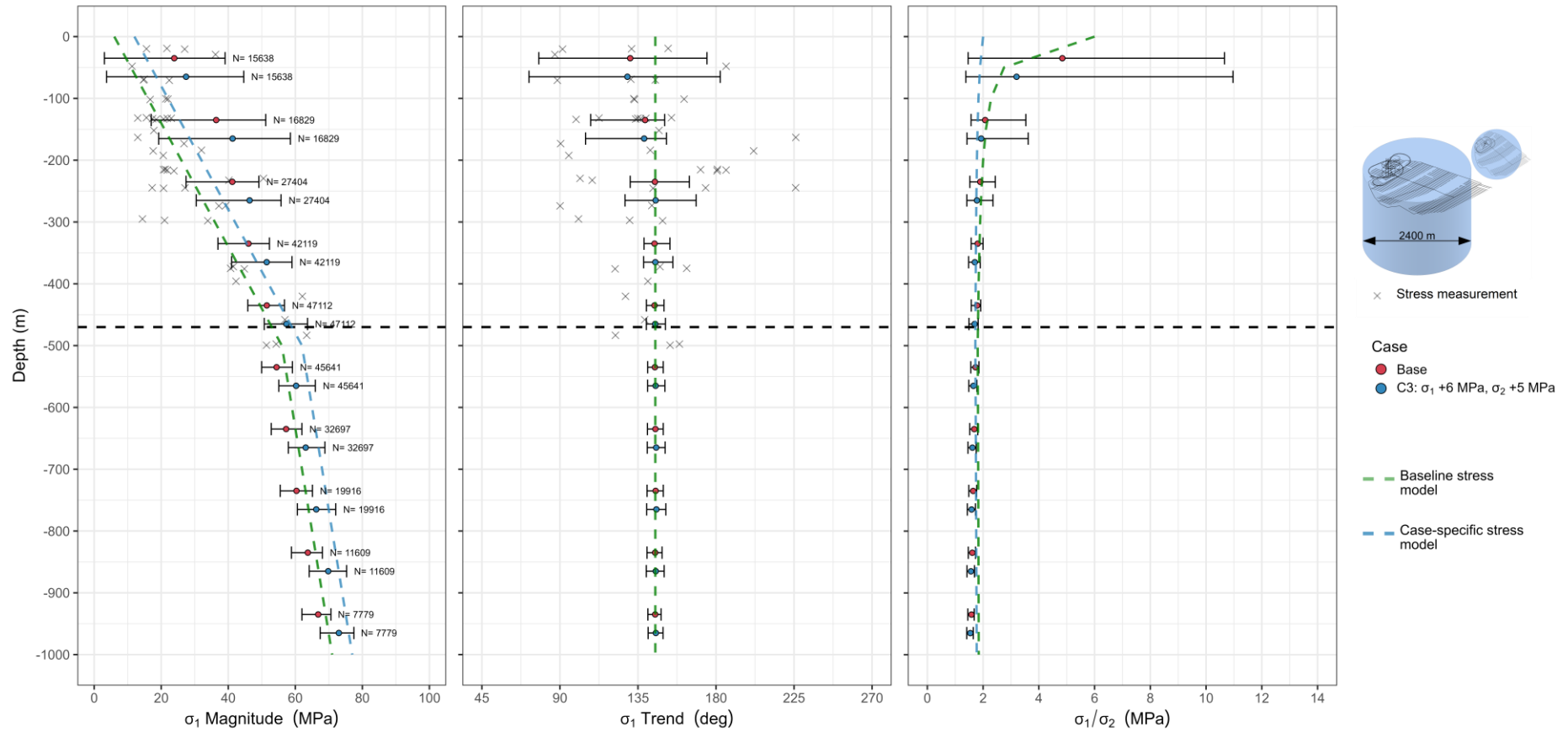


Figure A4- 6. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 3 after glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target ratio of σ_1/σ_2 for case 3. Field stress measurements indicated with grey "x" markers.

Cylinder data: Pre-Glacial

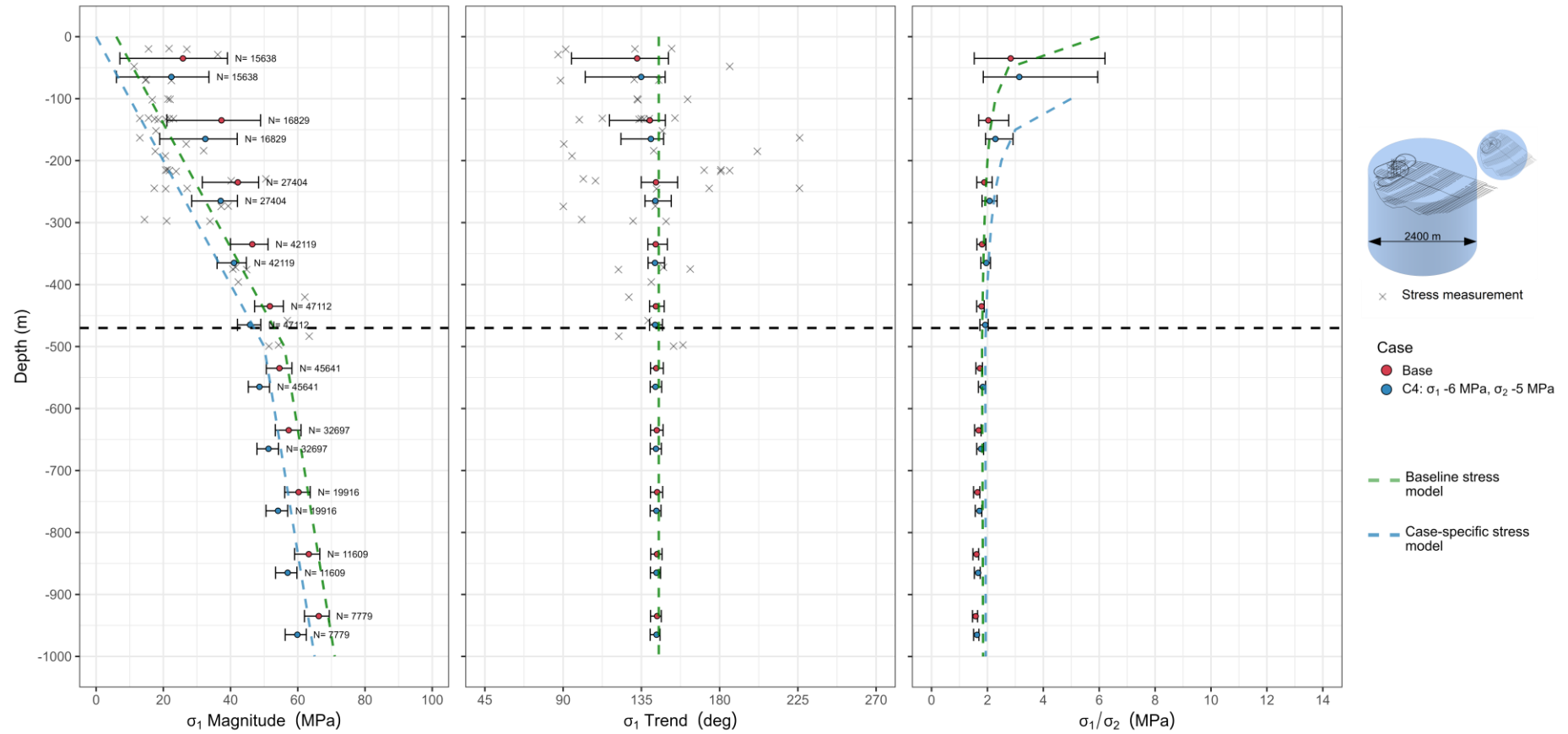


Figure A4- 7. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 4 before glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target ratio of σ_1/σ_2 for case 4. Field stress measurements indicated with grey “x” markers.

Cylinder data: Post-Glacial

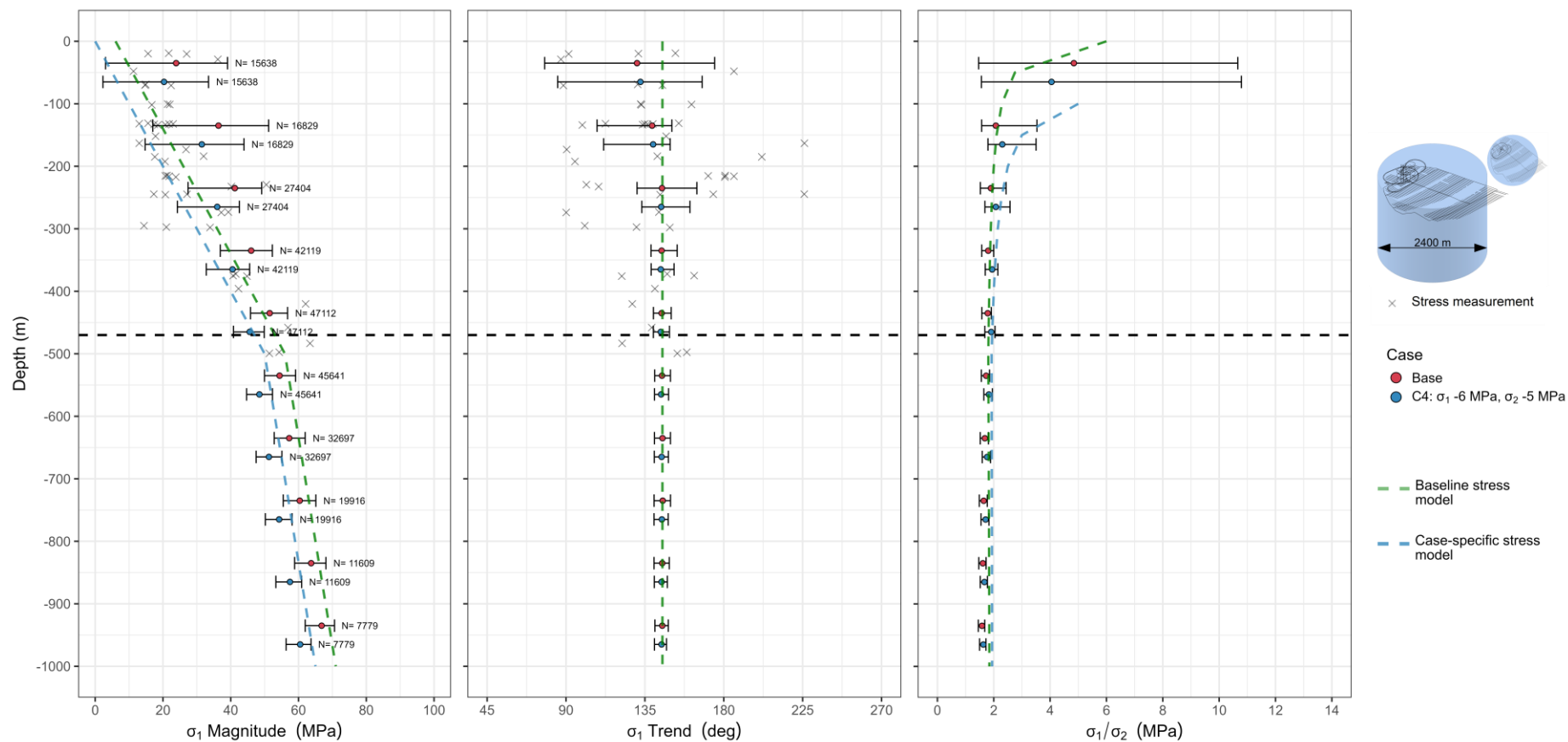


Figure A4- 8. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 4 after glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dashed line indicates the target ratio of σ_1/σ_2 for case 4. Field stress measurements indicated with grey "x" markers.

Cylinder data: Pre-Glacial

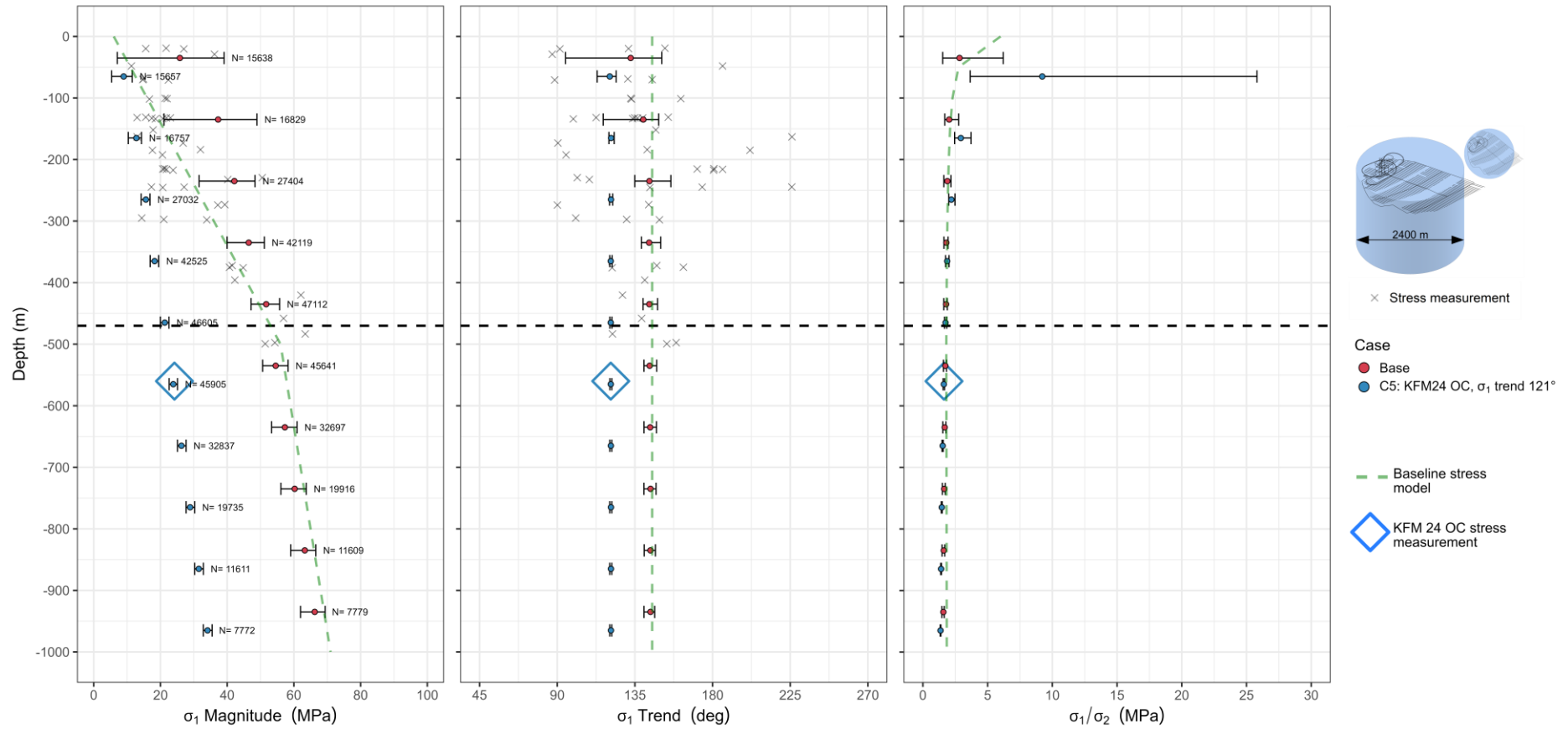


Figure A4- 9. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 5 before glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dots indicate the target ratio of σ_1/σ_2 for case 5, based on KFM24 OC stress measurement. Field stress measurements indicated with grey “x” markers.

Cylinder data: Post-Glacial

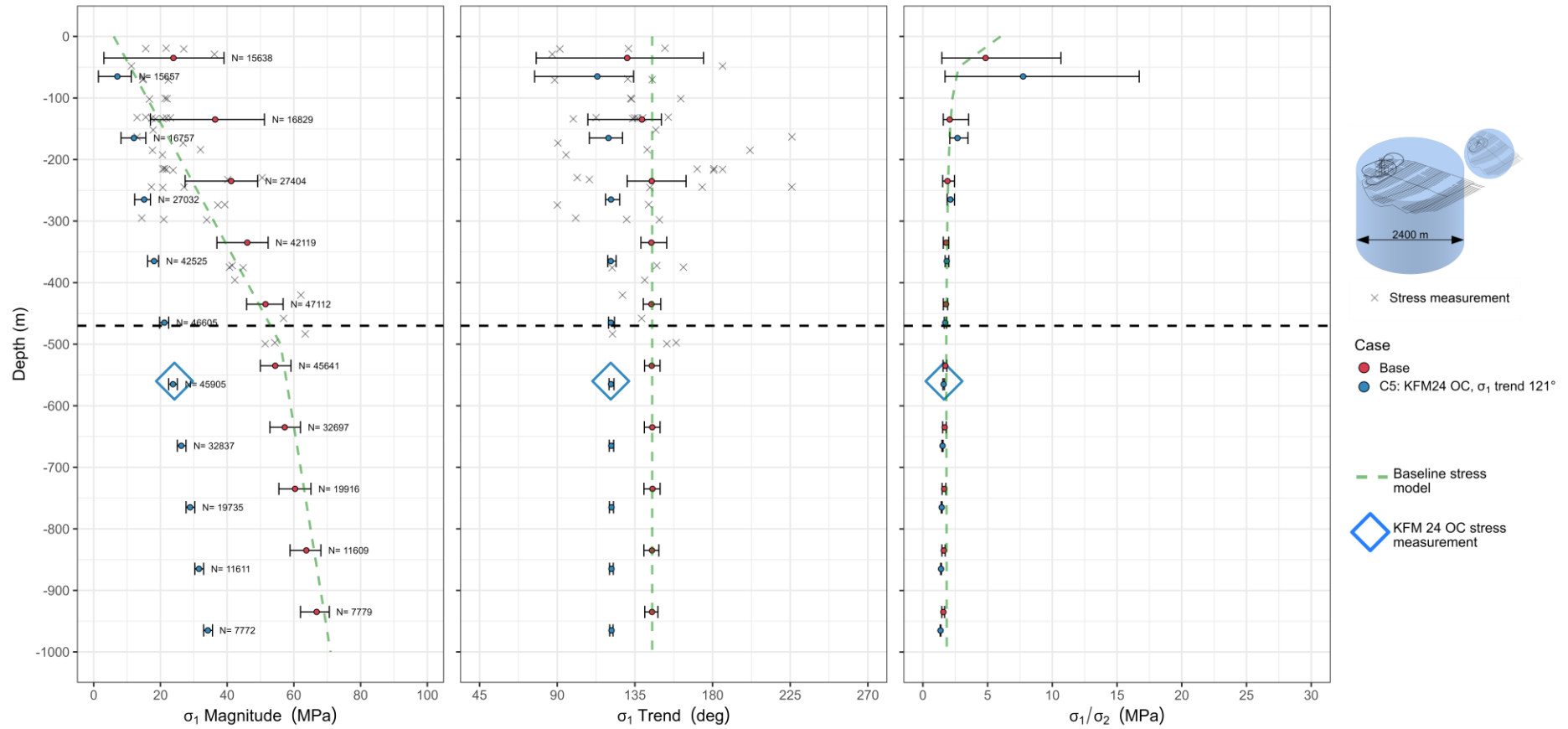


Figure A4- 10. Mean and 95% variation interval of σ_1 magnitude, trend and the ratio of σ_1 and σ_2 at hundred meter intervals for the Base case and case 5 after glaciation for a cylinder covering the repository footprint. The Baseline stress model is indicated with a green dashed line and the repository depth with a horizontal dashed black line. The blue dots indicate the target ratio of σ_1/σ_2 for case 5, based on KFM24 OC stress measurement. Field stress measurements indicated with grey "x" markers.

Appendix 5. Principal stress mean and variation for hundred meter intervals (95 % variation interval) vs stress measurements

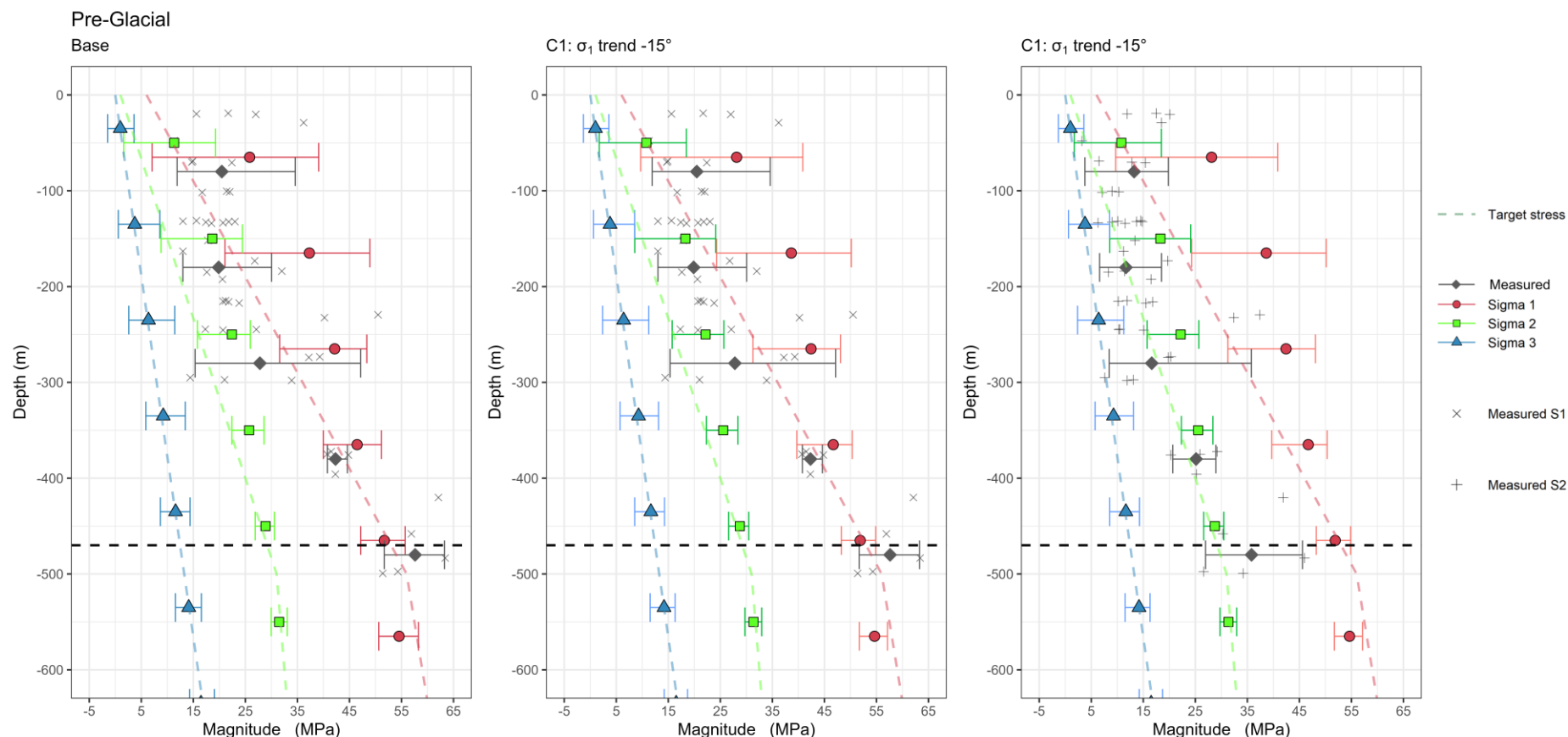


Figure A5- 1. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 1 simulations before glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey "+" or "x" symbols, with the mean and 95% variation interval also in grey.

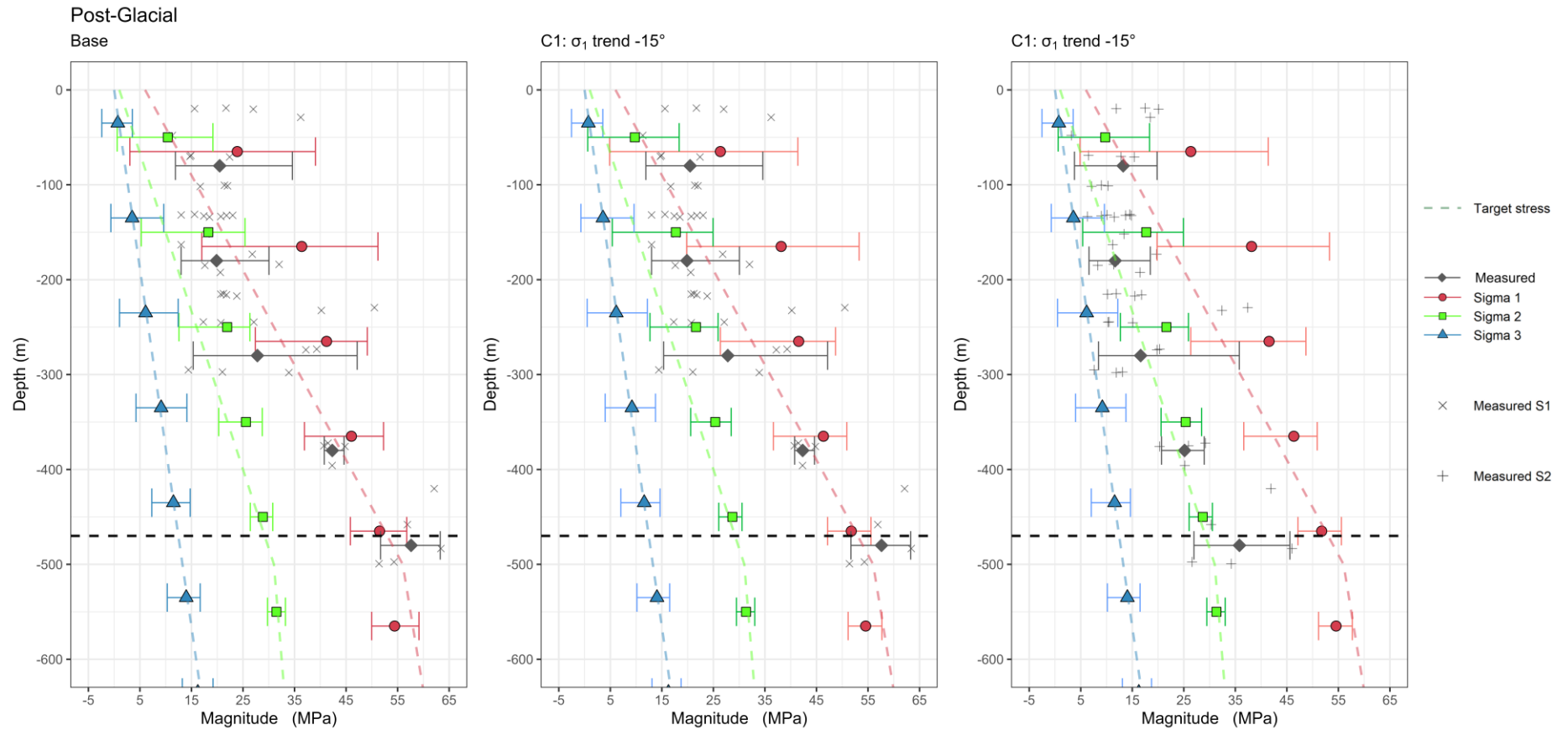


Figure A5- 2. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 1 simulations after glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

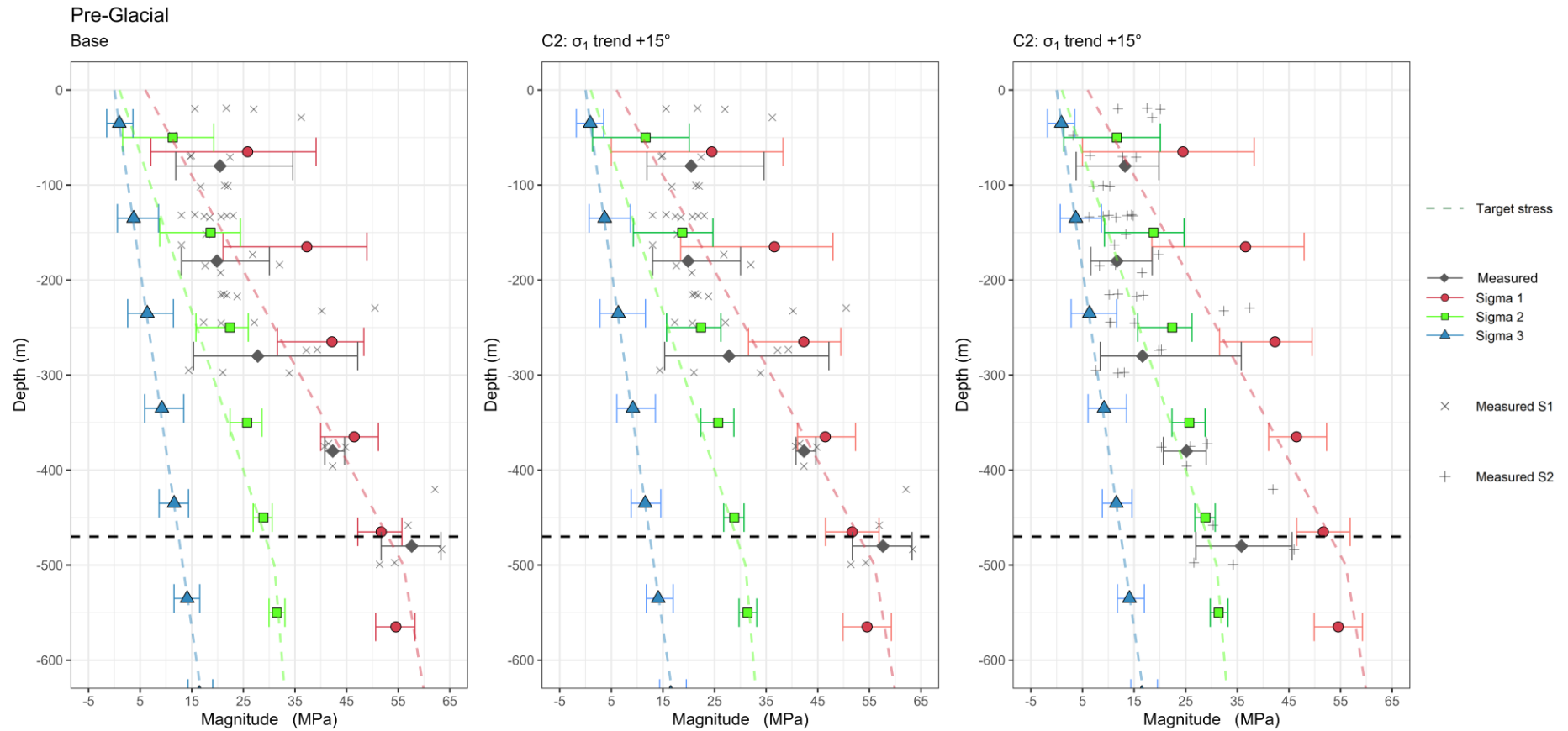


Figure A5- 3. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 2 simulations before glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

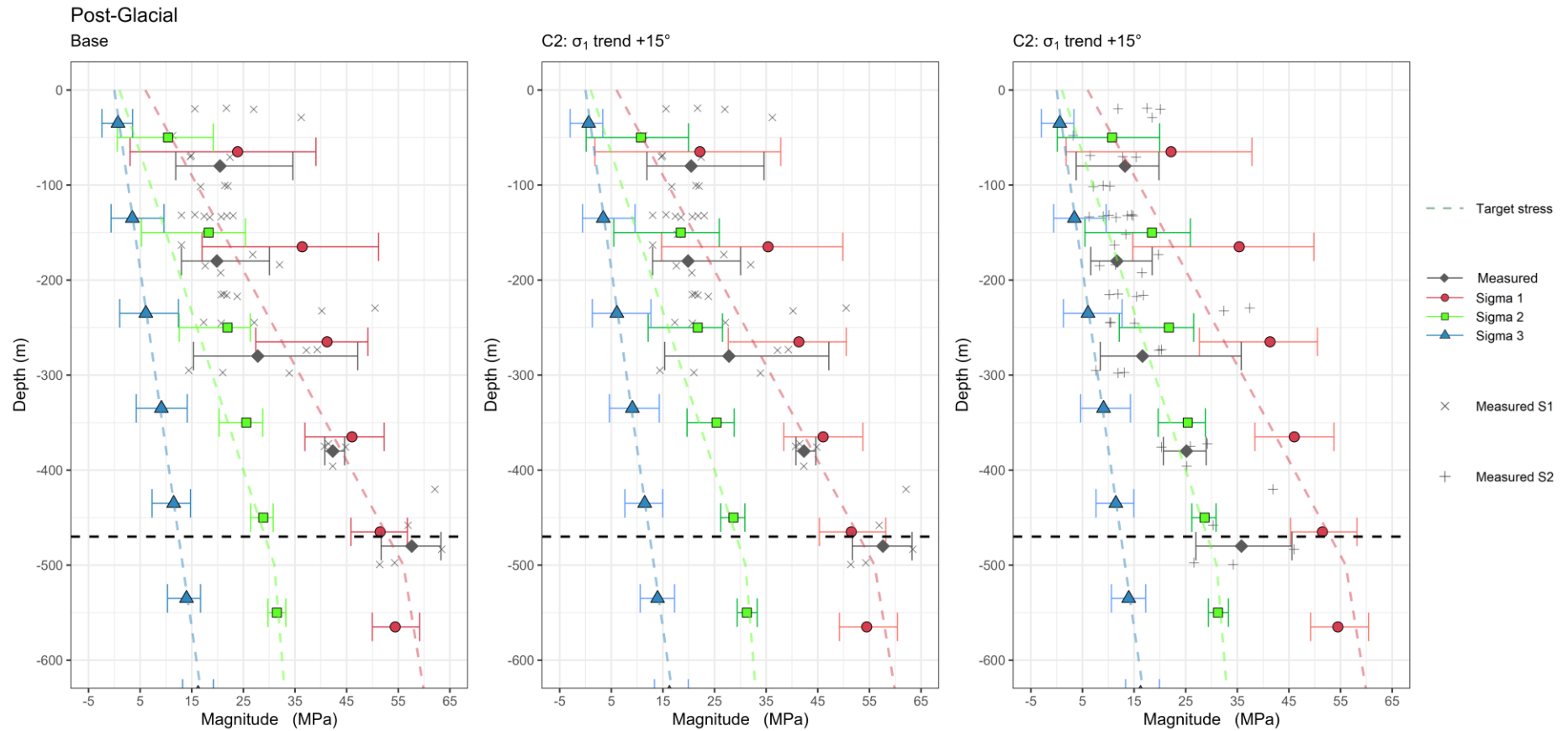


Figure A5- 4. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 2 simulations after glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

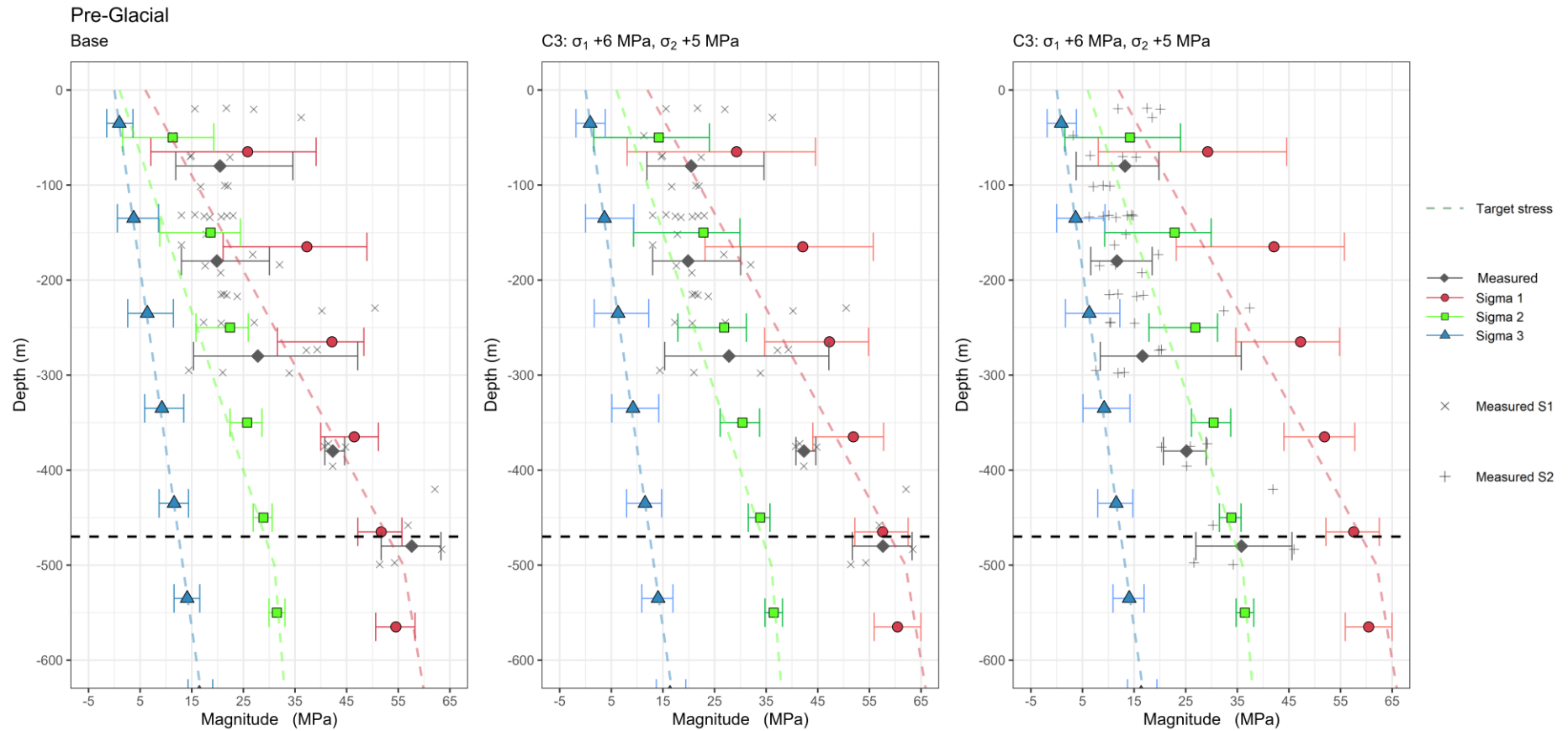


Figure A5- 5. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 3 simulations before glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

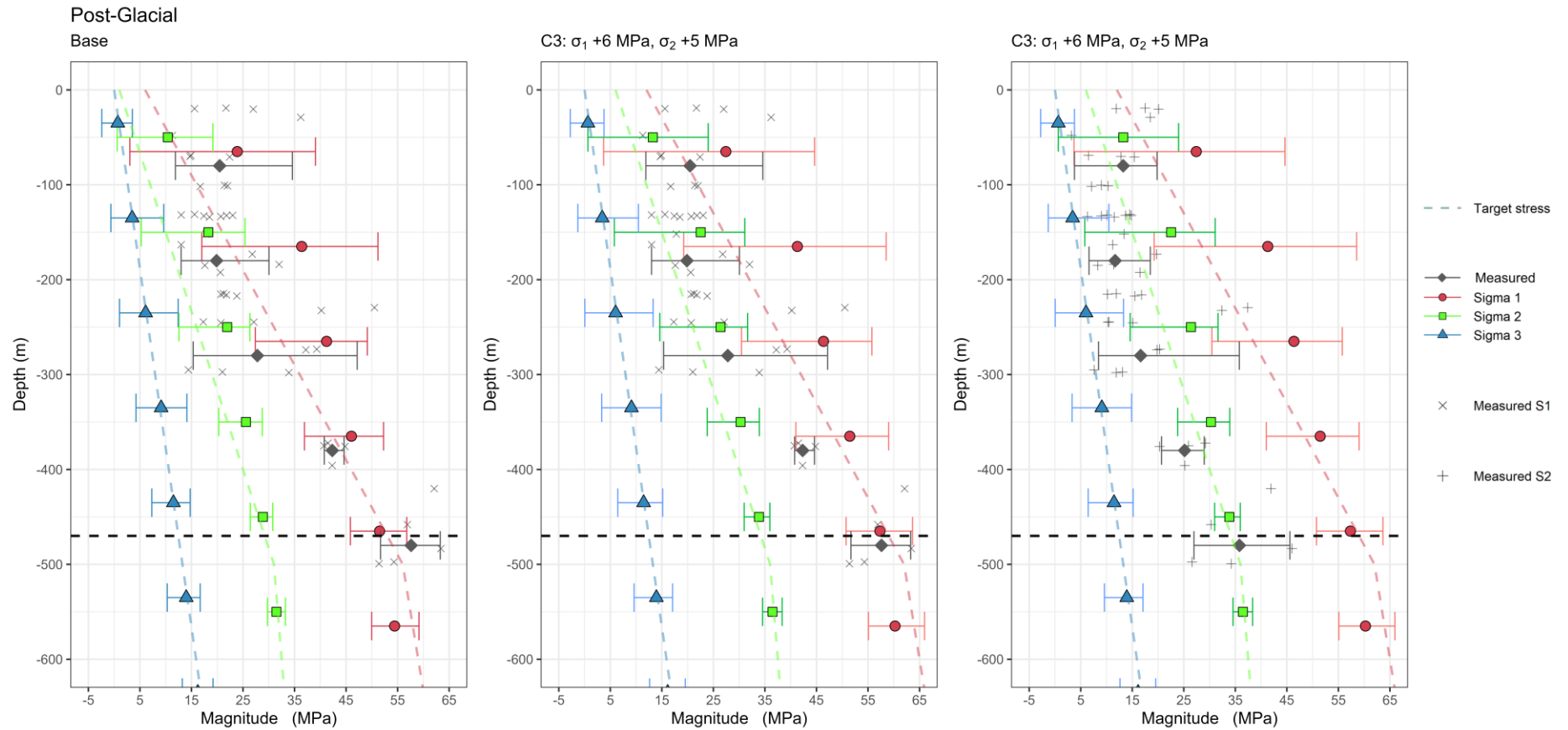


Figure A5- 6. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 3 simulations after glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

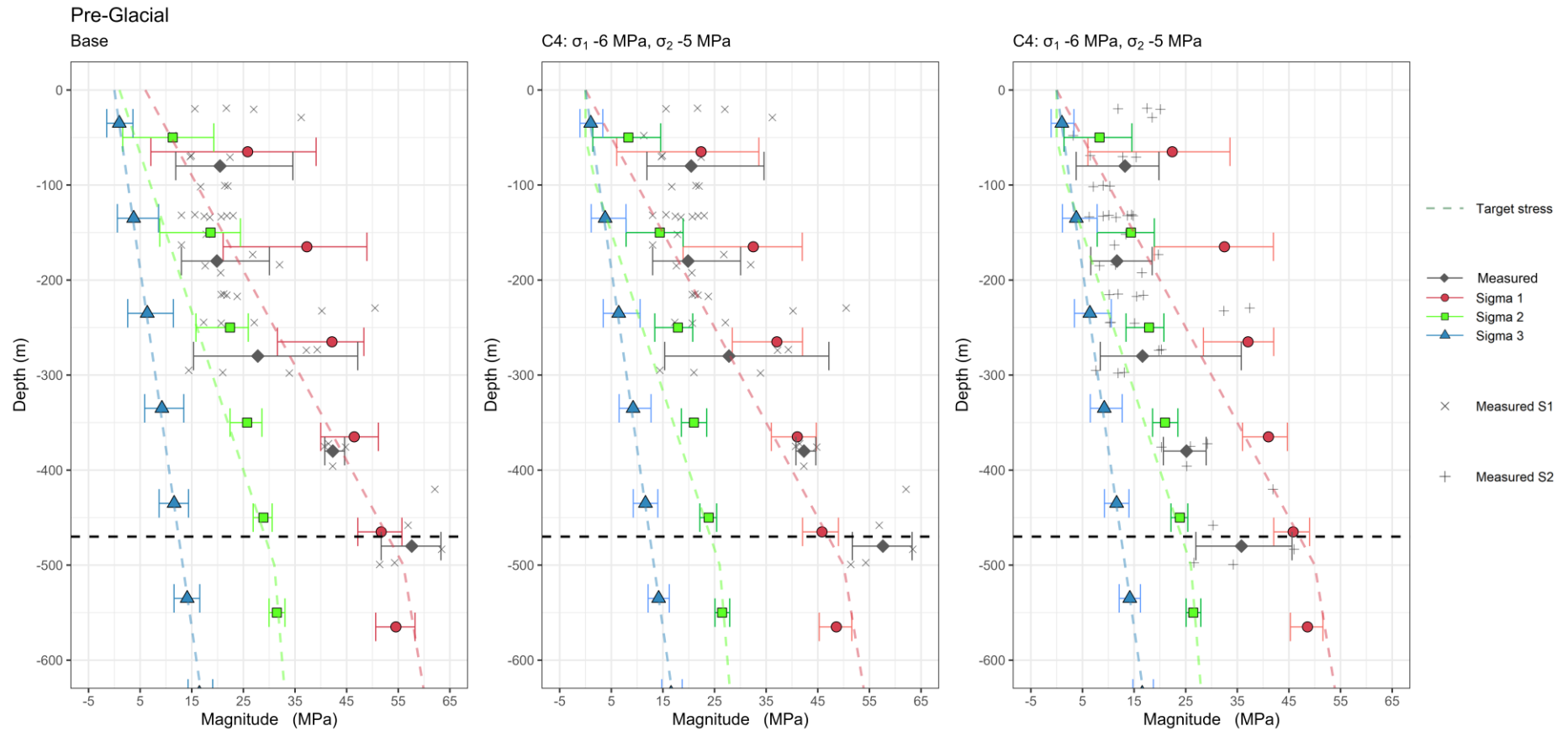


Figure A5- 7. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 4 simulations before glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

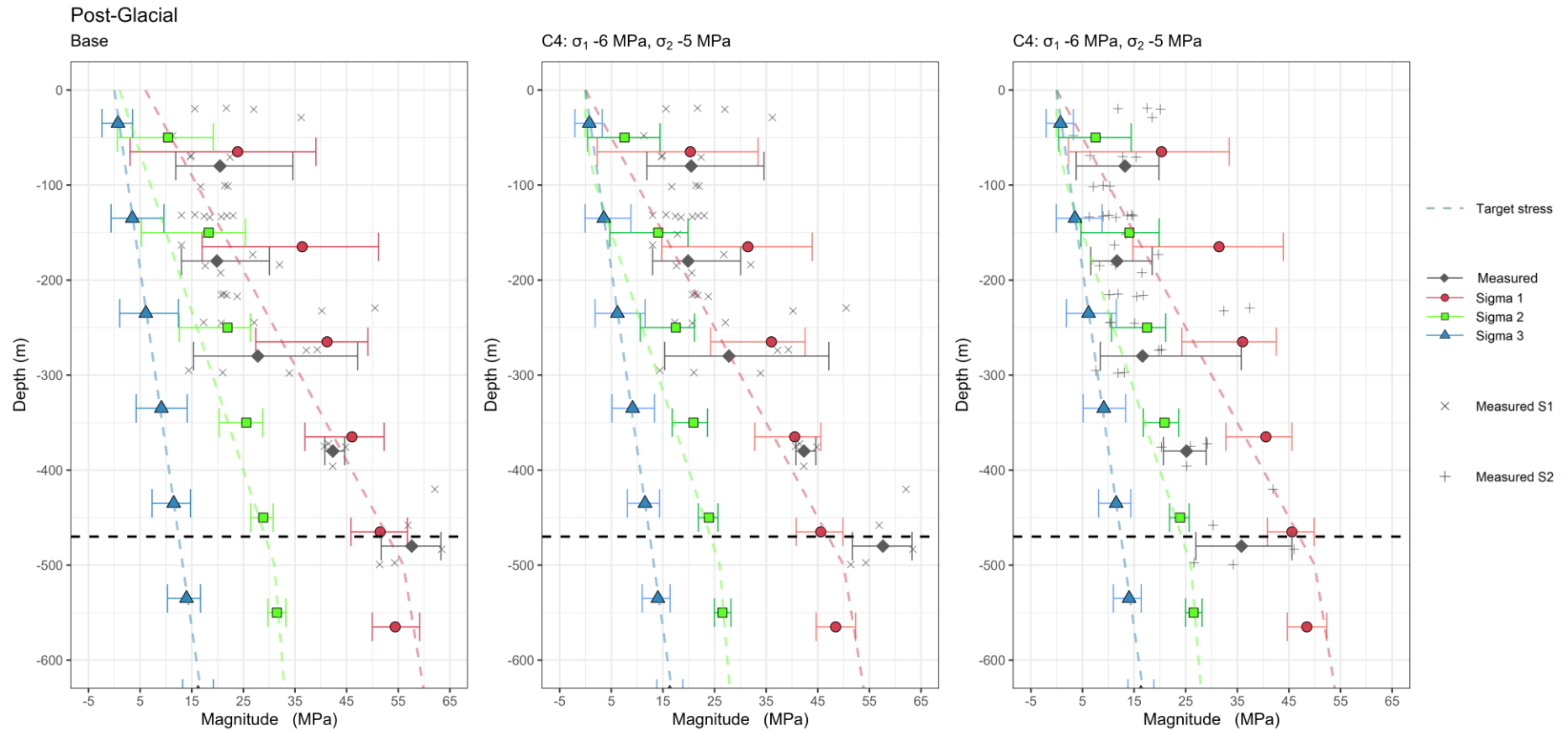


Figure A5- 8. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 4 simulations after glaciation from a cylinder covering the repository. The target stresses are indicated with coloured dashed lines and the repository depth with a horizontal dashed black line. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

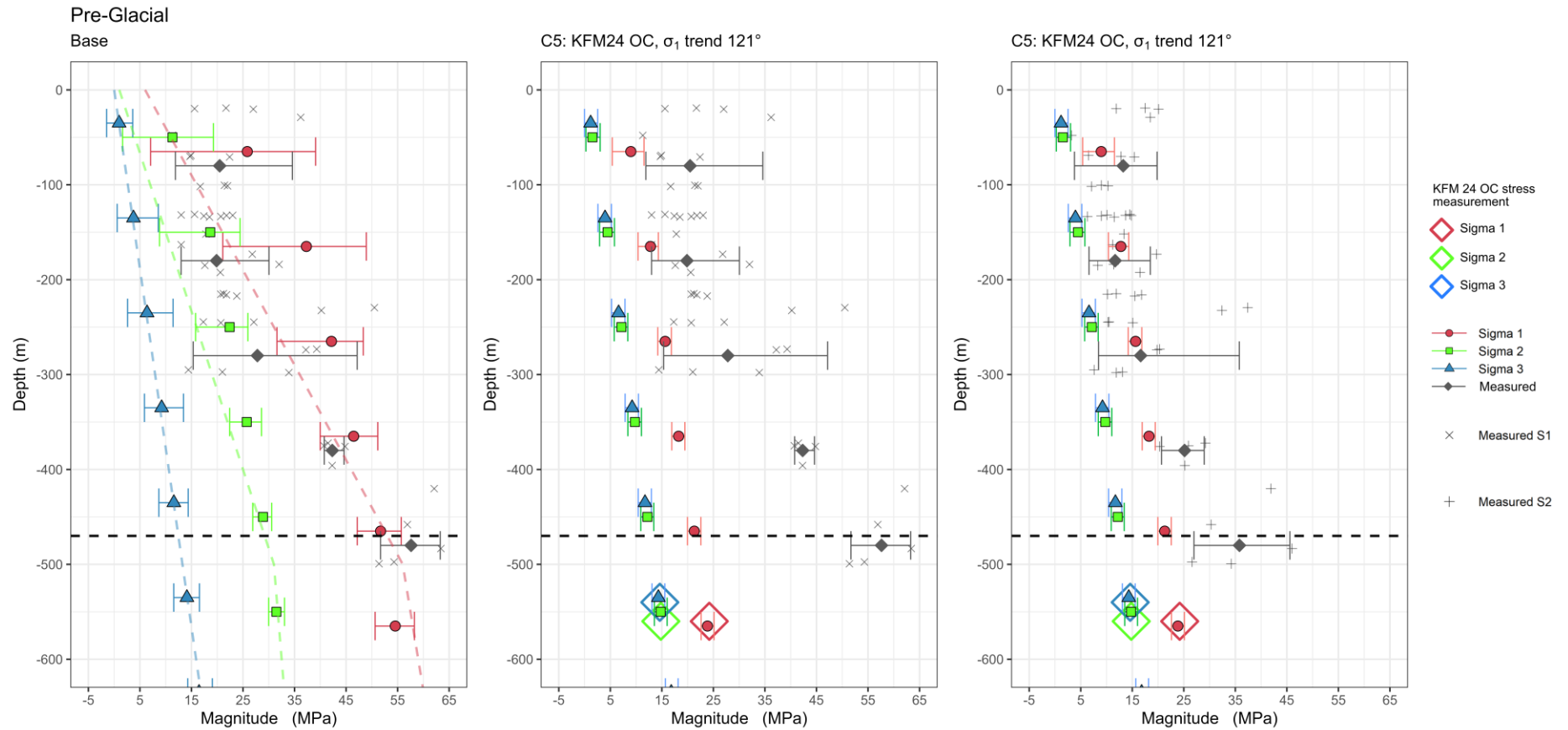


Figure A5- 9. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 5 simulations before glaciation from a cylinder covering the repository. The Baseline stress model is indicated with coloured dashed lines and the repository depth with a horizontal dashed black line, whereas the KFM24 OC stress measurement is presented at the -560m depth with diamonds. Field stress measurements indicated with grey “+” or “x” symbols, with the mean and 95% variation interval also in grey.

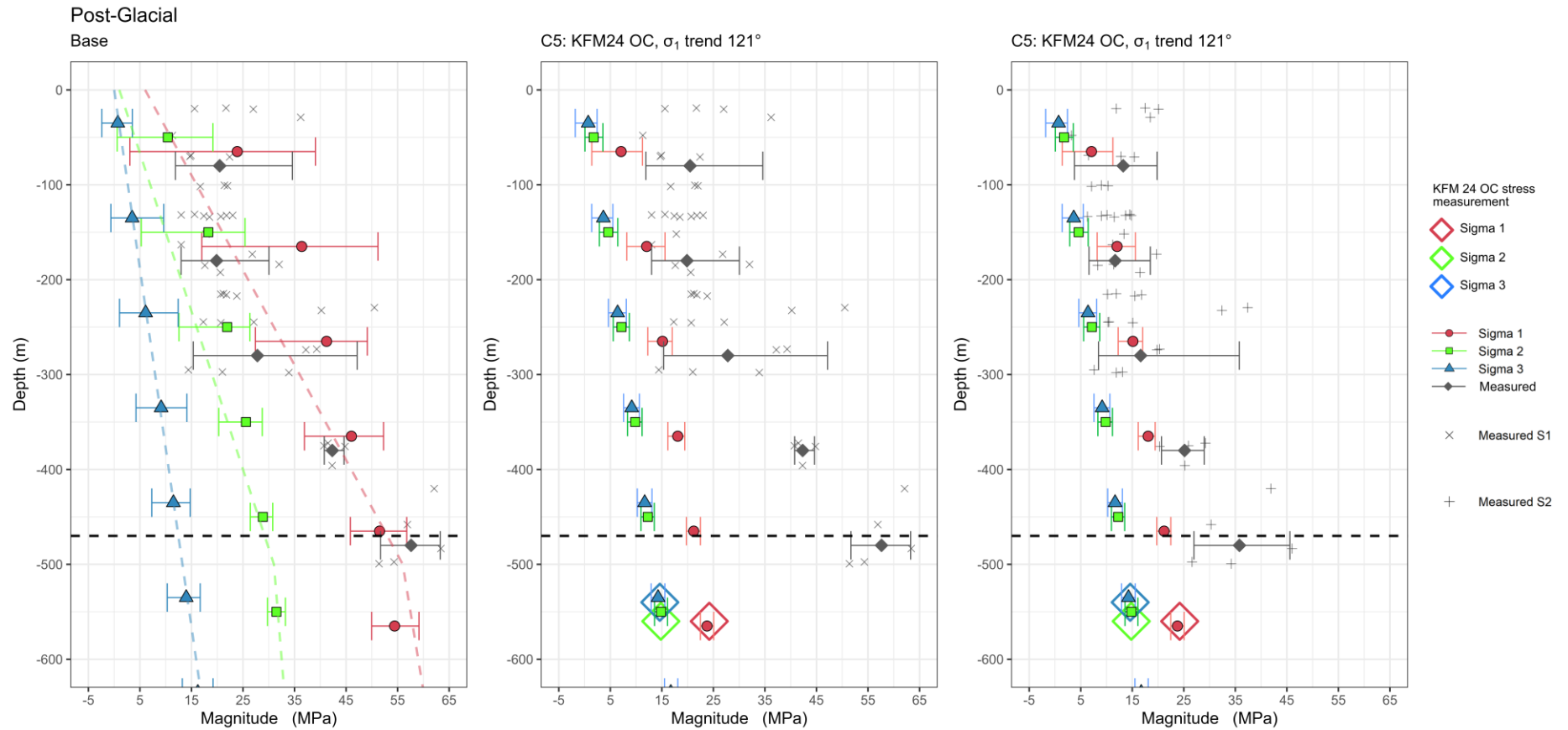


Figure A5- 10. Mean and 95% variation interval of the principal stress magnitudes versus measured stresses at hundred meter intervals for the Base case and case 5 simulations after glaciation from a cylinder covering the repository. The Baseline stress model is indicated with coloured dashed lines and the repository depth with a horizontal dashed black line, whereas the KFM24 OC stress measurement is presented at the -560m depth with diamonds. Field stress measurements indicated with grey "+" or "x" symbols, with the mean and 95% variation interval also in grey.

Appendix 6. Principal stress lower hemisphere projections

Pre-Glacial cylinder data, depth 400-500 m

Base

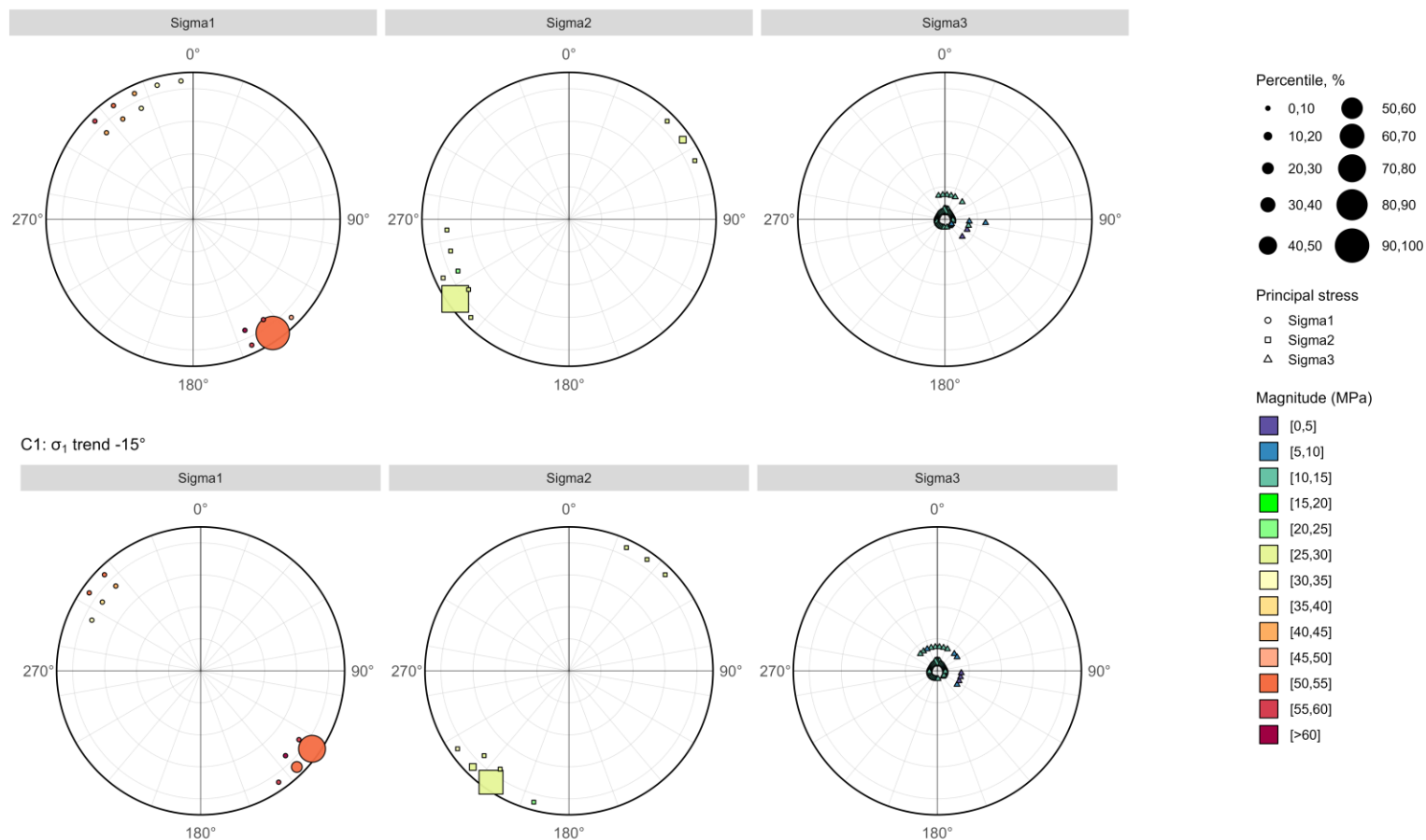
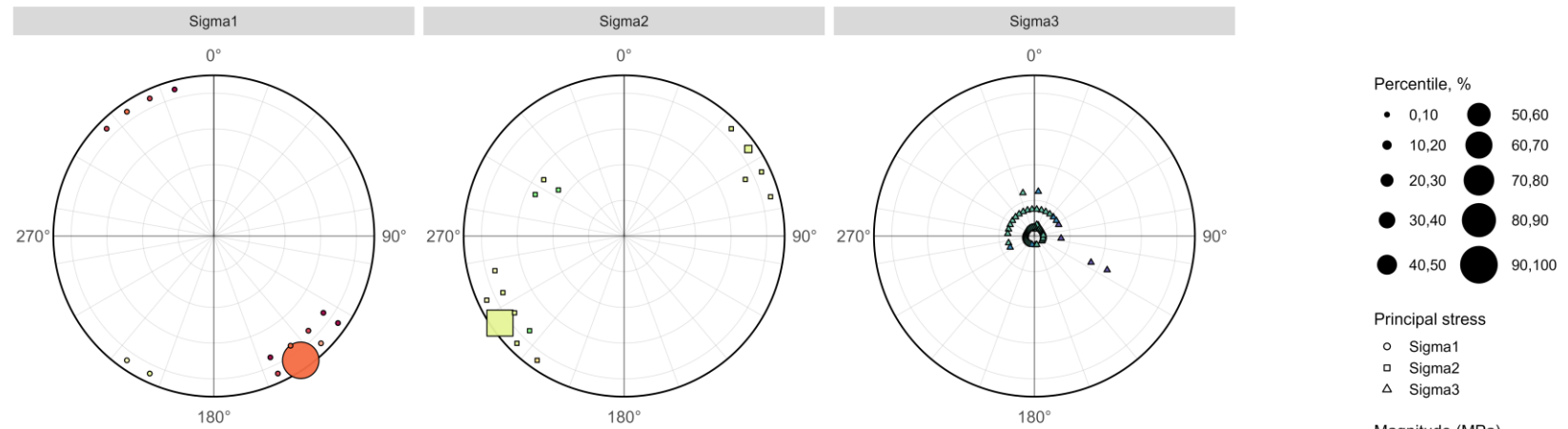


Figure A6- 1. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 1 simulations before glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Post-Glacial cylinder data, depth 400-500 m

Base



C1: σ_1 trend -15°

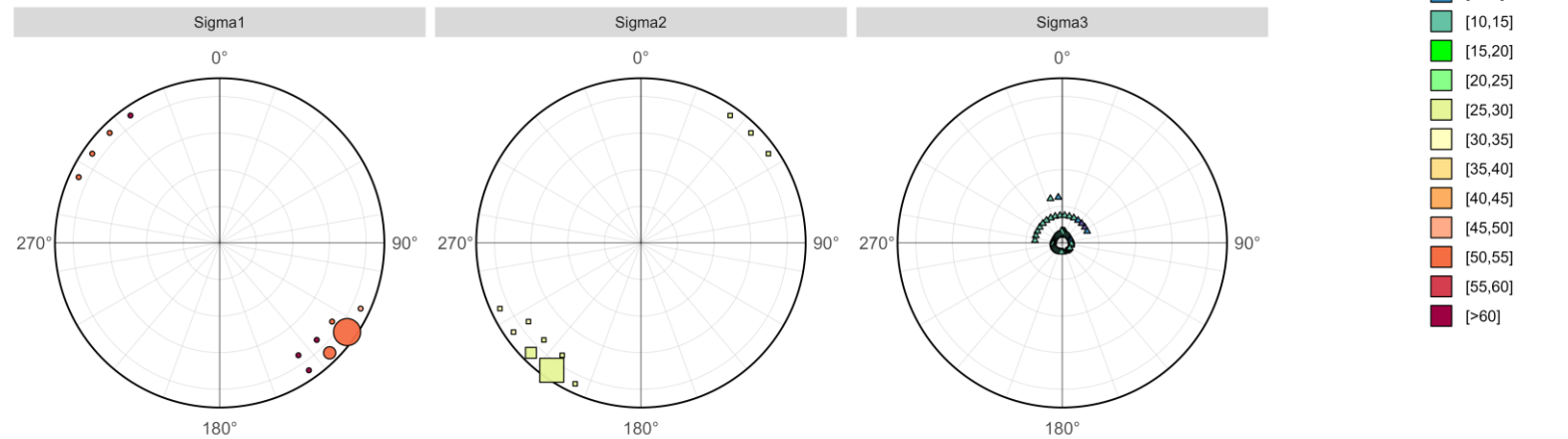


Figure A6- 2. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 1 simulations after glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Pre-Glacial cylinder data, depth 400-500 m

Base

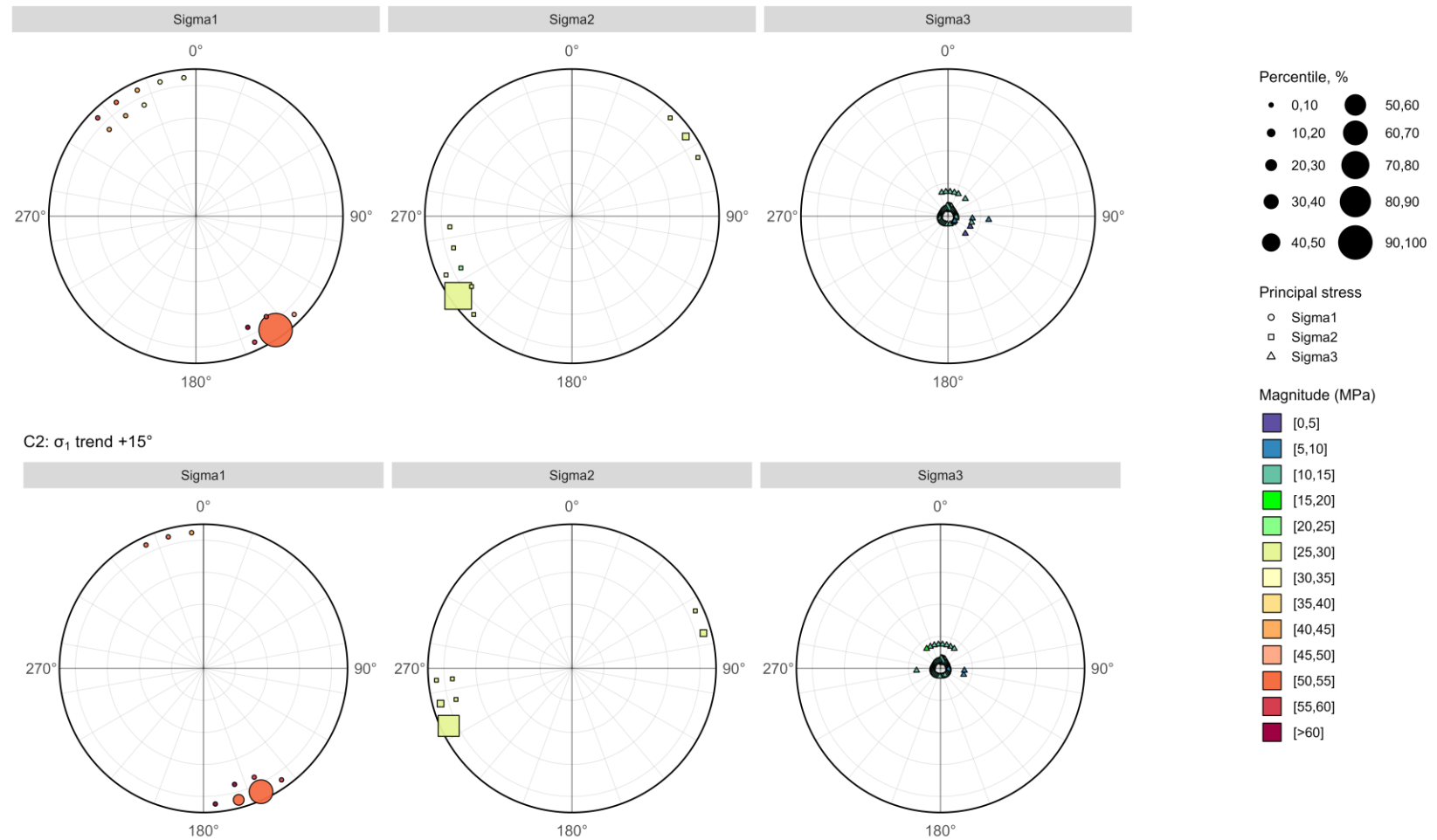


Figure A6- 3. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 2 simulations before glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Post-Glacial cylinder data, depth 400-500 m

Base

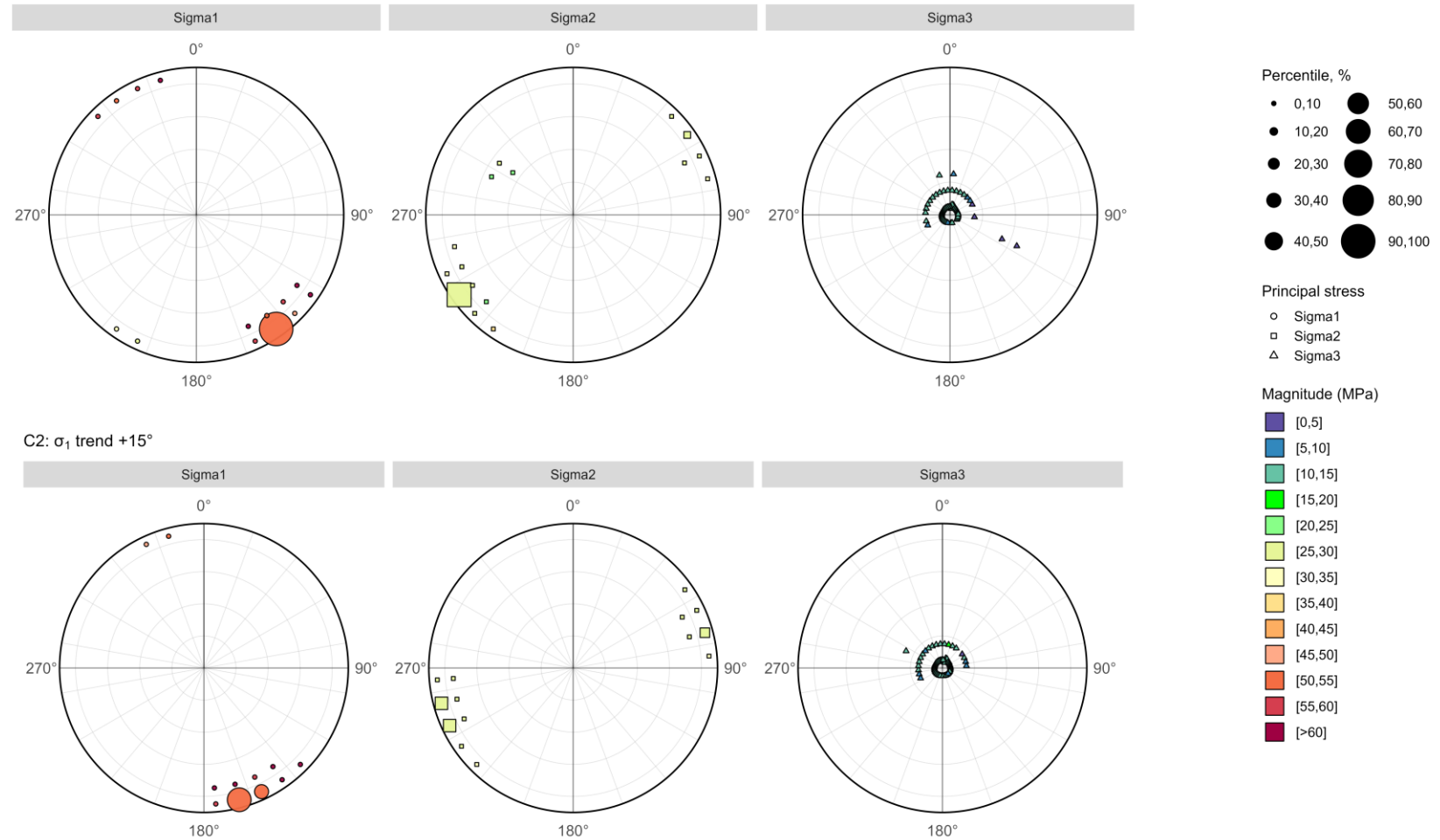


Figure A6- 4. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 2 simulations after glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Pre-Glacial cylinder data, depth 400-500 m

Base

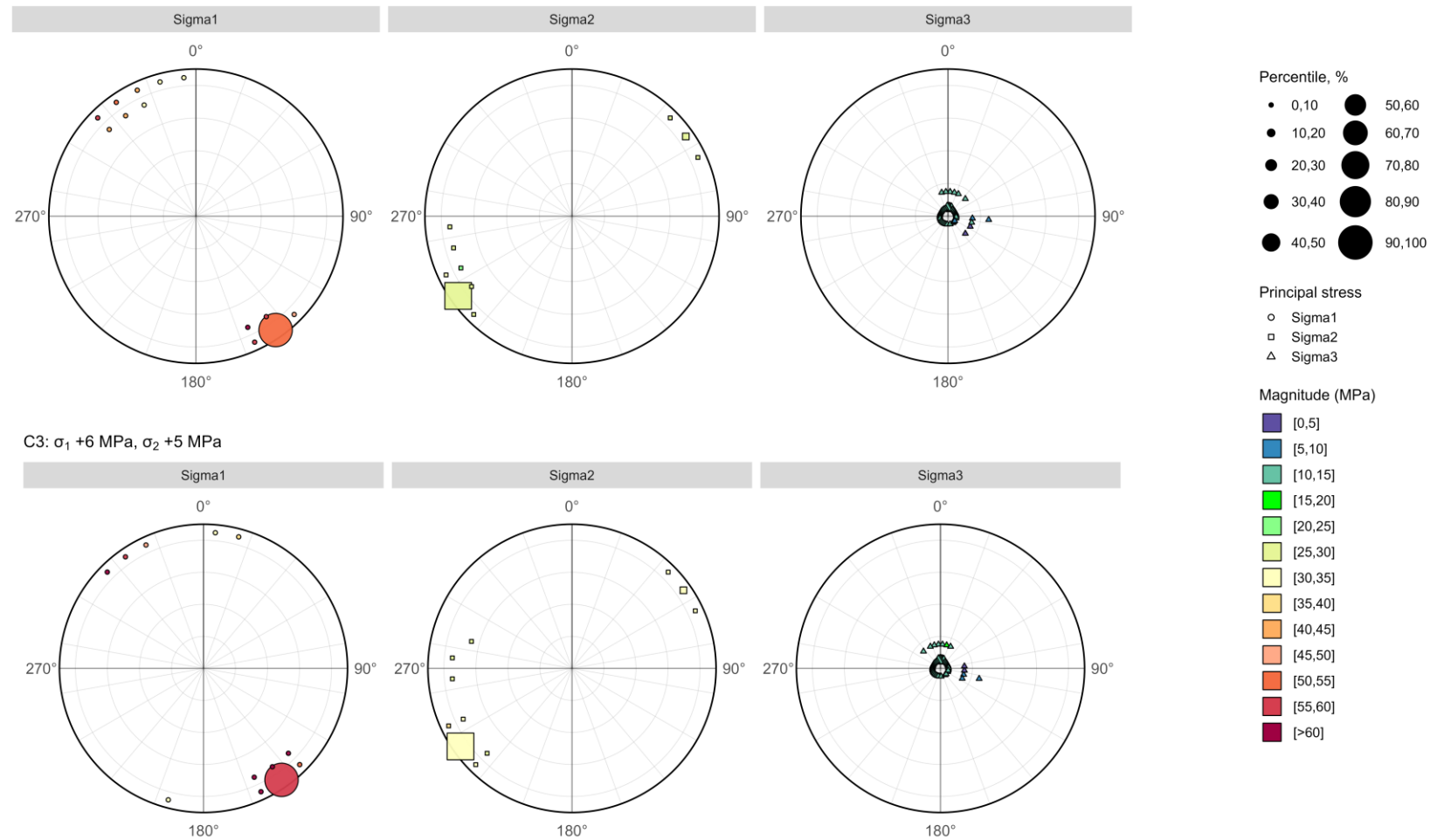


Figure A6- 5. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 3 simulations before glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Post-Glacial cylinder data, depth 400-500 m

Base

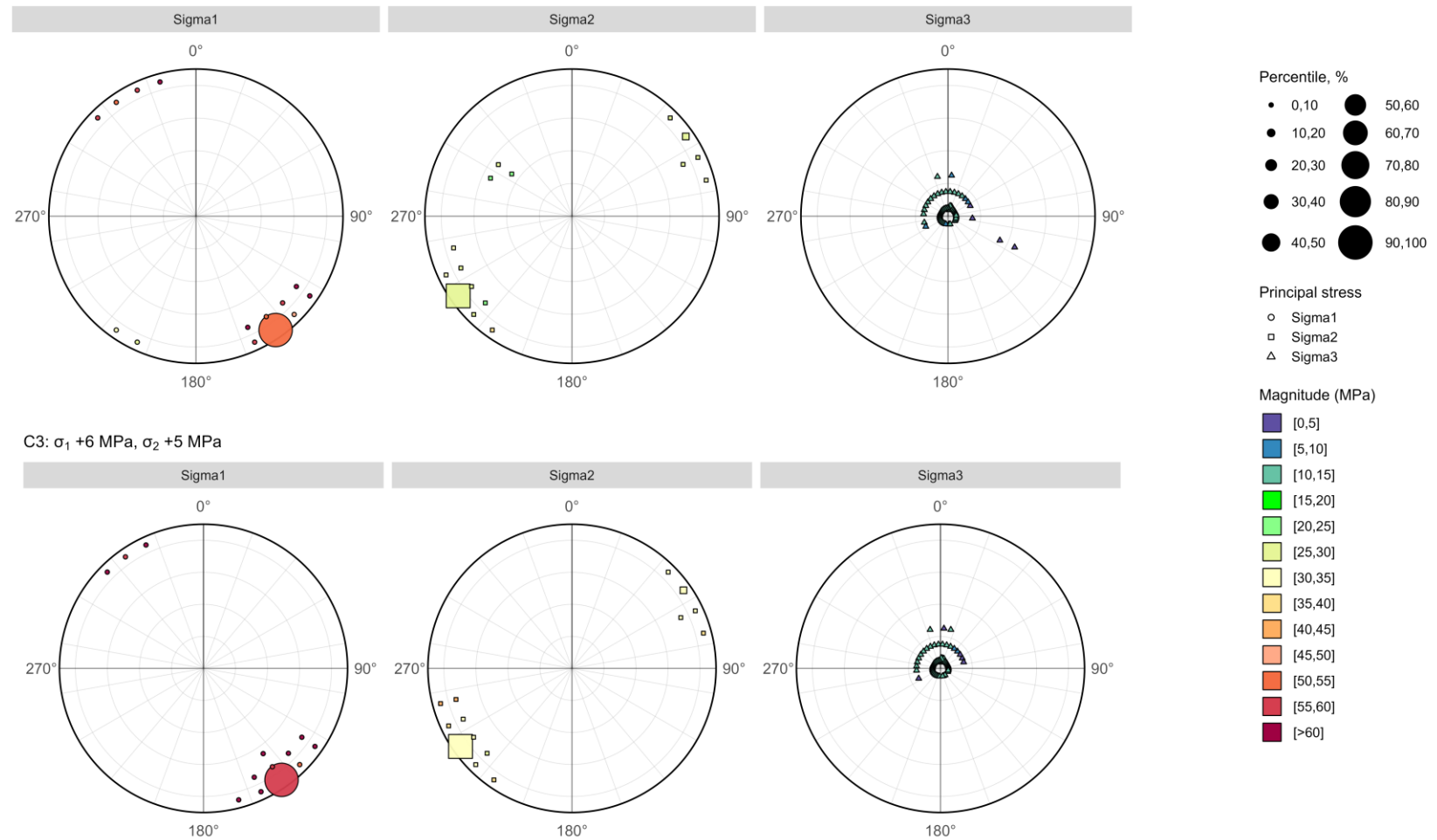


Figure A6- 6. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 3 simulations after glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Pre-Glacial cylinder data, depth 400-500 m

Base

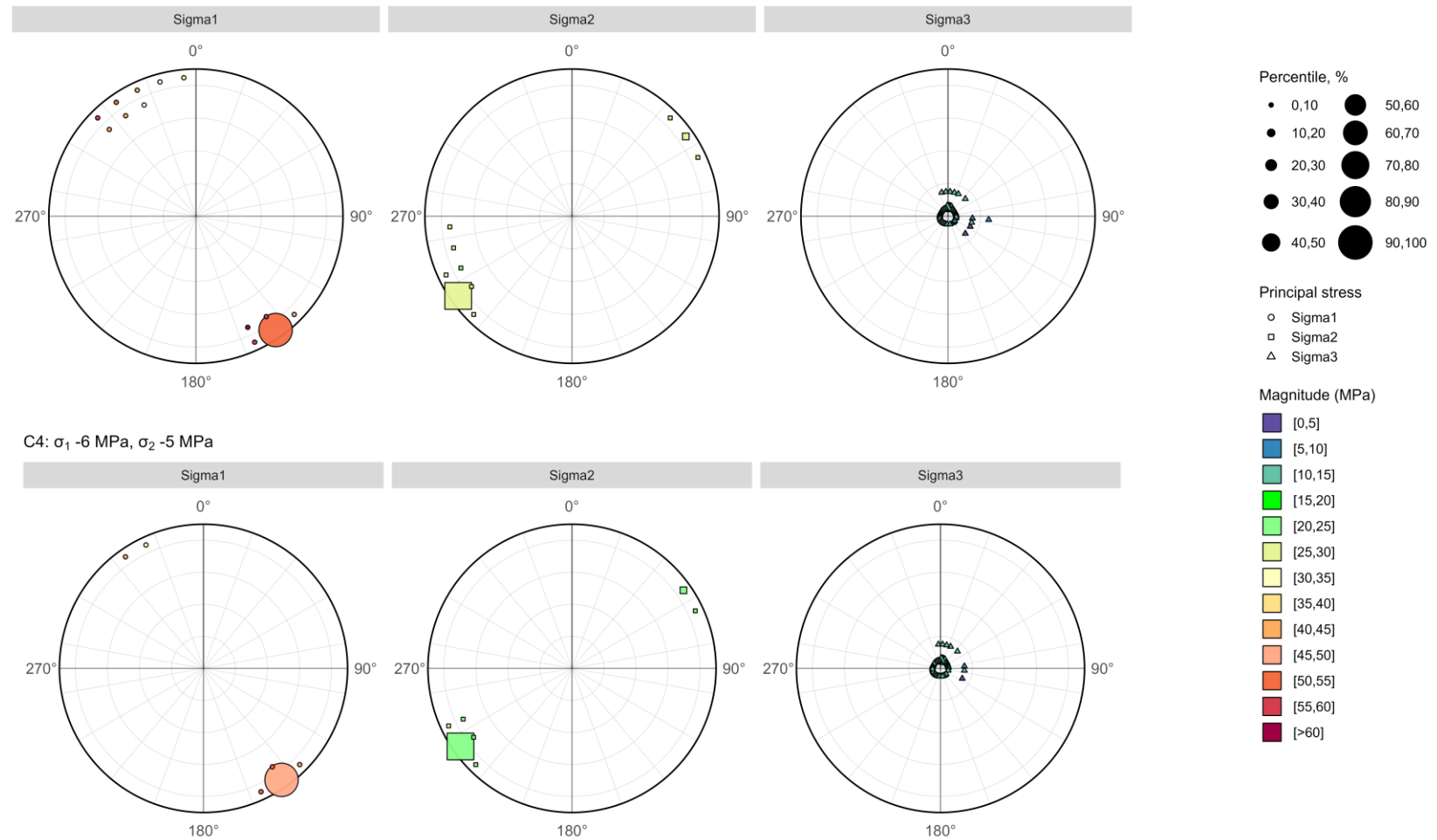
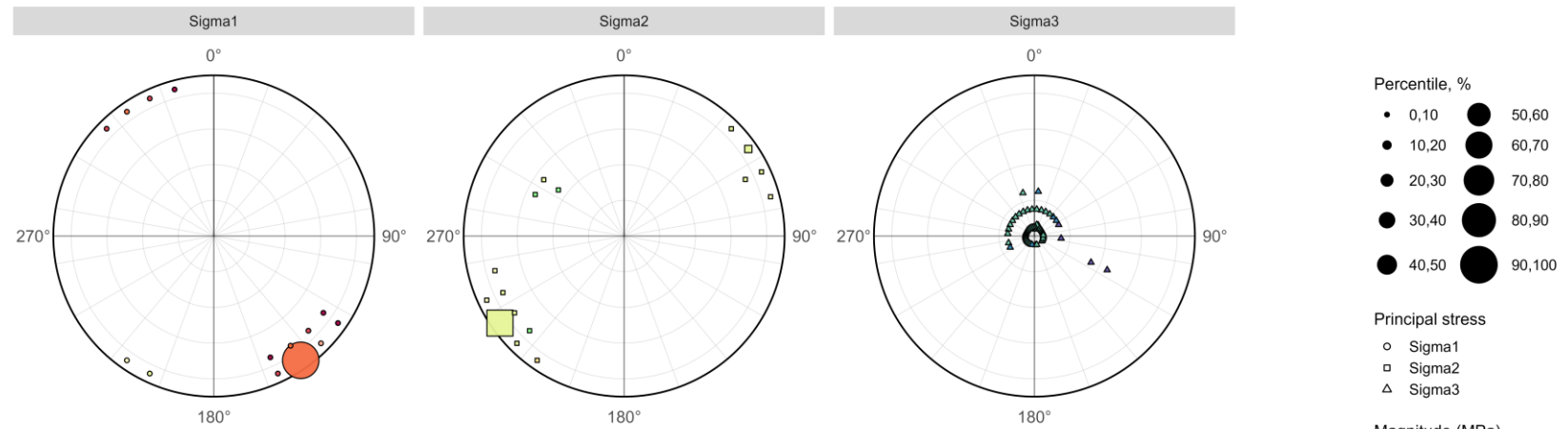


Figure A6- 7. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 4 simulations before glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Post-Glacial cylinder data, depth 400-500 m

Base



C4: σ_1 -6 MPa, σ_2 -5 MPa

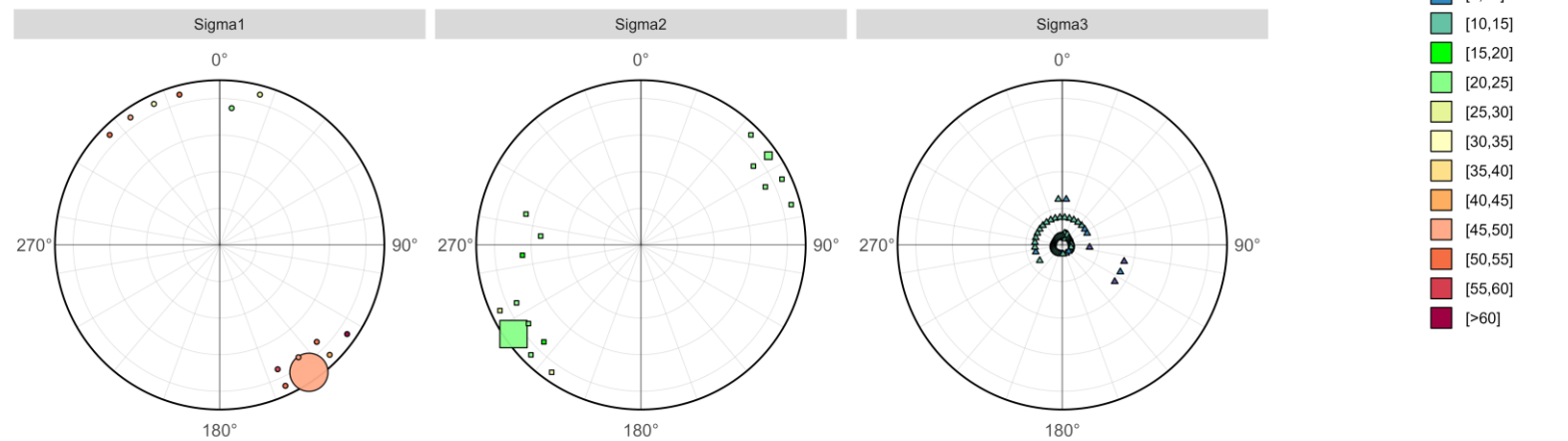


Figure A6- 8. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 4 simulations after glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Pre-Glacial cylinder data, depth 400-500 m

Base

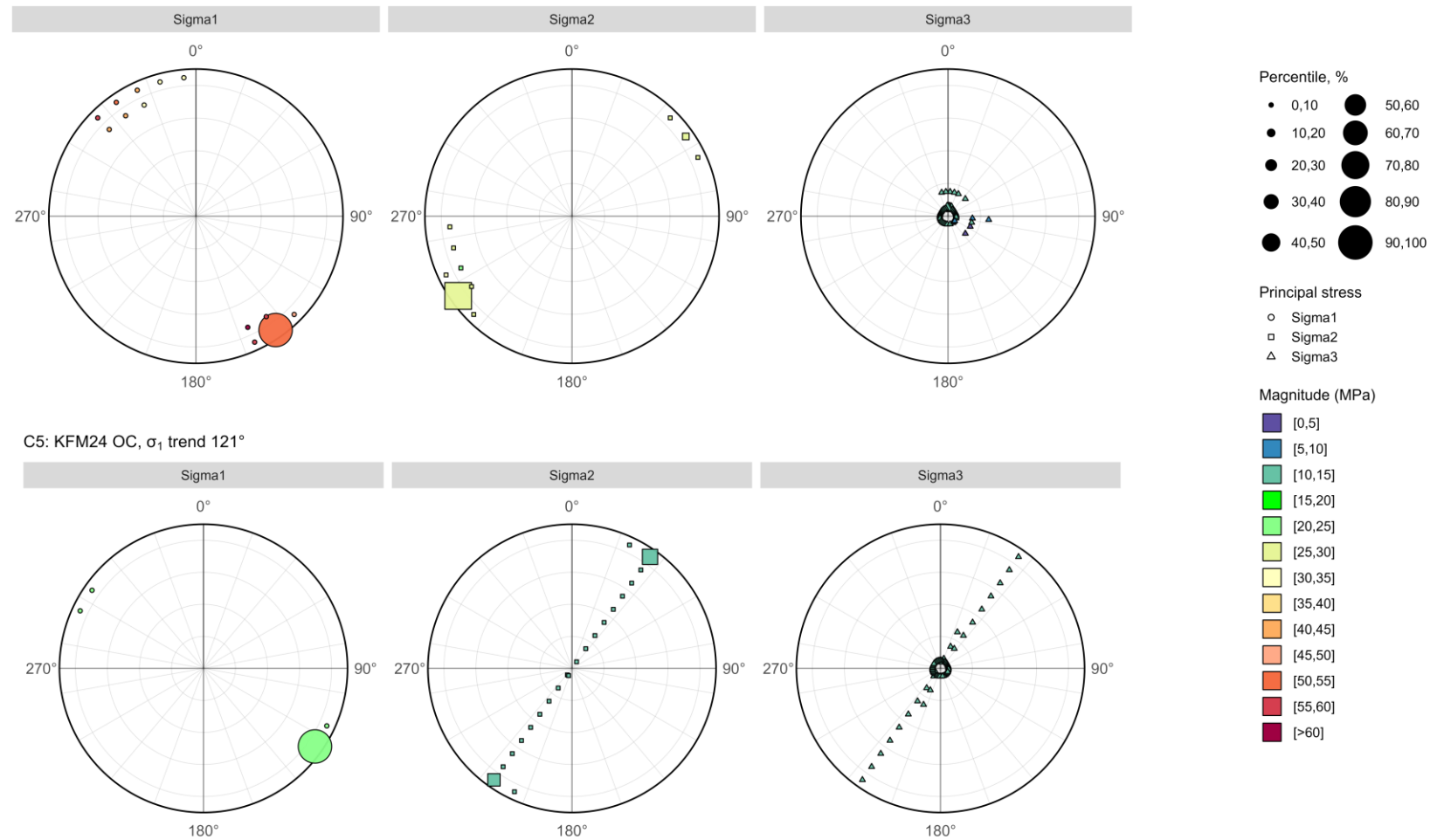


Figure A6- 9. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 5 simulations before glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Post-Glacial cylinder data, depth 400-500 m

Base

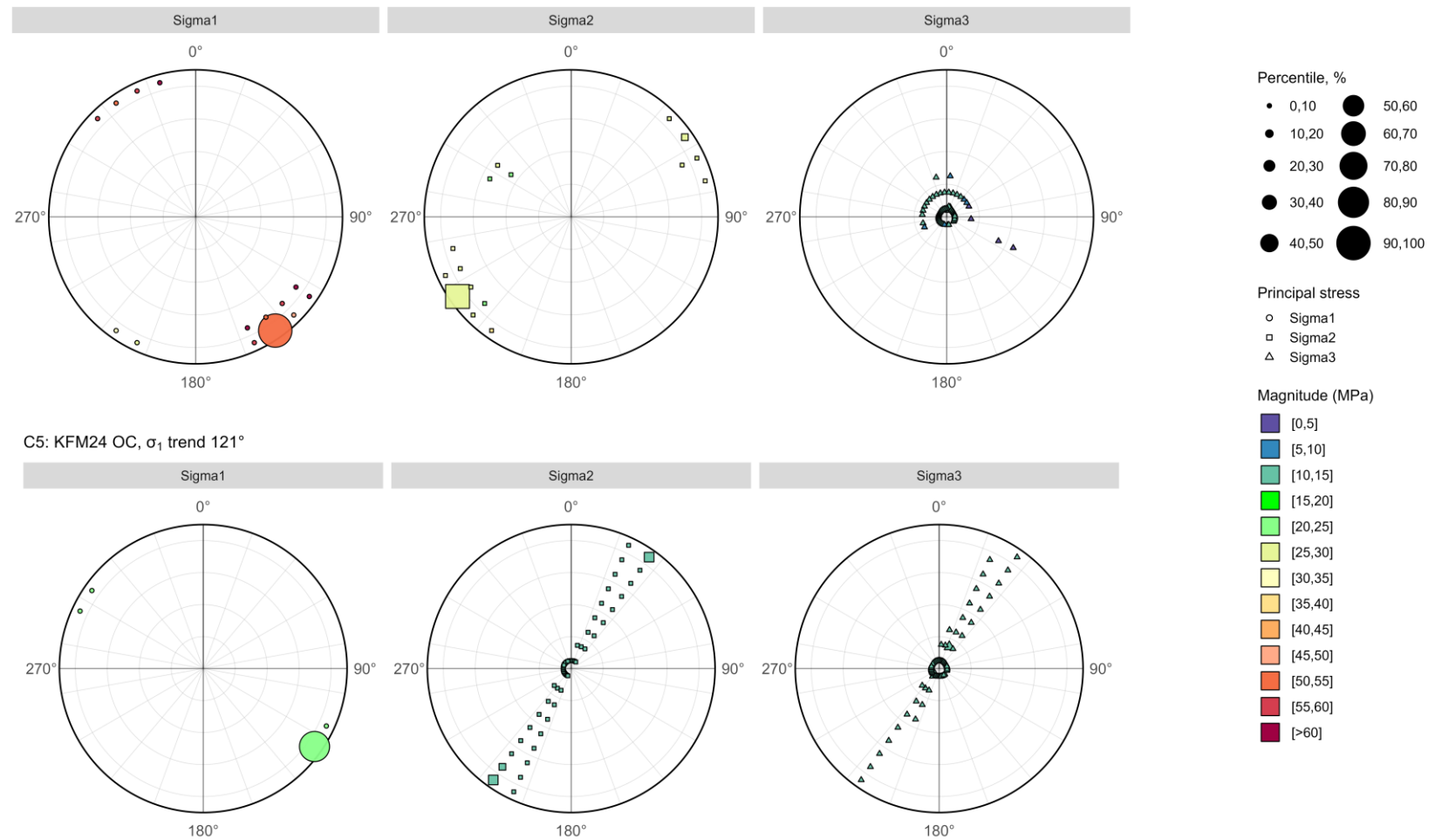


Figure A6- 10. Lower hemisphere projection polar plot of the principal stresses at 20° intervals obtained from a depth section of a cylinder covering the repository footprint (Figure 4-1) for the Base case and case 5 simulations after glaciation, coloured according to magnitude and symbol sizes by percentile. $z = 400 - 500$ m.

Appendix 7. Frequency of σ_1 trend and magnitude variation at repository depth

Repository depth data: Pre-Glacial

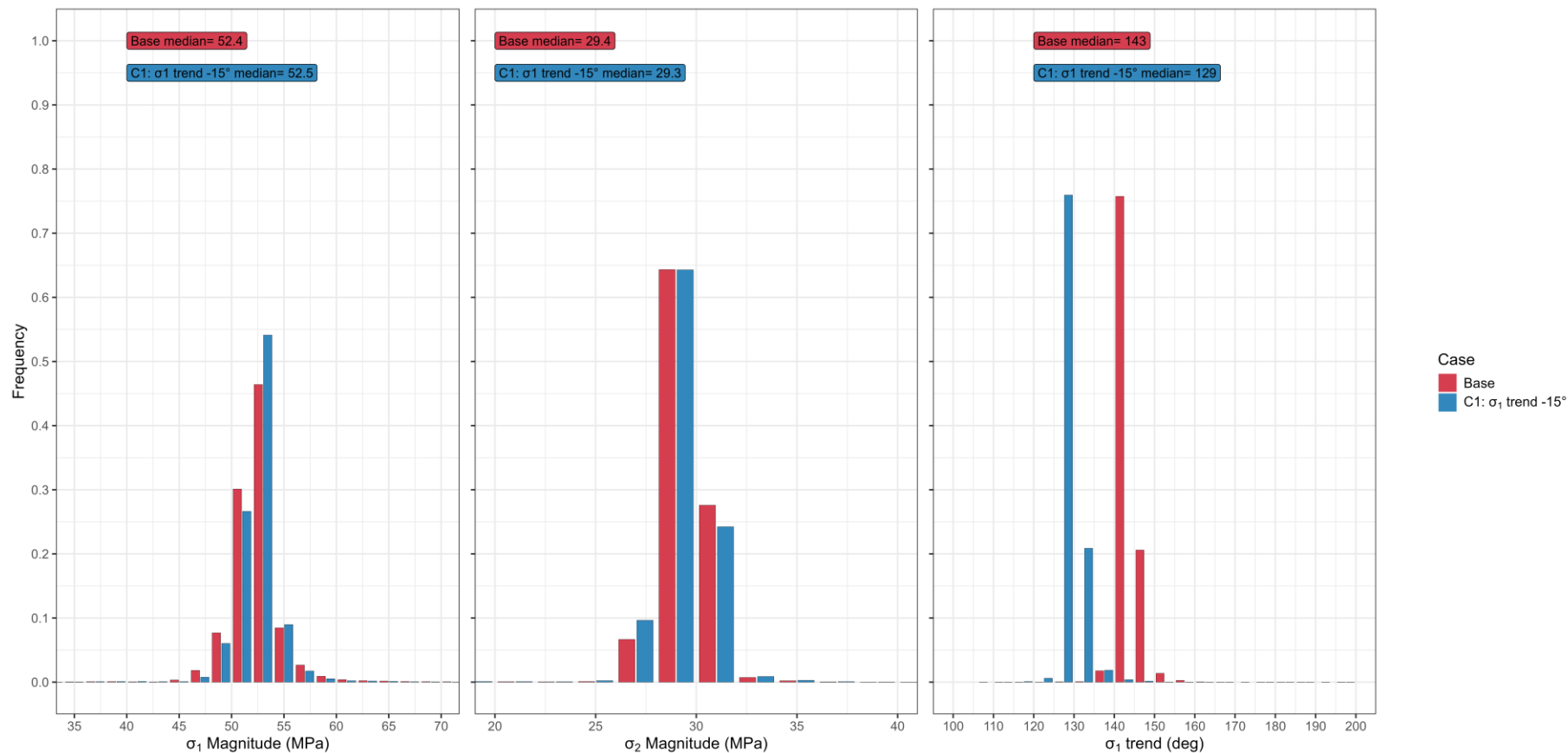


Figure A7- 1. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) before glaciation for the Base case and case 1 simulations.

Repository depth data: Post-Glacial

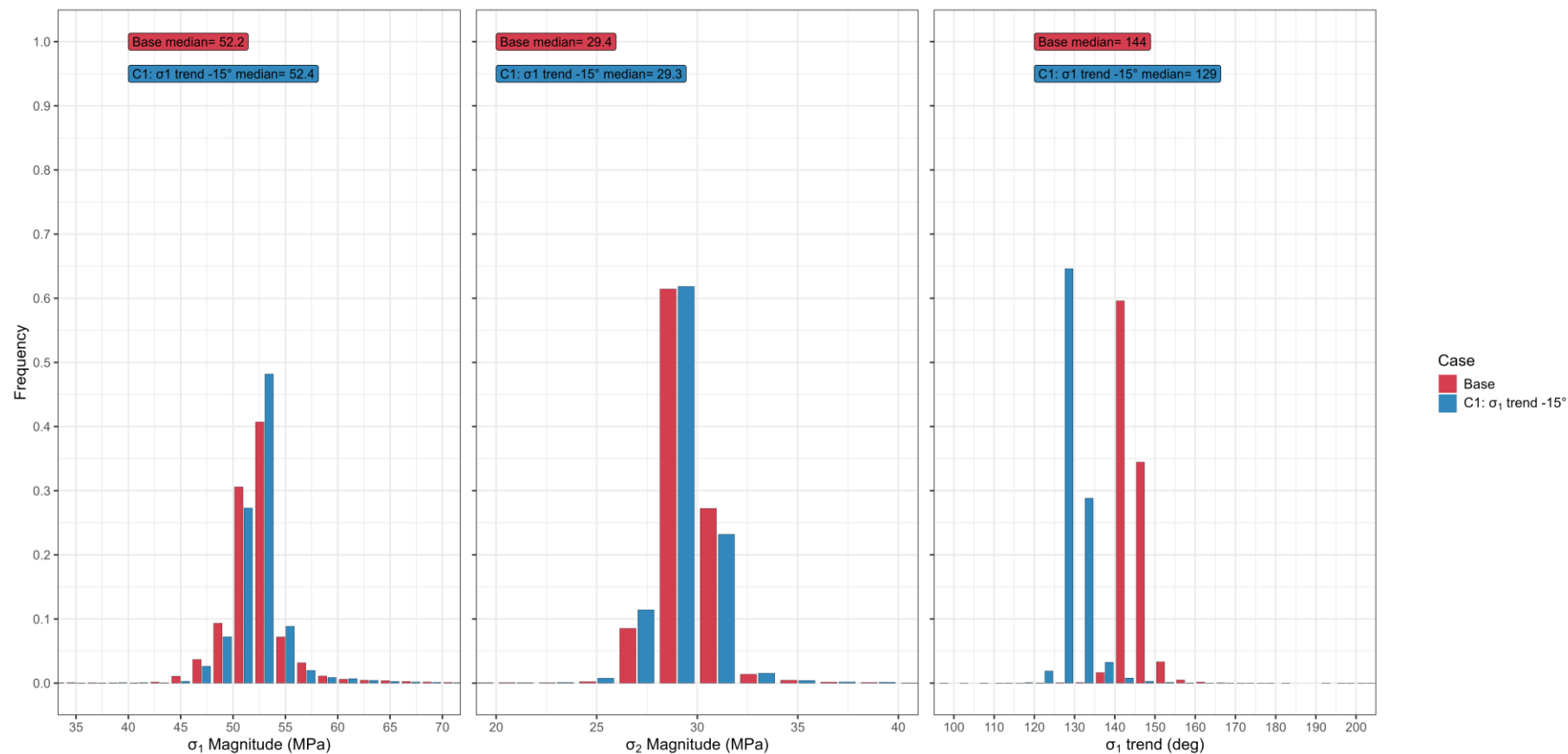


Figure A7- 2. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) after glaciation for the Base case and case 1 simulations.

Repository depth data: Pre-Glacial

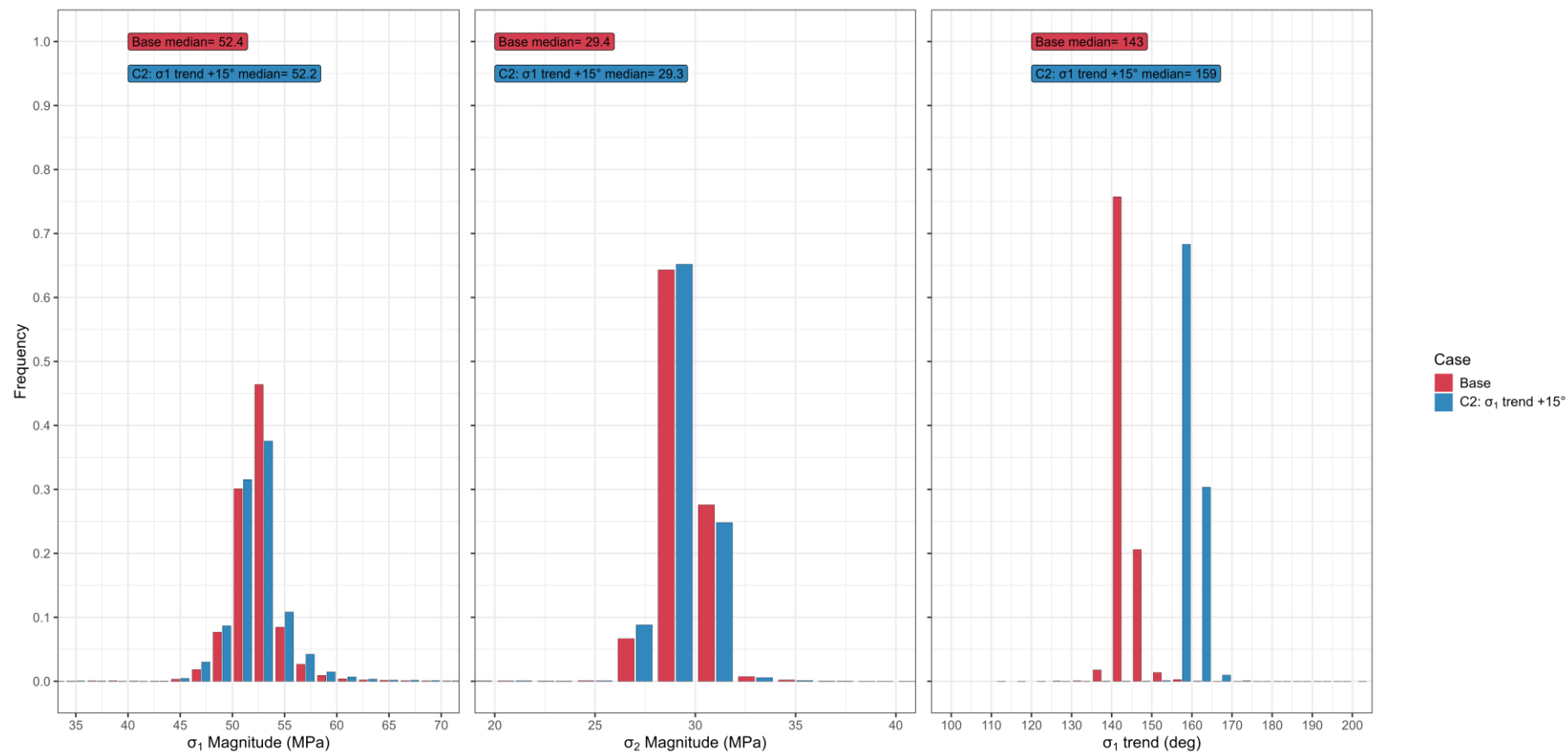


Figure A7- 3. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) before glaciation for the Base case and case 2 simulations.

Repository depth data: Post-Glacial

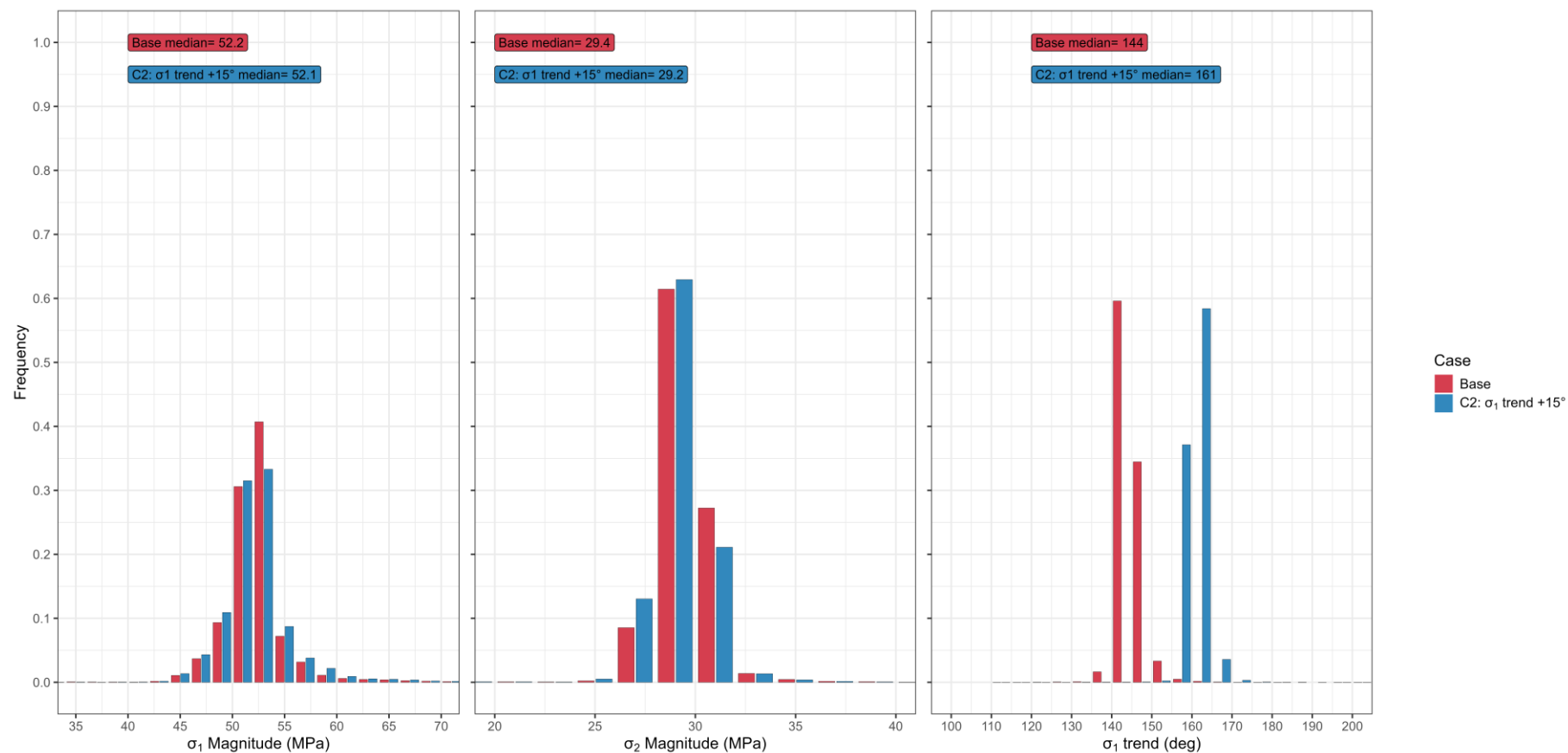


Figure A7- 4. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) after glaciation for the Base case and case 2 simulations.

Repository depth data: Pre-Glacial

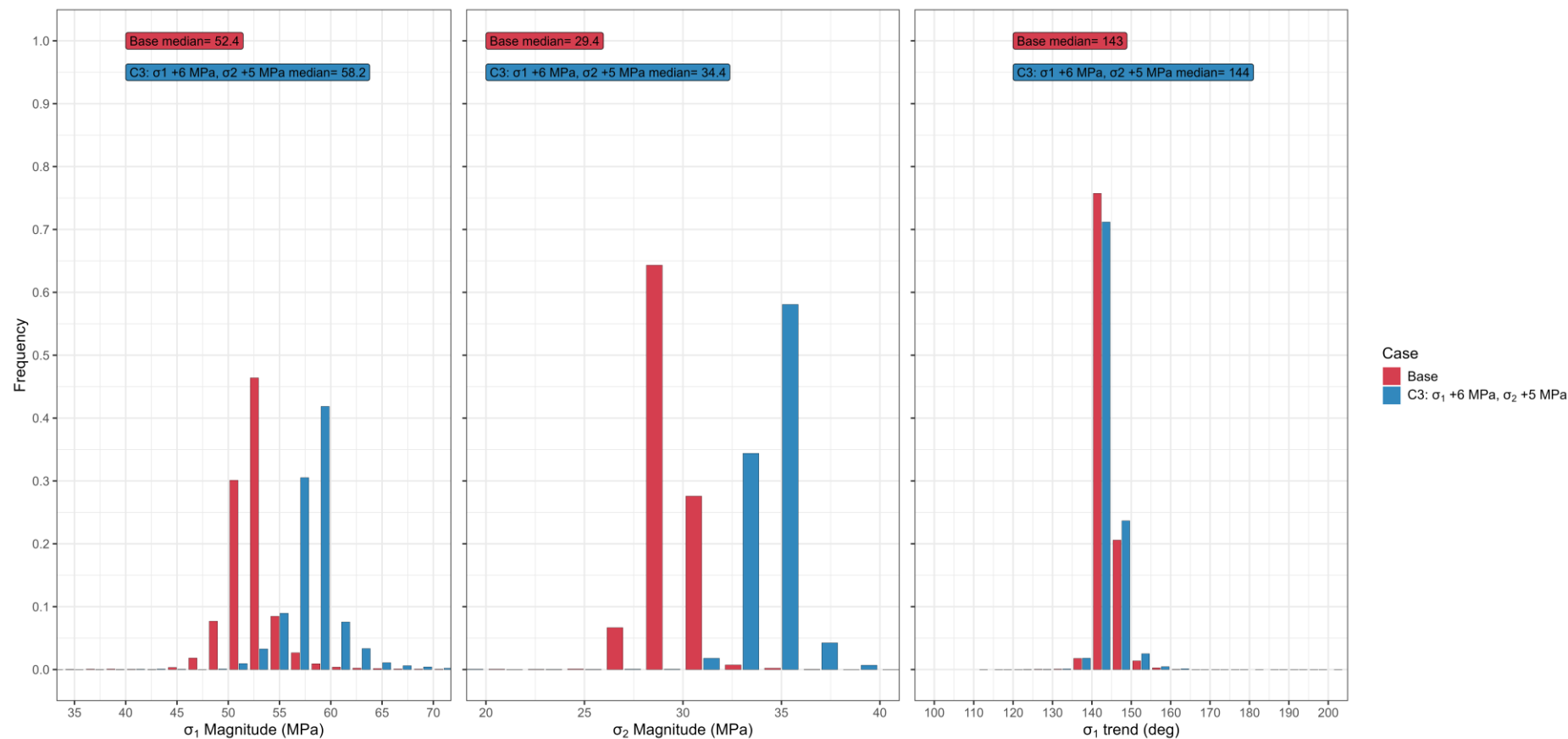


Figure A7- 5. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) before glaciation for the Base case and case 3 simulations.

Repository depth data: Post-Glacial

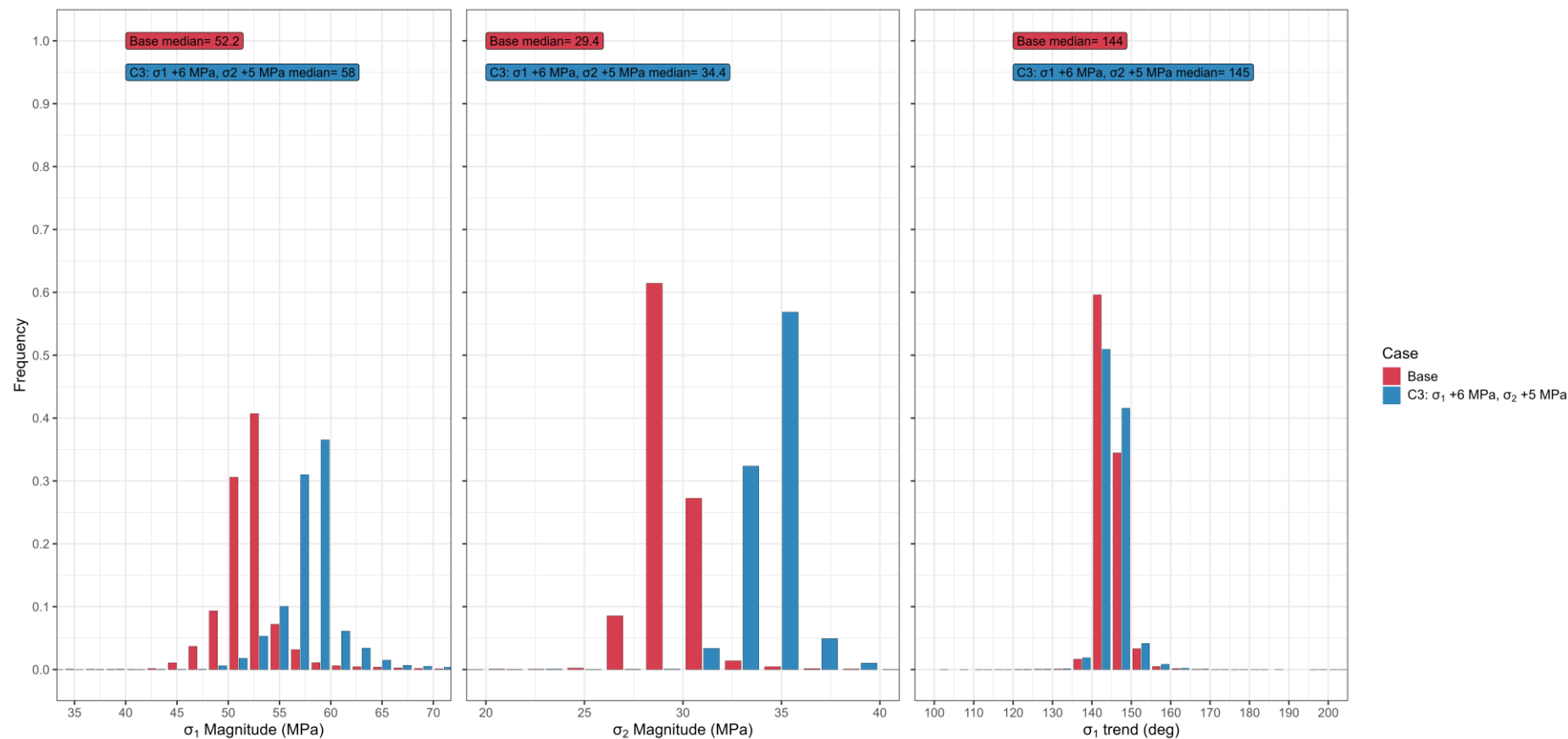


Figure A7- 6. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) after glaciation for the Base case and case 3 simulations.

Repository depth data: Pre-Glacial

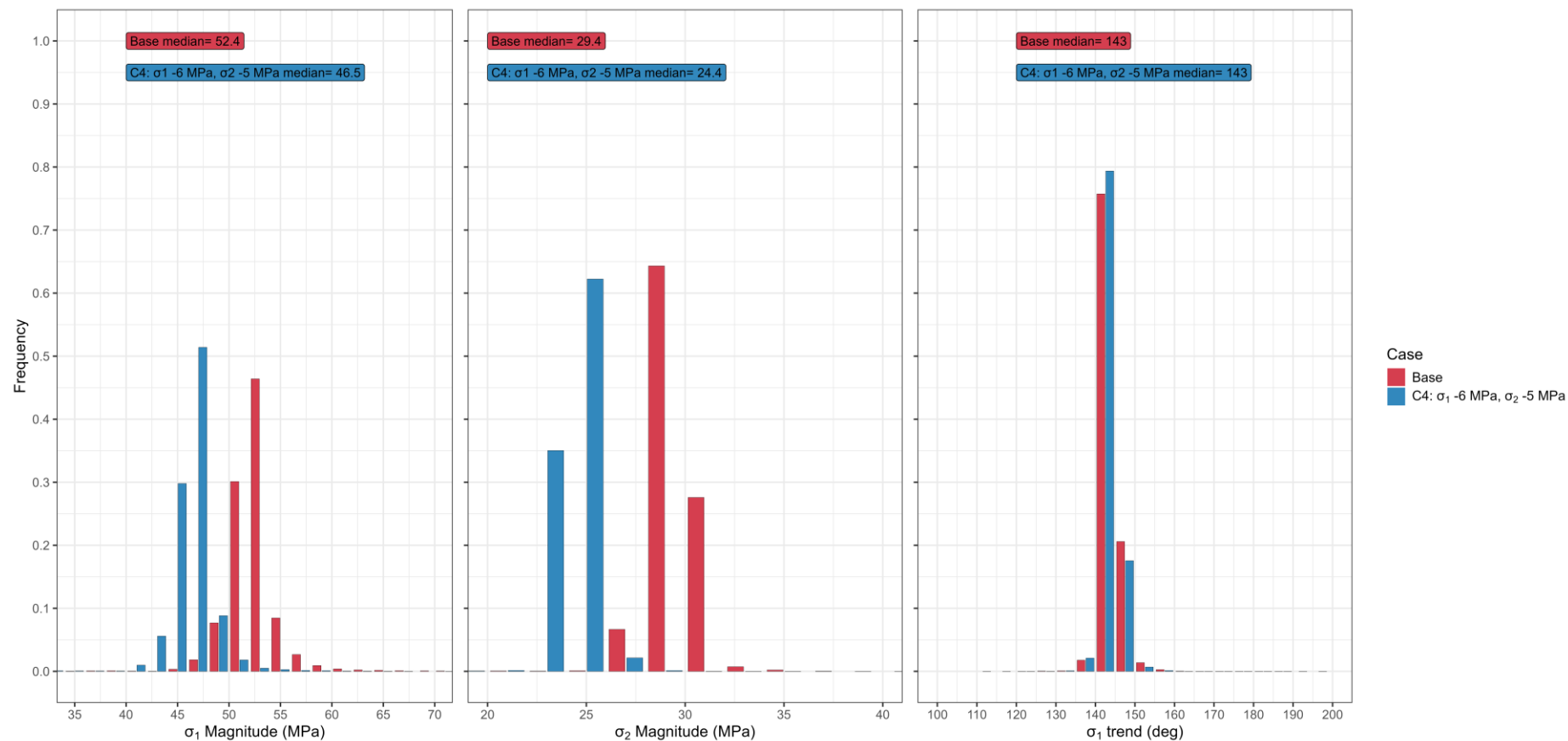


Figure A7- 7. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) before glaciation for the Base case and case 4 simulations.

Repository depth data: Post-Glacial

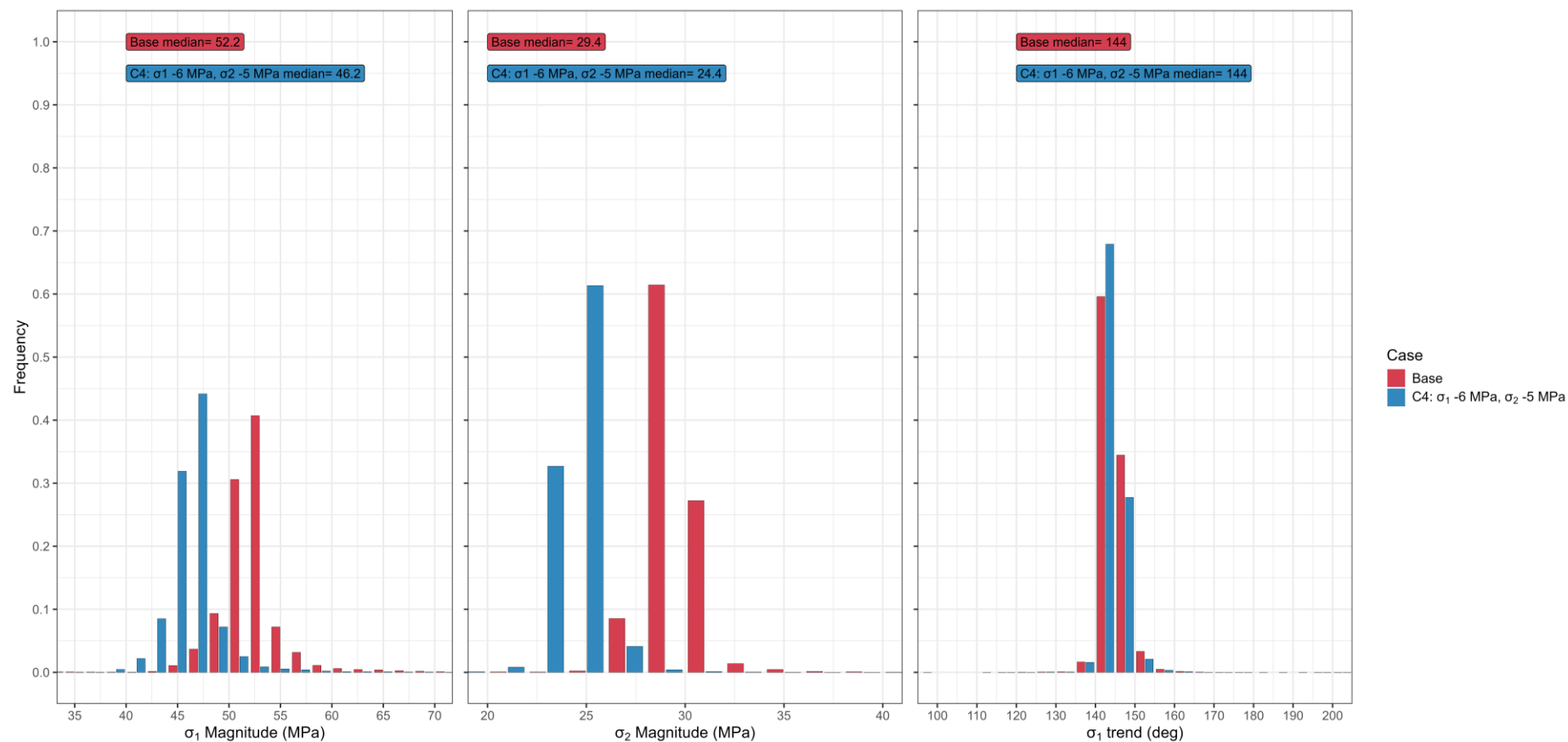


Figure A7- 8. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) after glaciation for the Base case and case 4 simulations.

Repository depth data: Pre-Glacial

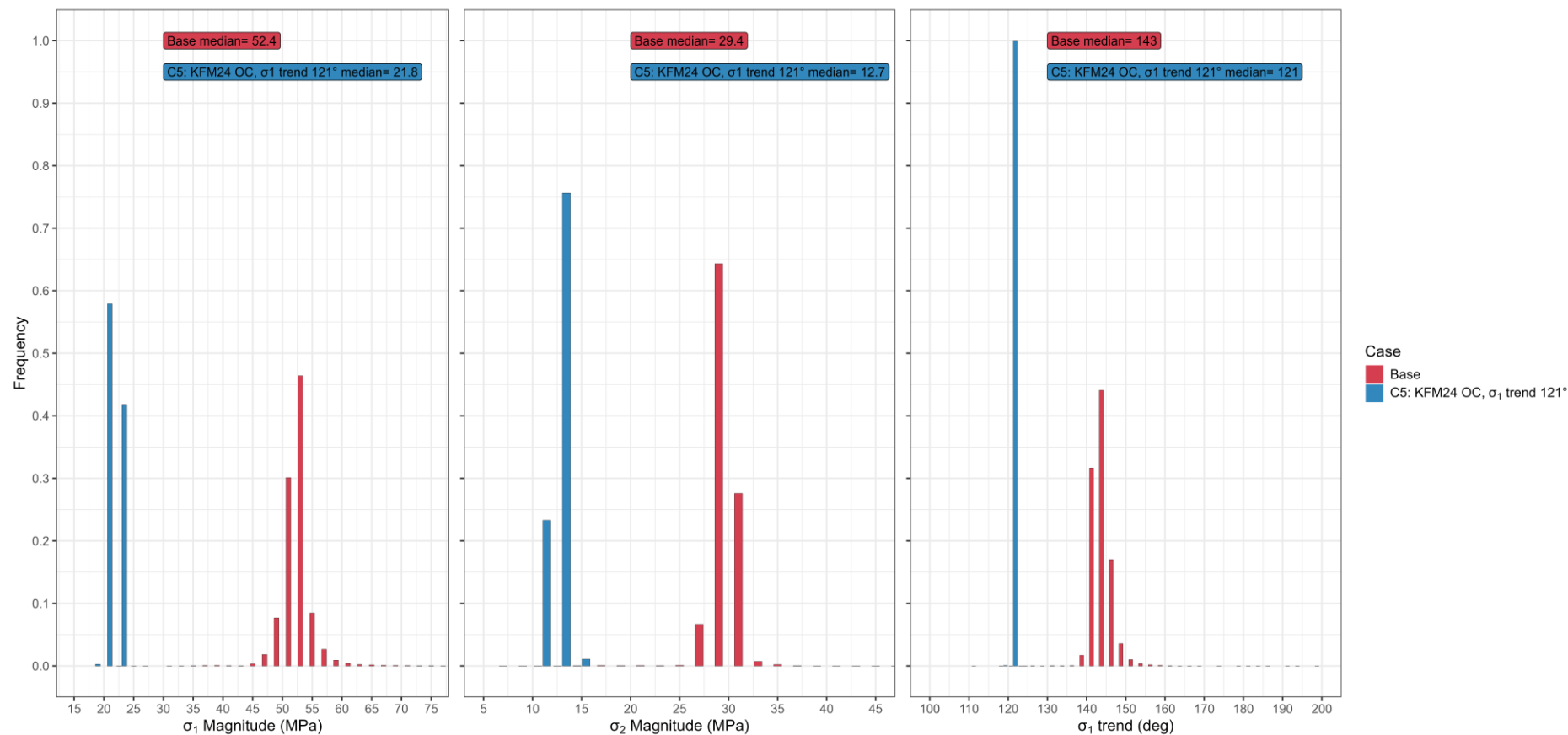


Figure A7- 9. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) before glaciation for the Base case and case 5 simulations.

Repository depth data: Post-Glacial

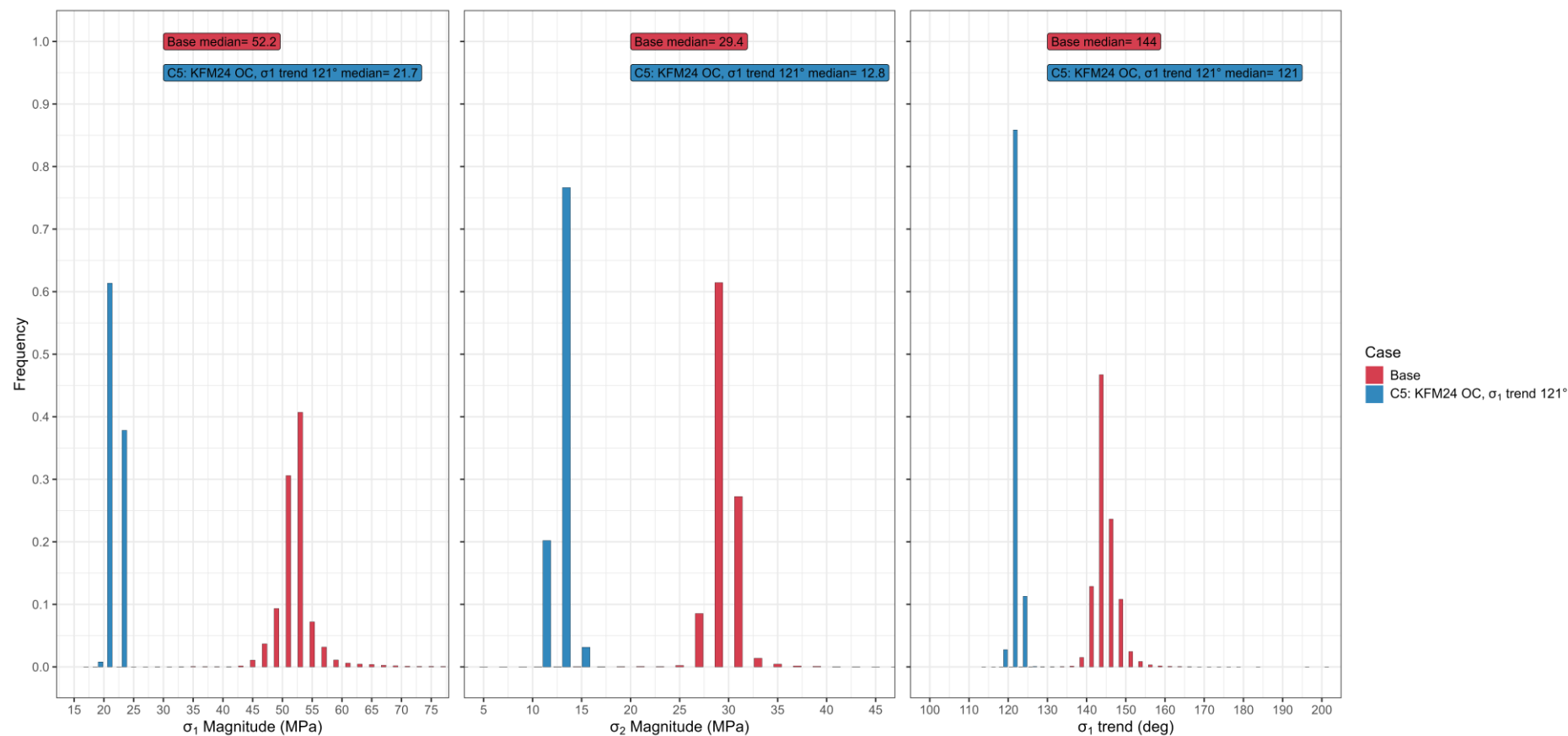


Figure A7- 10. Distribution of σ_1 , σ_2 magnitude and σ_1 trend at repository depth from a cylinder covering the repository footprint (Figure 4-1) after glaciation for the Base case and case 5 simulations.

Appendix 8. Change in σ_1 magnitude at repository depth

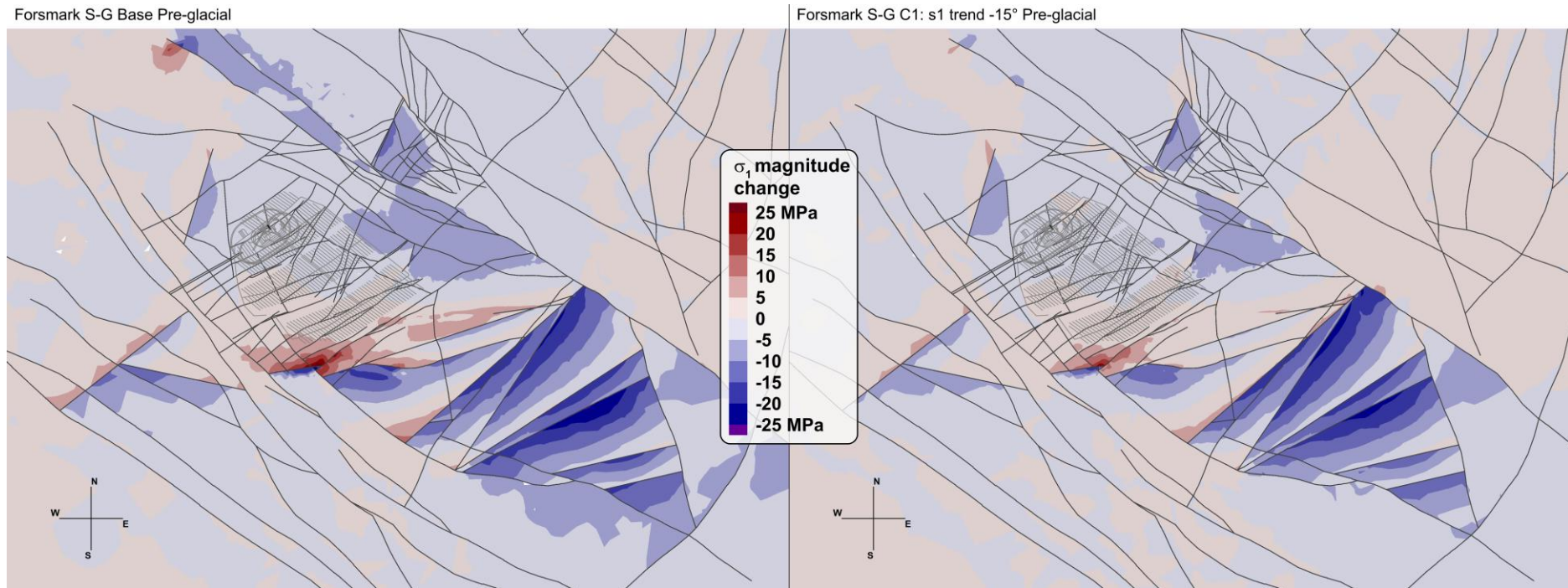


Figure A8- 1. The change in σ_1 magnitude before glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C1: s1 trend -15° Post-glacial

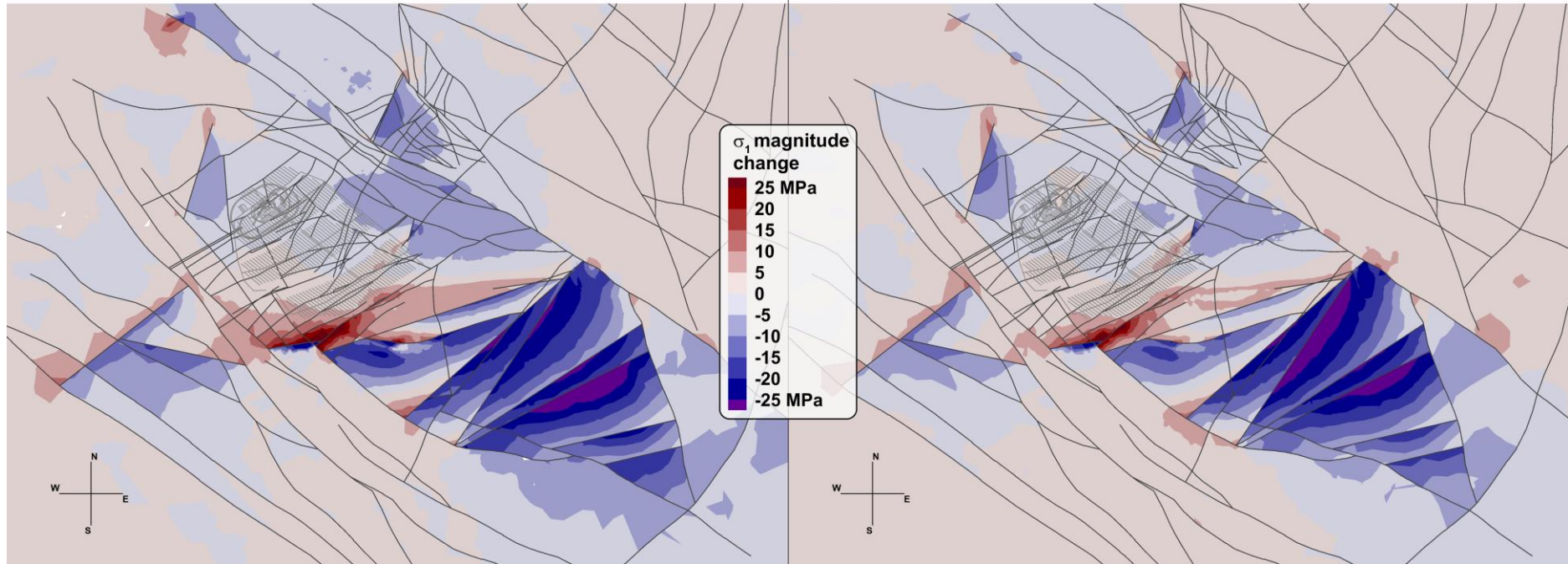


Figure A8- 2. The change in σ_1 magnitude after glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

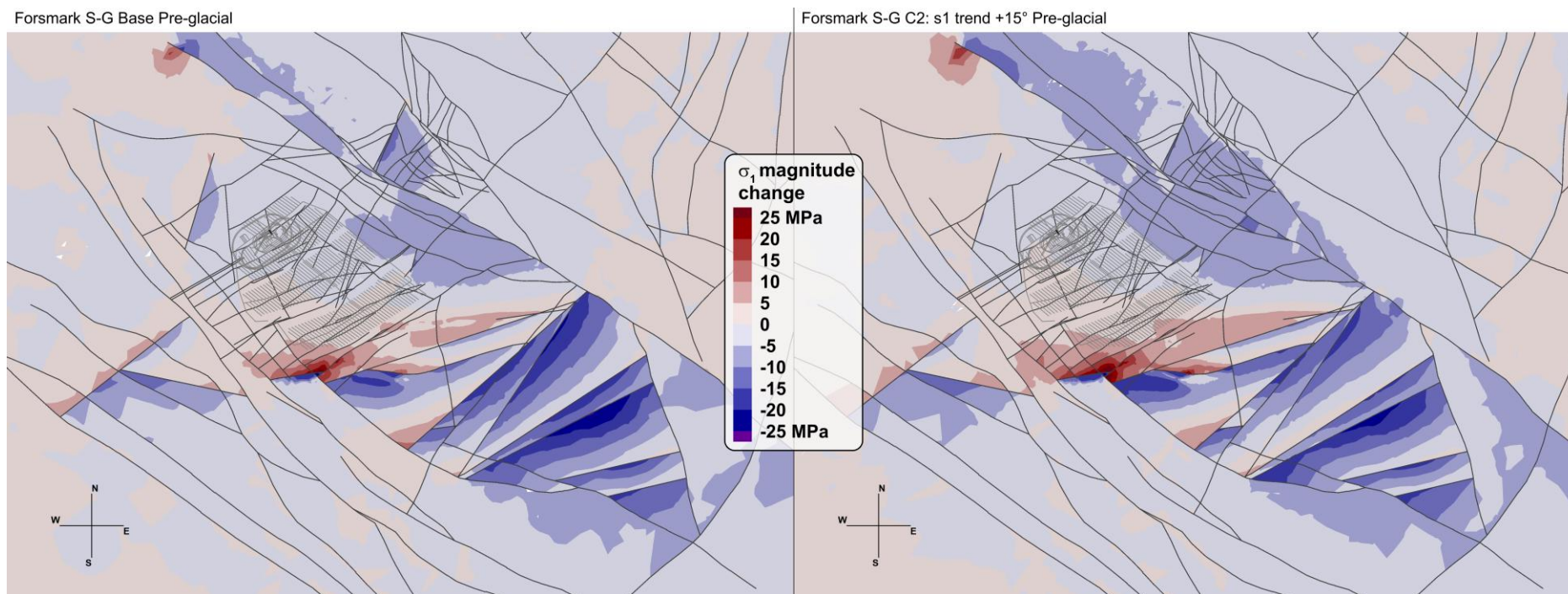


Figure A8- 3. The change in σ_1 magnitude before glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C2: s1 trend +15° Post-glacial

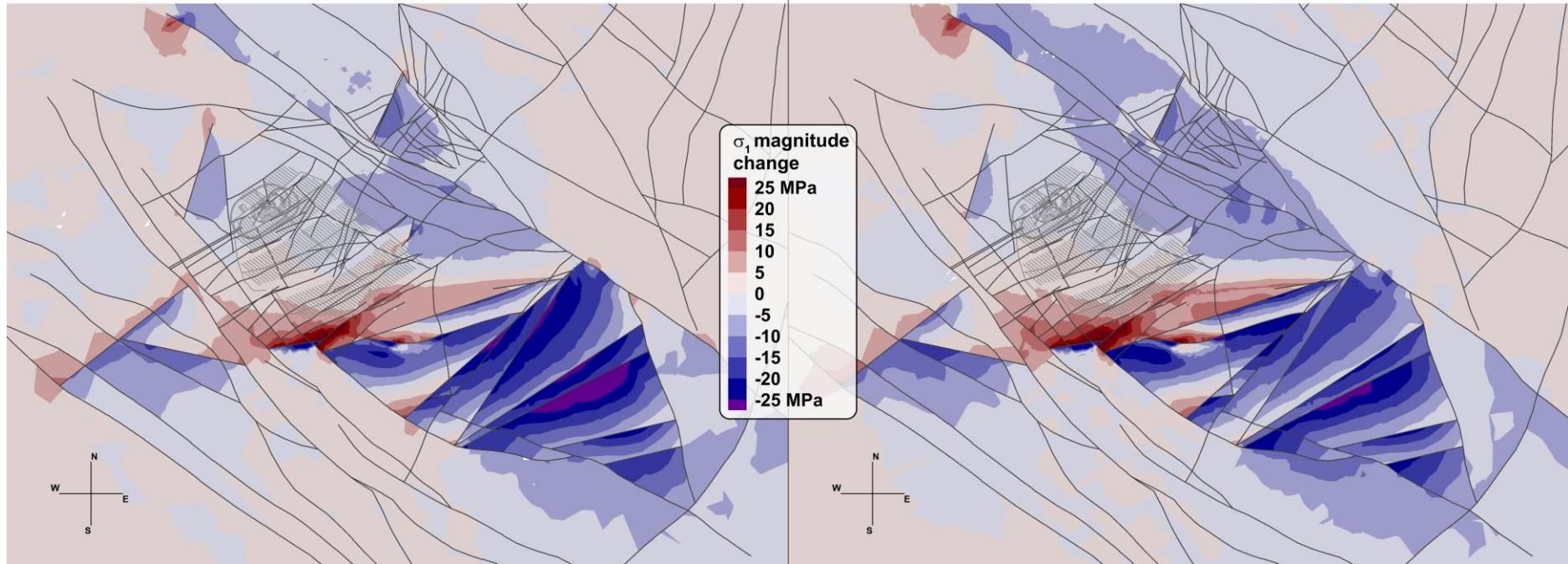


Figure A8- 4. The change in σ_1 magnitude after glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Pre-glacial

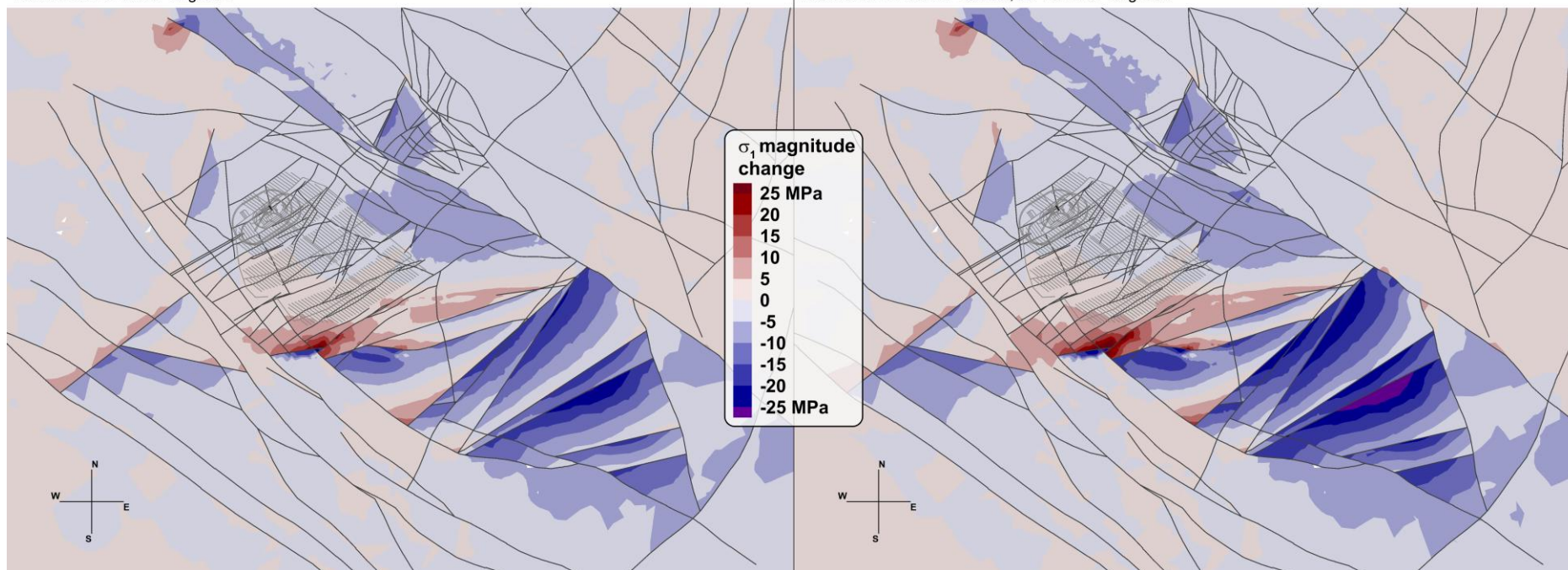


Figure A8- 5. The change in σ_1 magnitude before glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Post-glacial

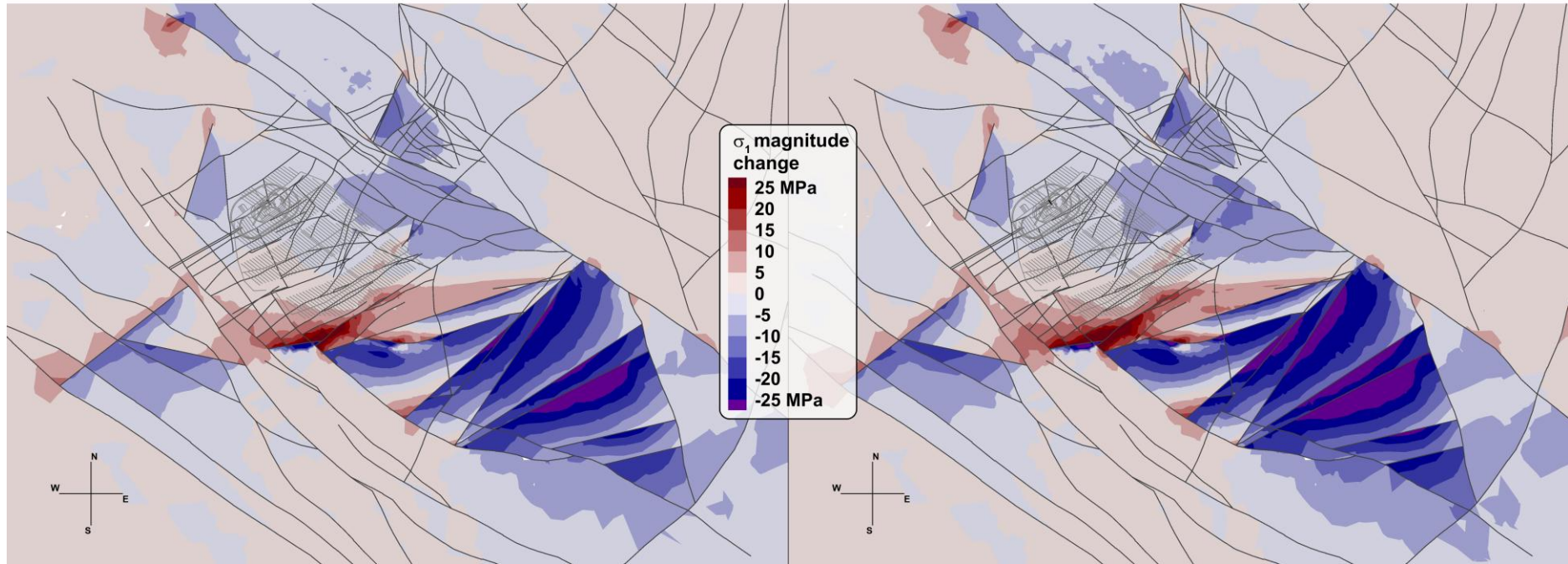


Figure A8- 6. The change in σ_1 magnitude after glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Pre-glacial

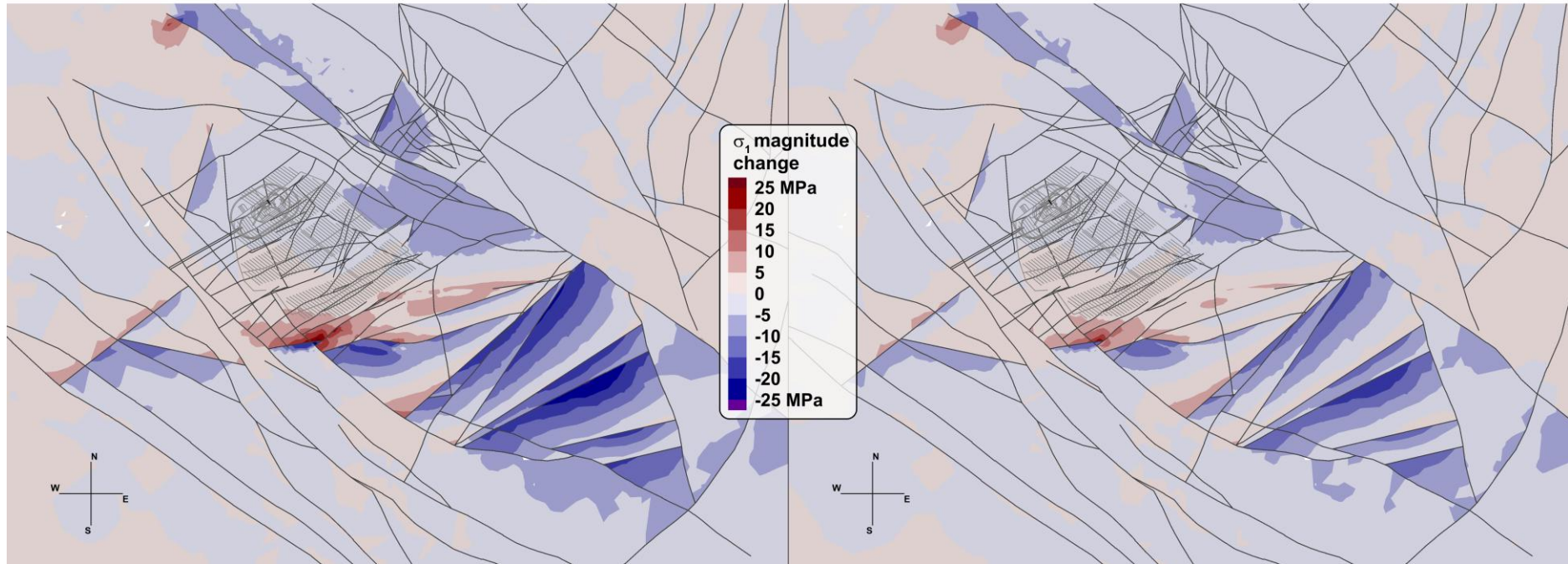


Figure A8- 7. The change in σ_1 magnitude before glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Post-glacial

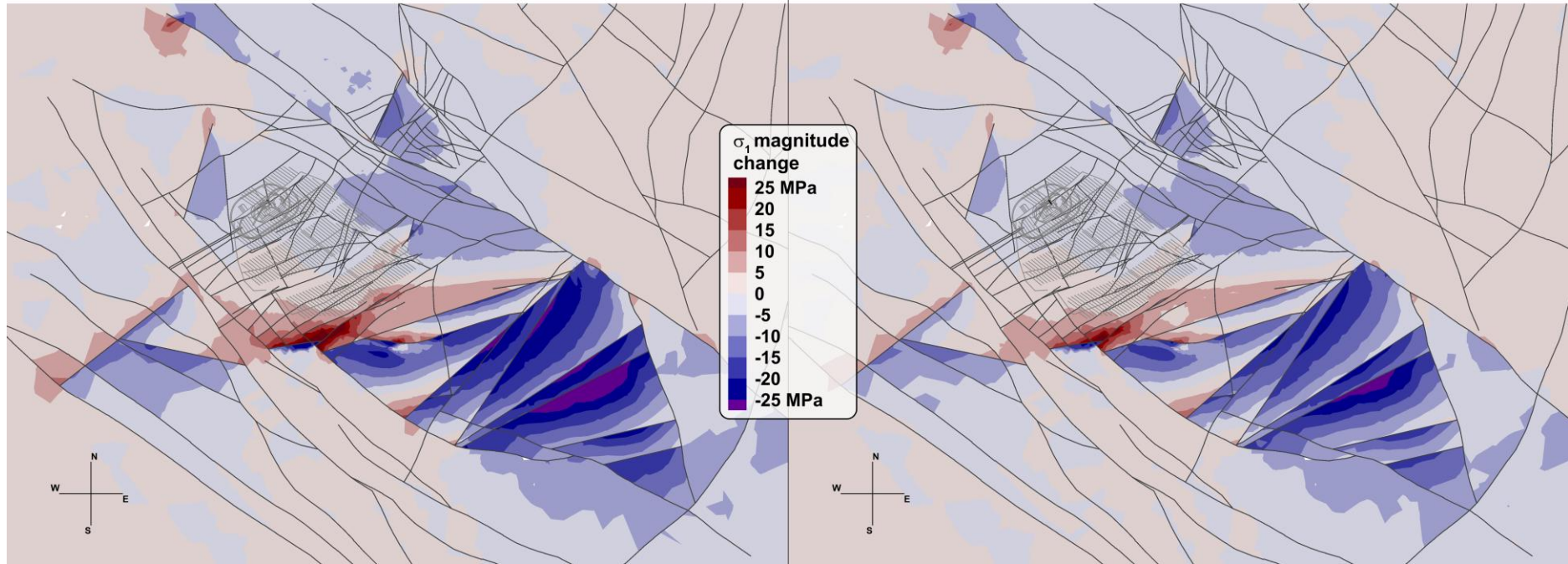


Figure A8- 8. The change in σ_1 magnitude after glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Pre-glacial

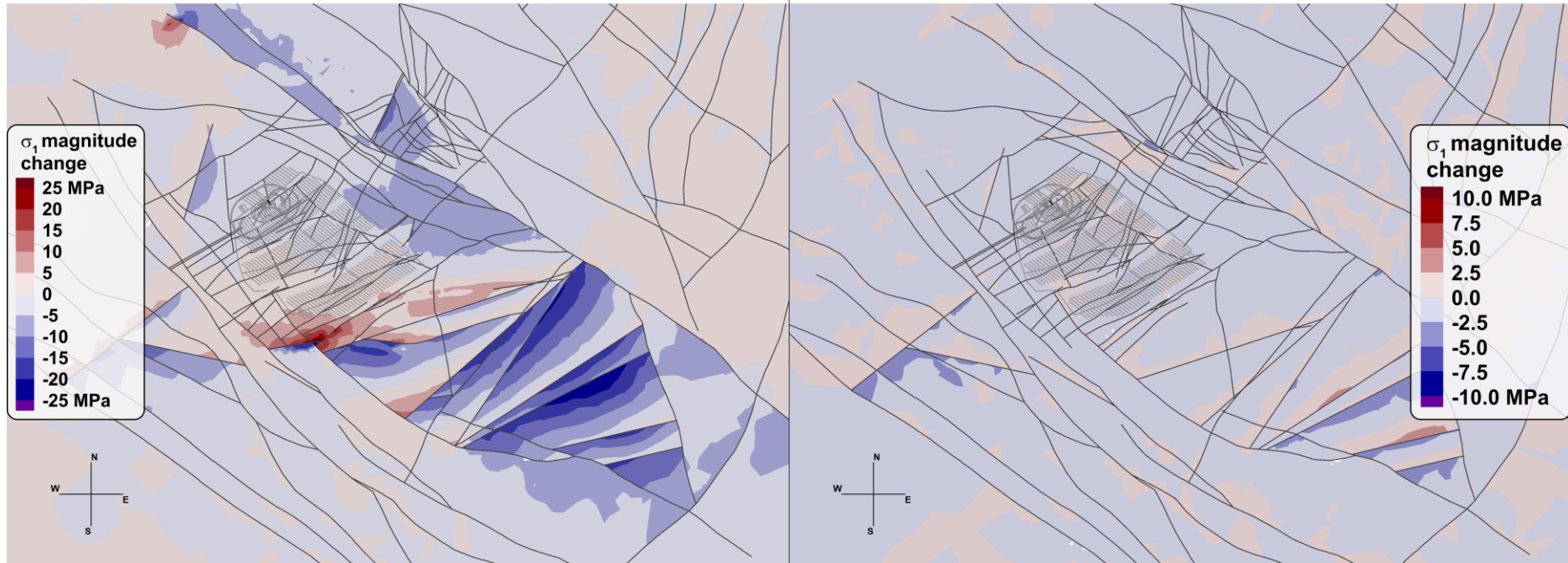


Figure A8- 9. The change in σ_1 magnitude before glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent. Note the case 5 scale (right) differs from the reference base case scale (left).*

Forsmark S-G Base Post-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Post-glacial

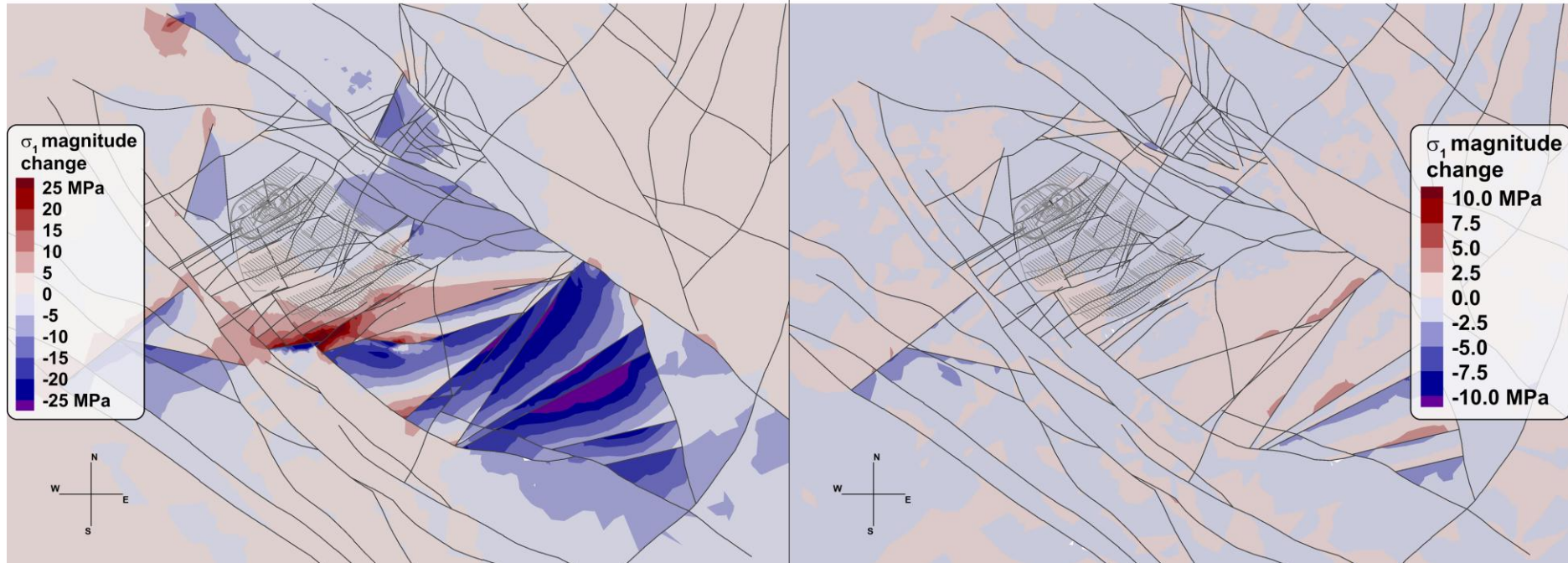


Figure A8- 10. The change in σ_1 magnitude after glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent. Note the case 5 scale (right) differs from the reference base case scale (left).*

Appendix 9. Change in σ_2 magnitude at repository depth

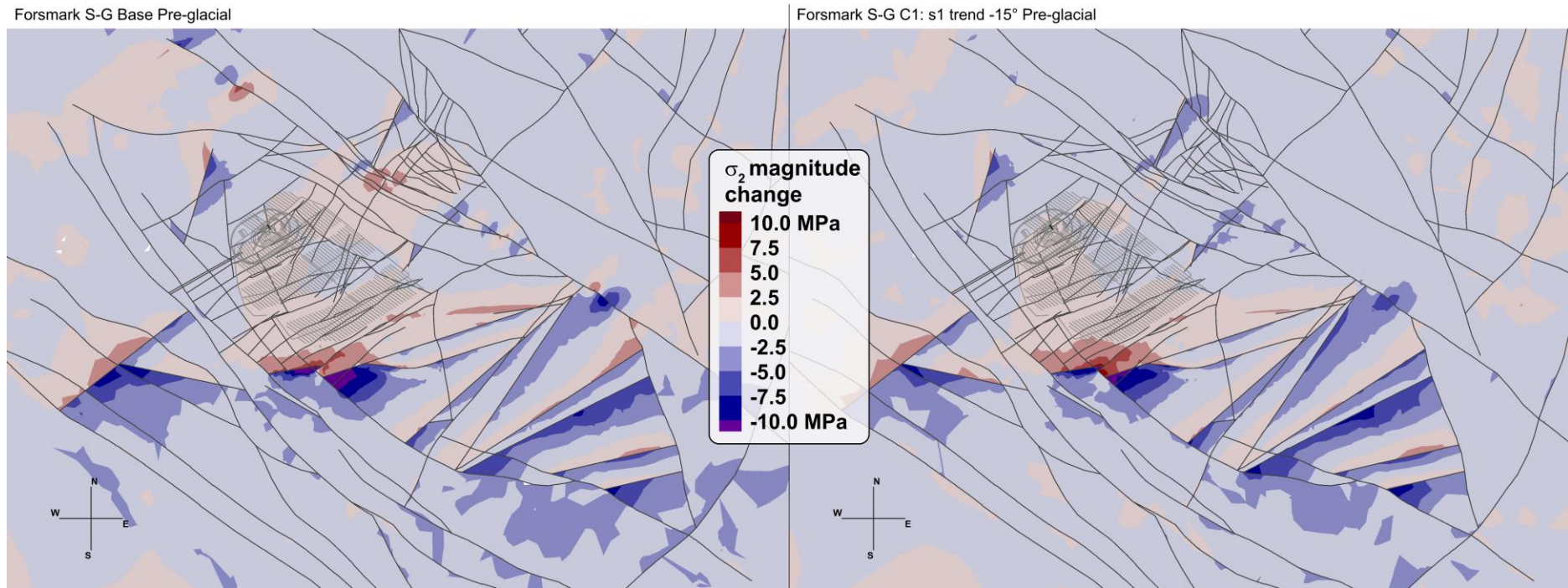


Figure A9- 1. The change in σ_2 magnitude before glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C1: s1 trend -15° Post-glacial

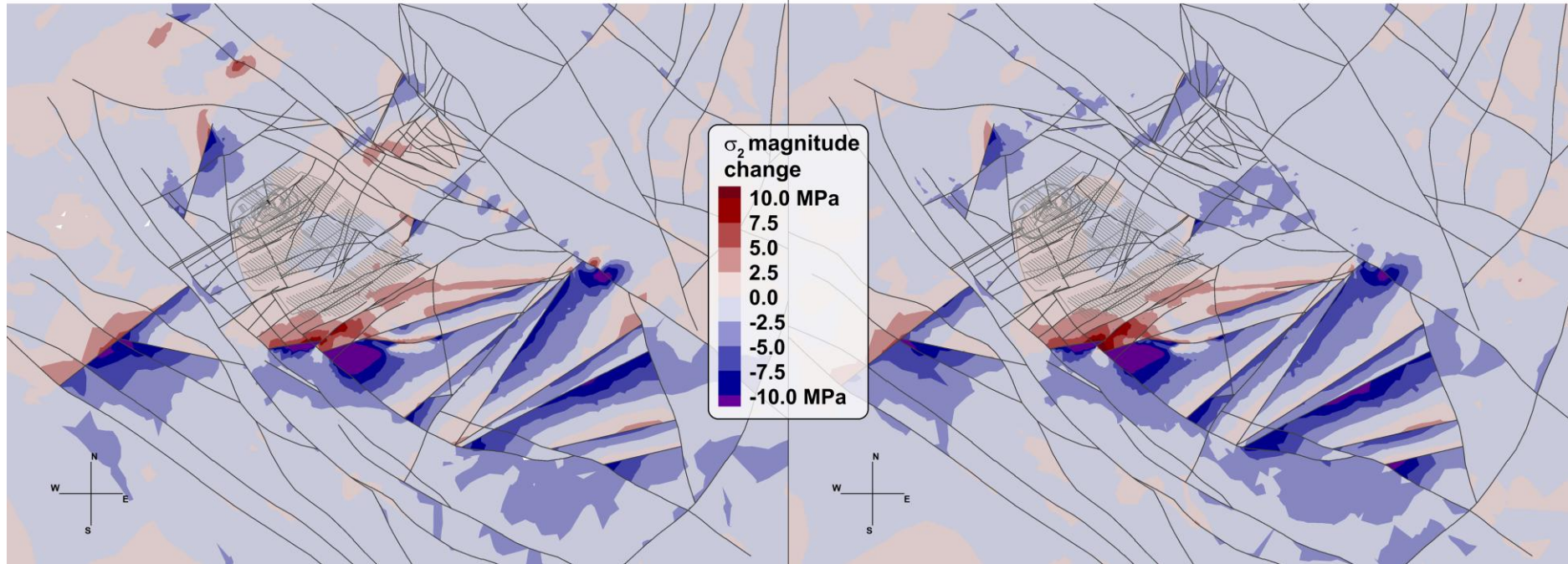


Figure A9- 2. The change in σ_2 magnitude after glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

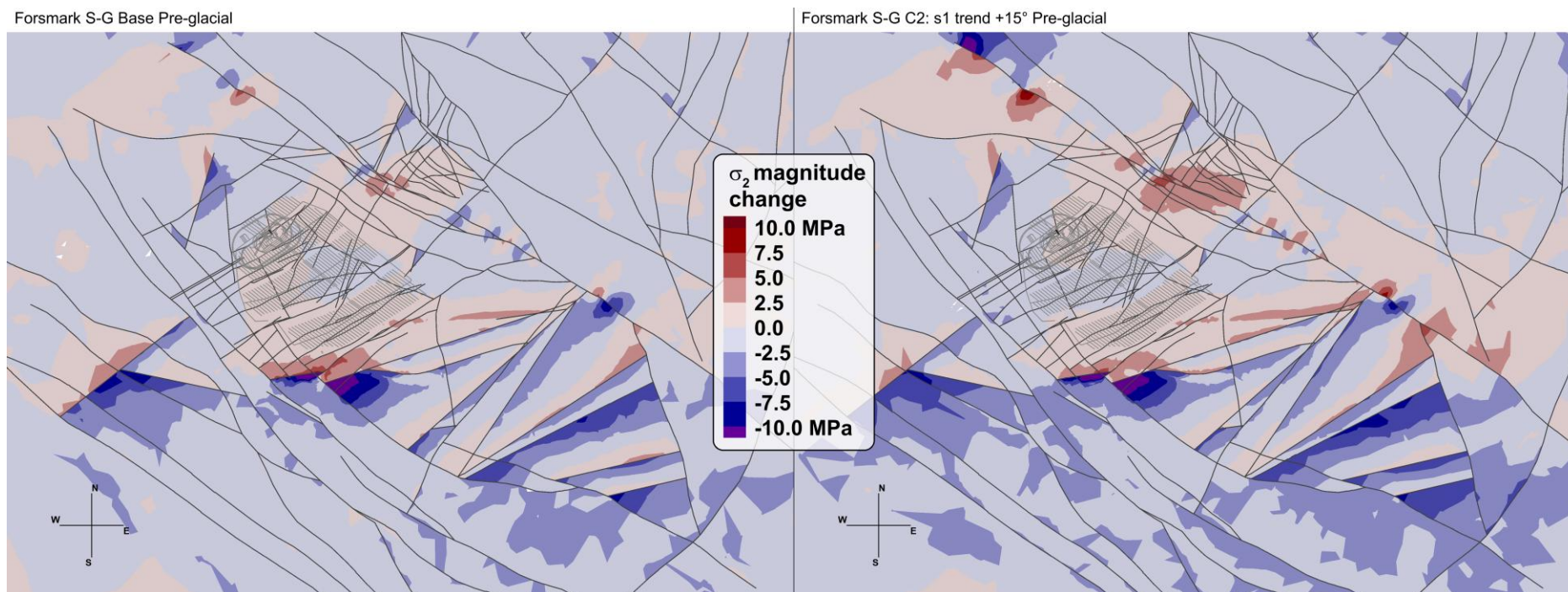


Figure A9- 3. The change in σ_2 magnitude before glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C2: s1 trend +15° Post-glacial

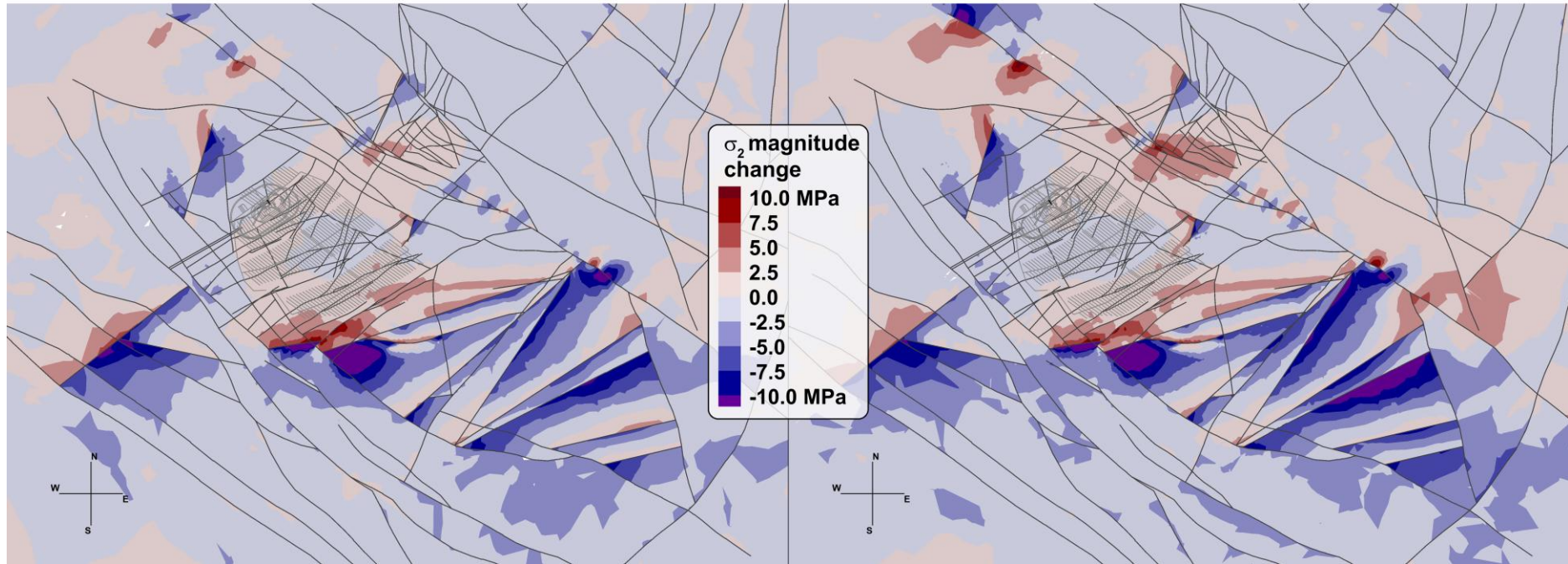


Figure A9- 4. The change in σ_2 magnitude after glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Pre-glacial

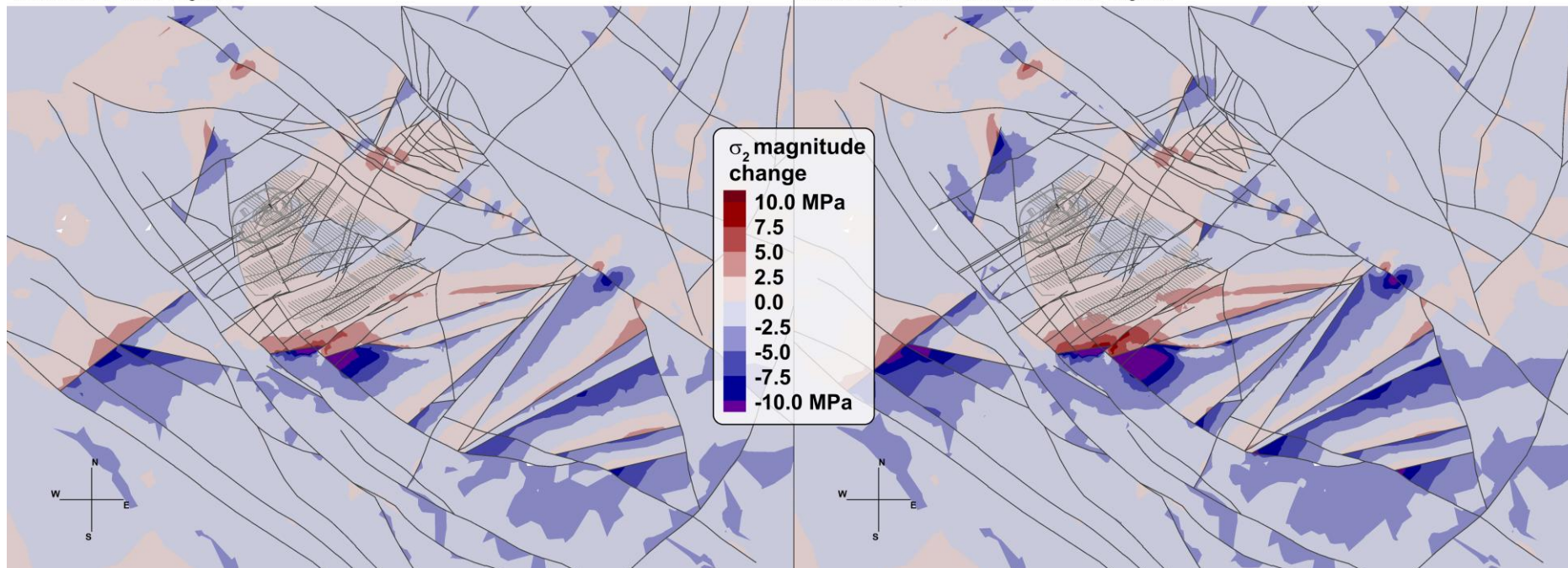


Figure A9- 5. The change in σ_2 magnitude before glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Post-glacial

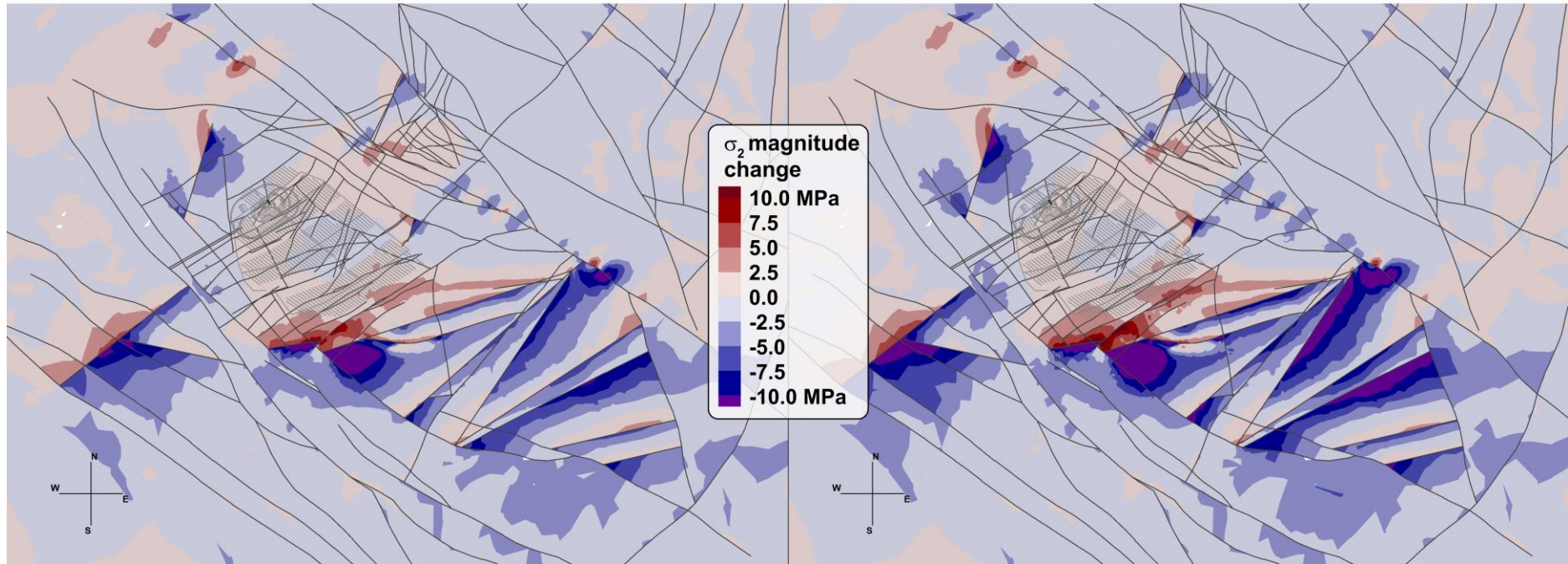


Figure A9- 6. The change in σ_2 magnitude after glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Pre-glacial

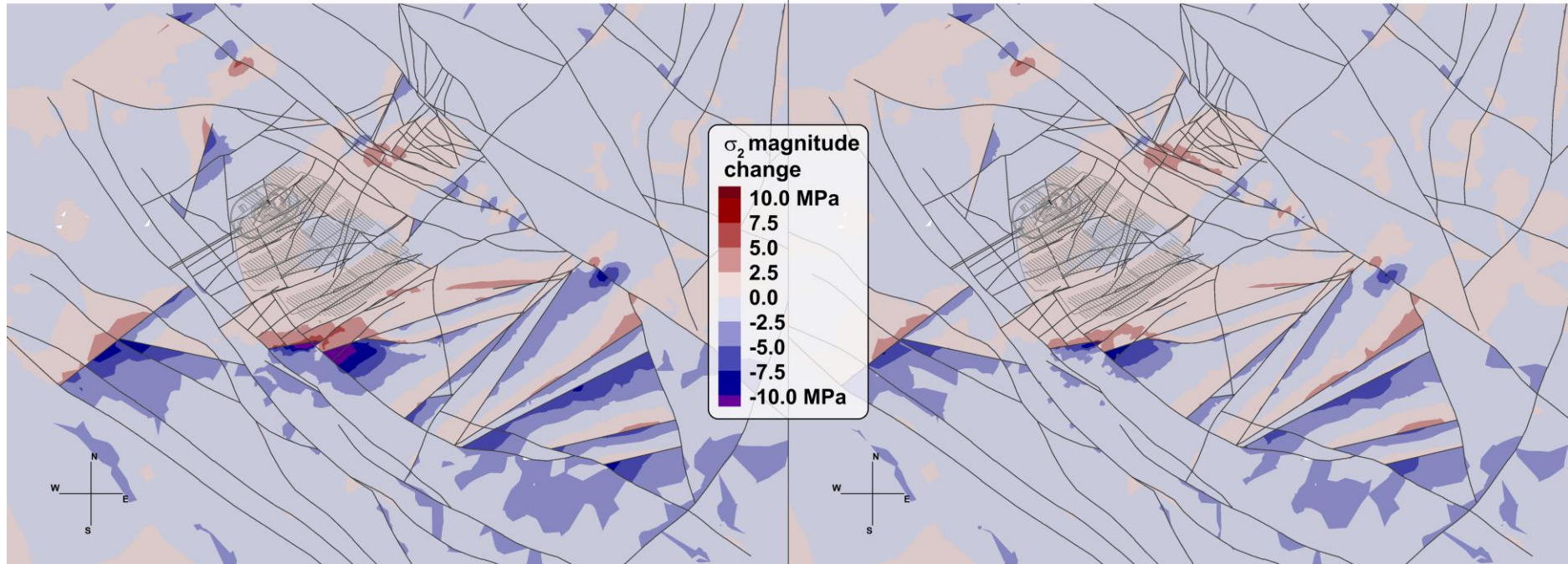


Figure A9- 7. The change in σ_2 magnitude before glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Post-glacial

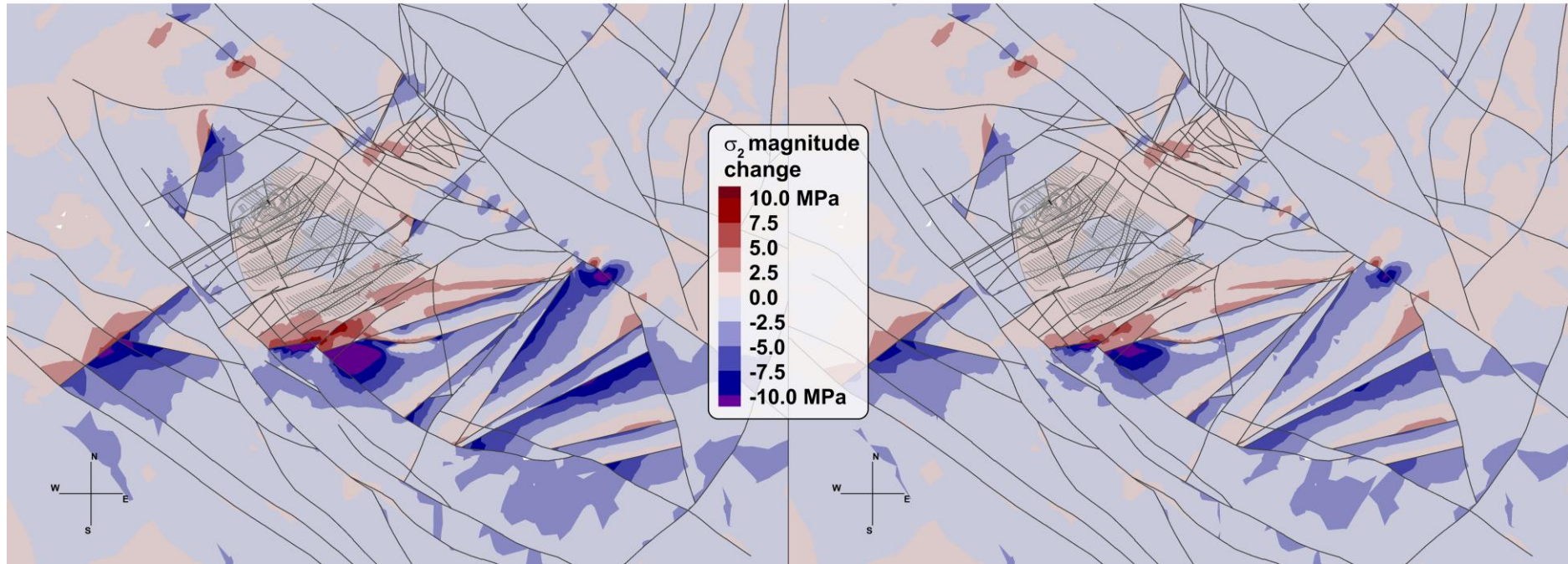


Figure A9- 8. The change in σ_2 magnitude after glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Pre-glacial

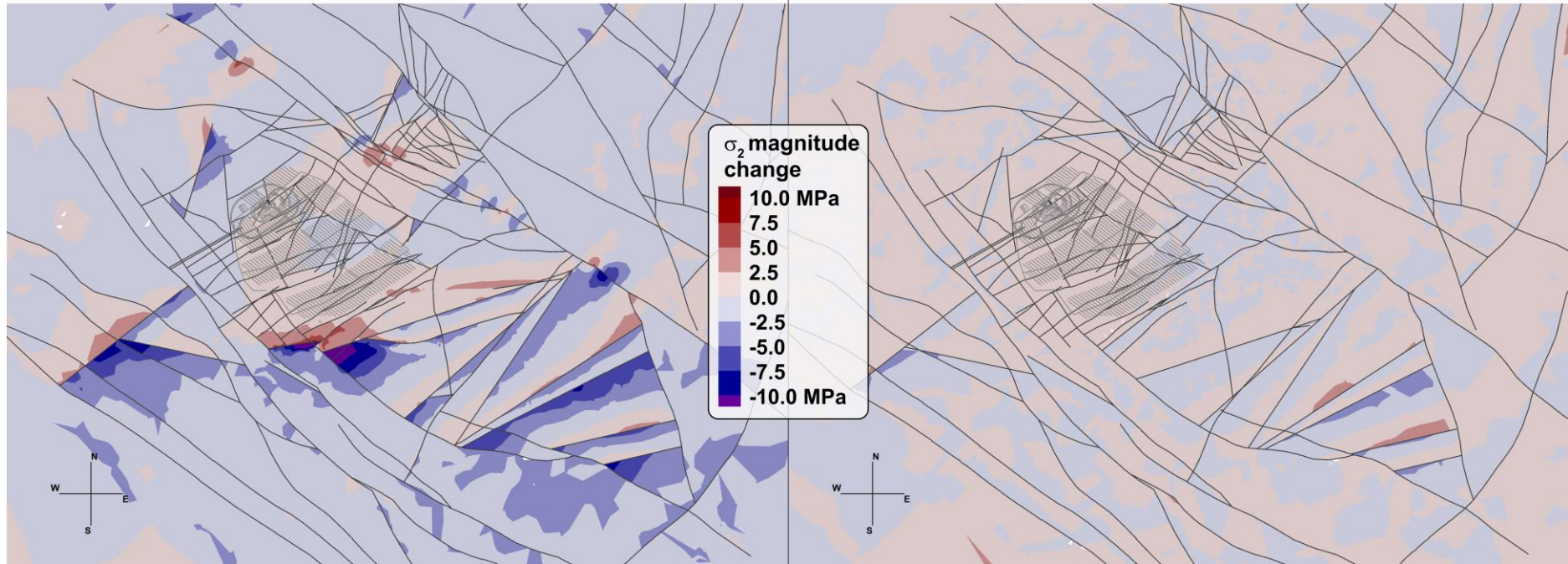


Figure A9- 9. The change in σ_2 magnitude before glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Post-glacial

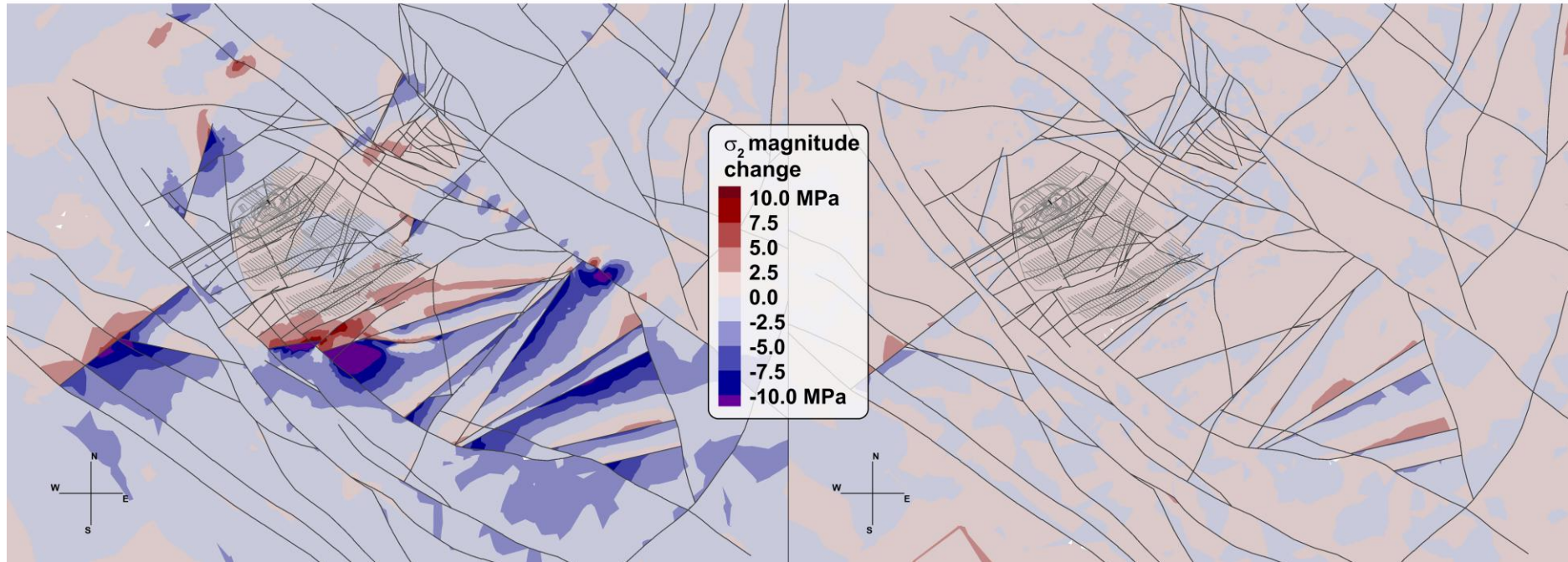


Figure A9- 10. The change in σ_2 magnitude after glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent.*

Appendix 10. Change in σ_3 magnitude at repository depth

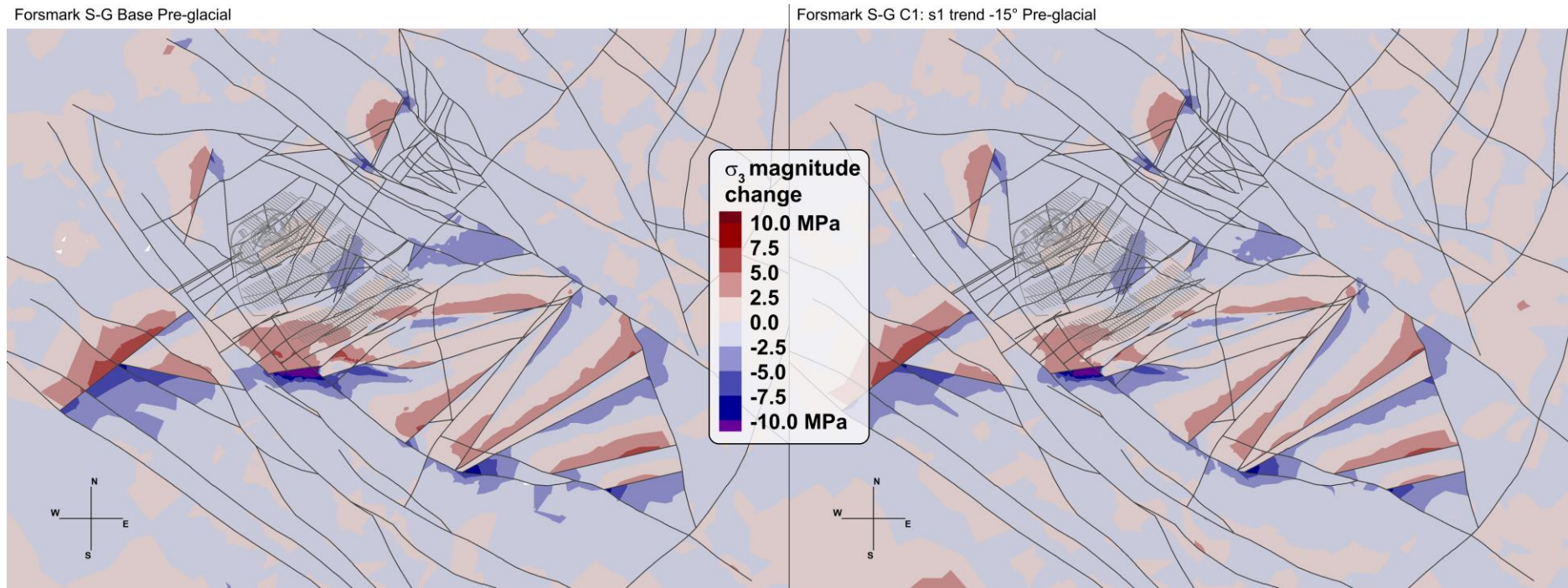


Figure A10- 1. The change in σ_3 magnitude before glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C1: s1 trend -15° Post-glacial

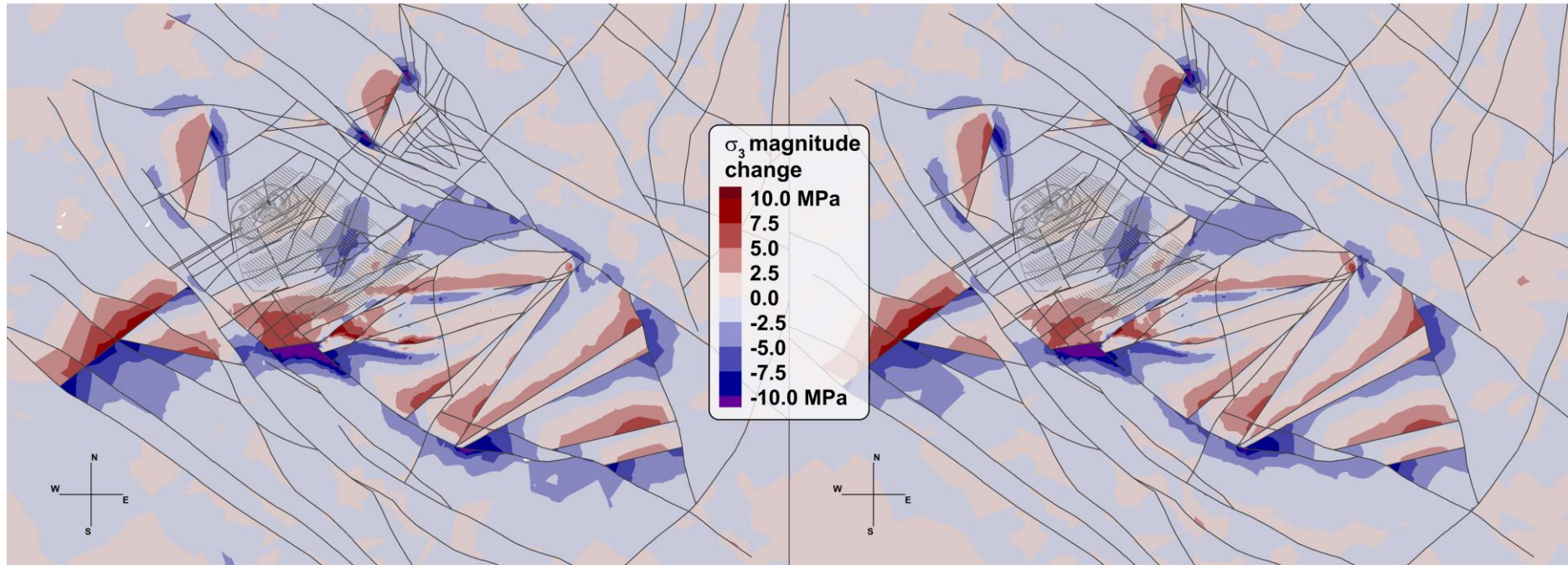


Figure A10- 2. The change in σ_3 magnitude after glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C2: s1 trend +15° Pre-glacial

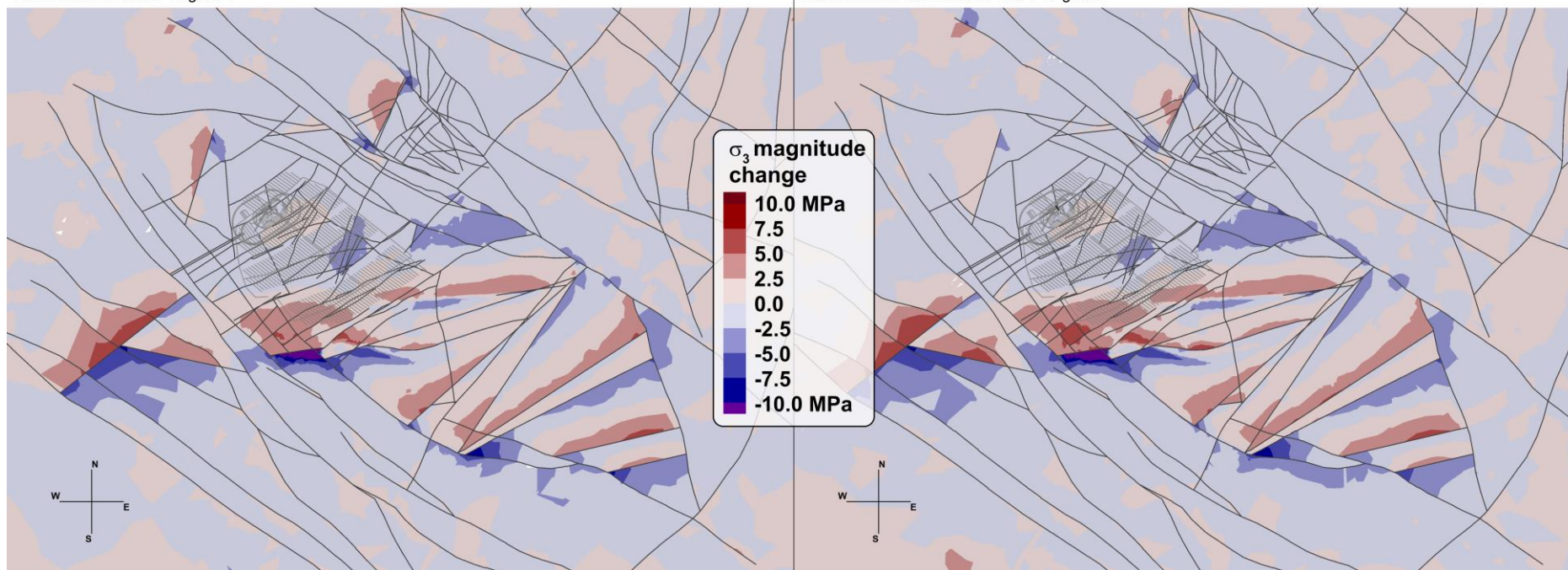


Figure A10- 3. The change in σ_3 magnitude before glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C2: s1 trend +15° Post-glacial

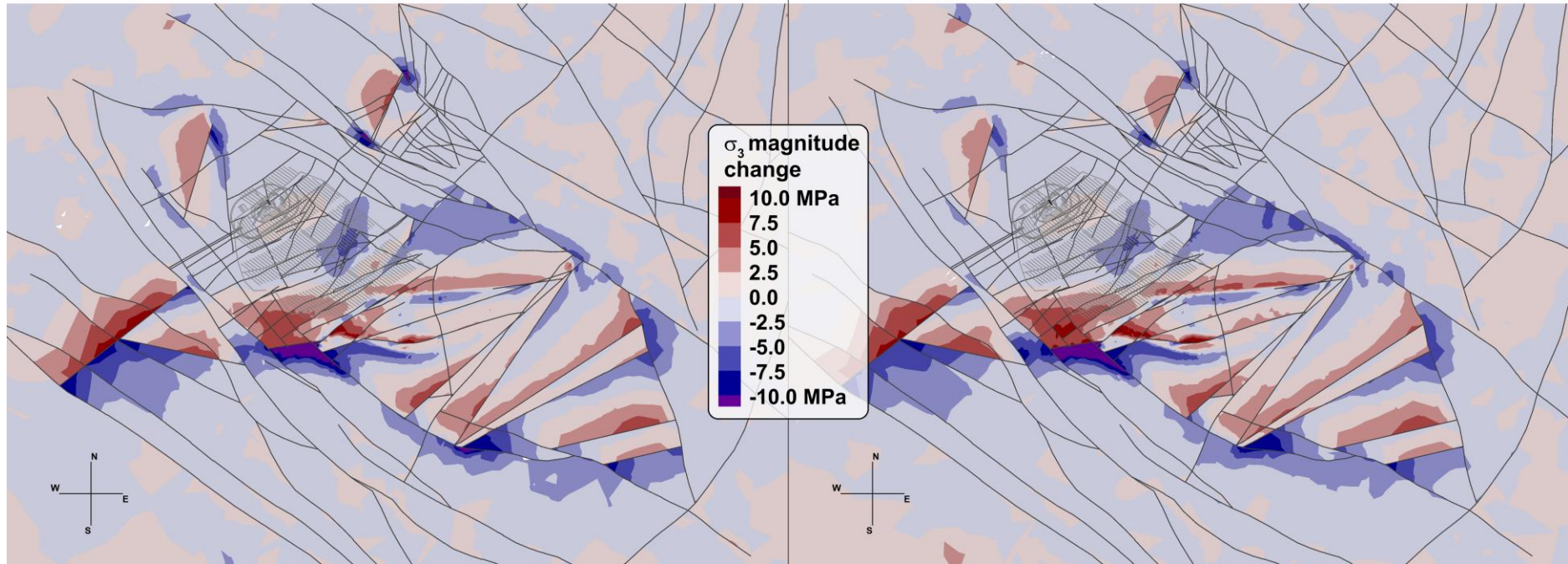


Figure A10- 4. The change in σ_3 magnitude after glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Pre-glacial

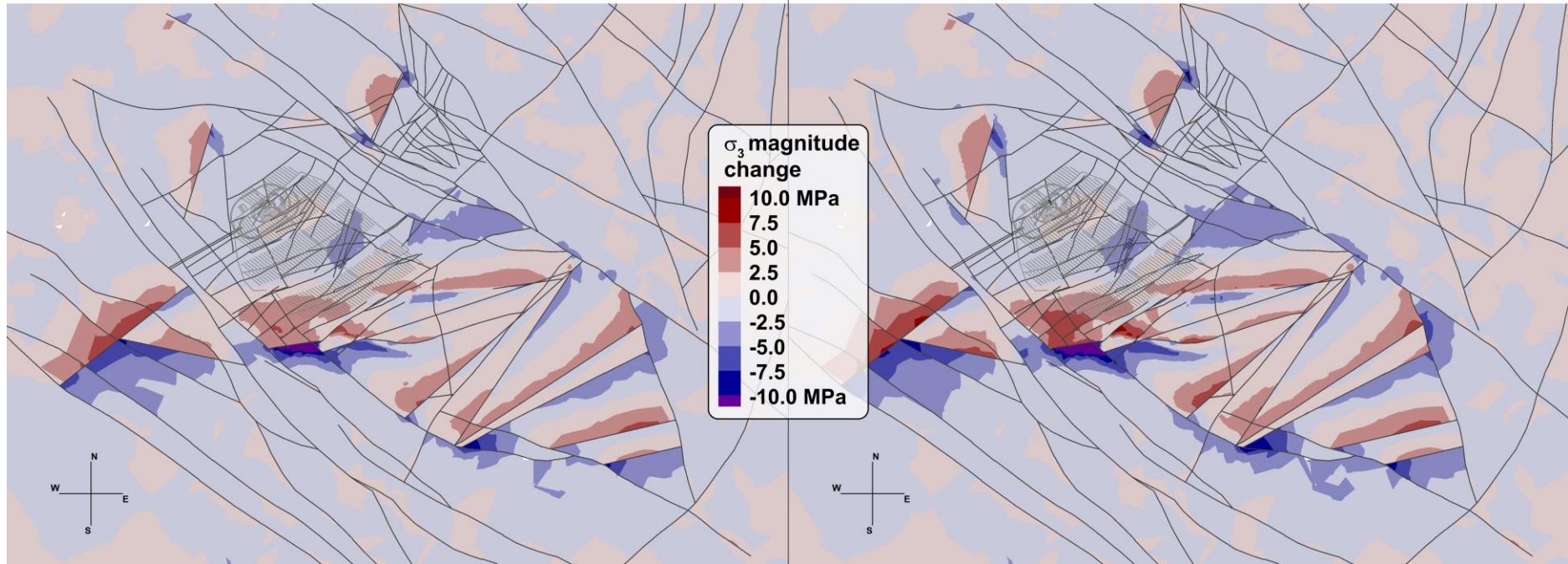


Figure A10- 5. The change in σ_3 magnitude before glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Post-glacial

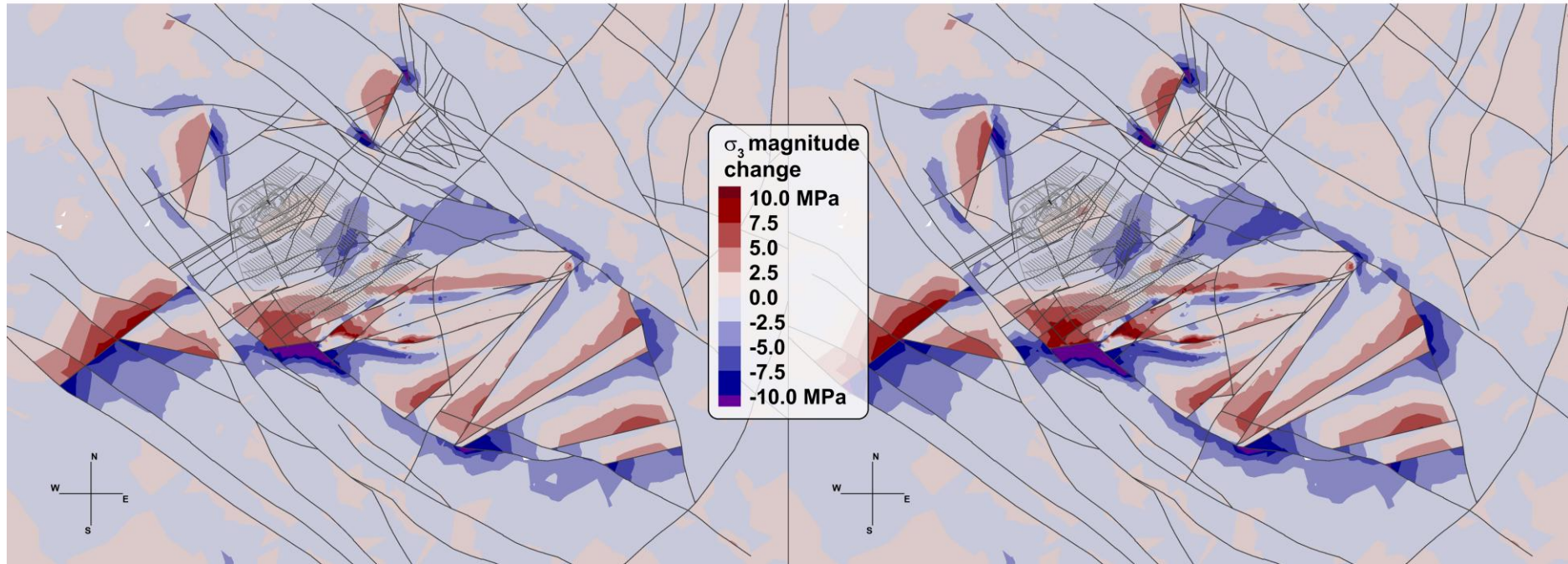


Figure A10- 6. The change in σ_3 magnitude after glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Pre-glacial

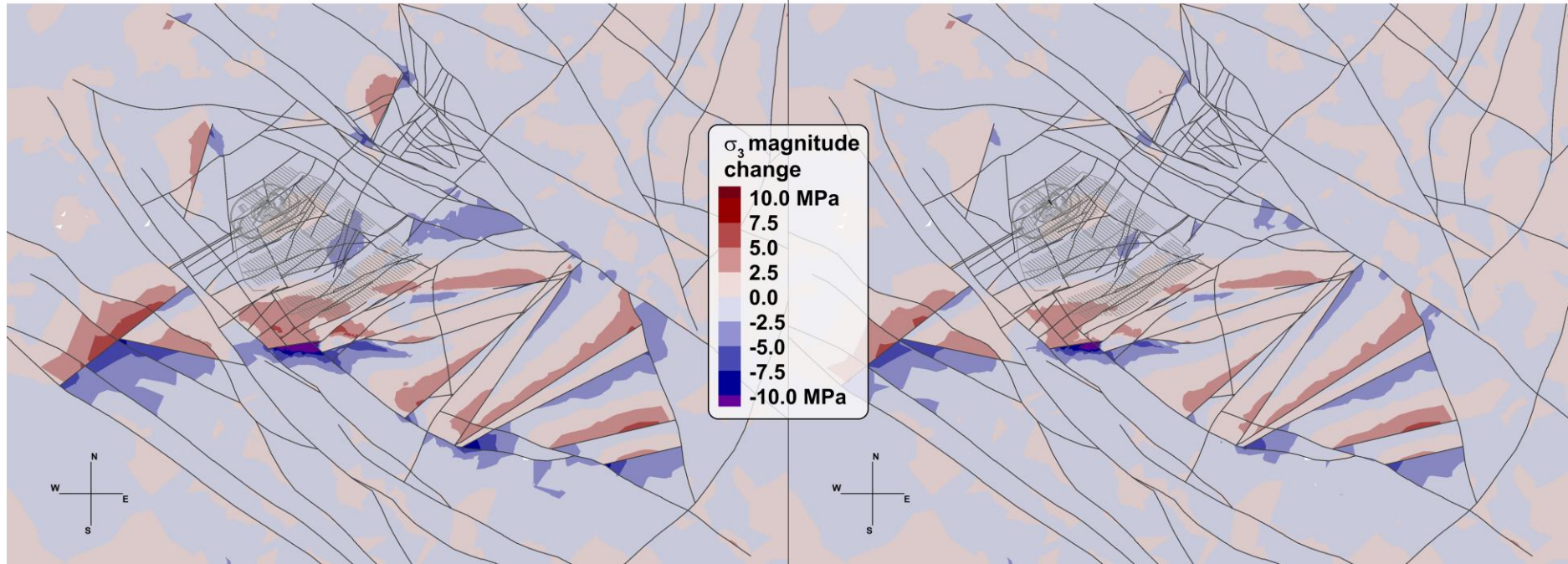


Figure A10- 7. The change in σ_3 magnitude before glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Post-glacial

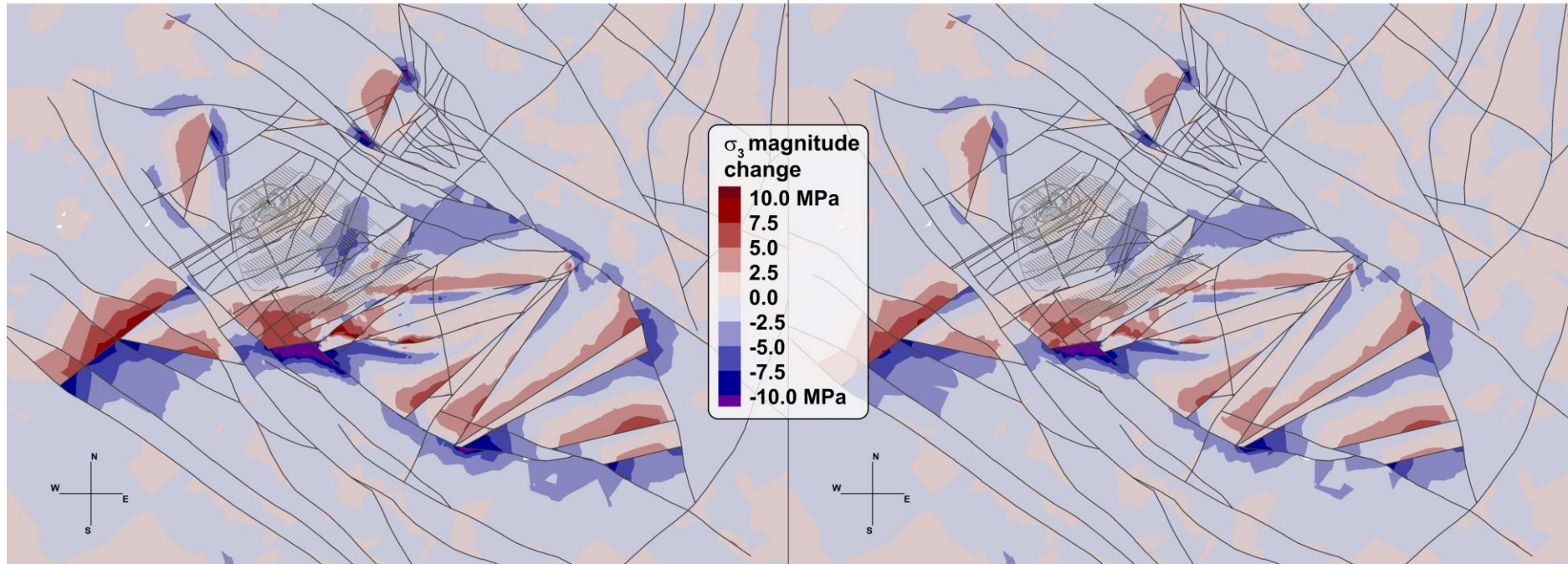


Figure A10- 8. The change in σ_3 magnitude after glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Pre-glacial

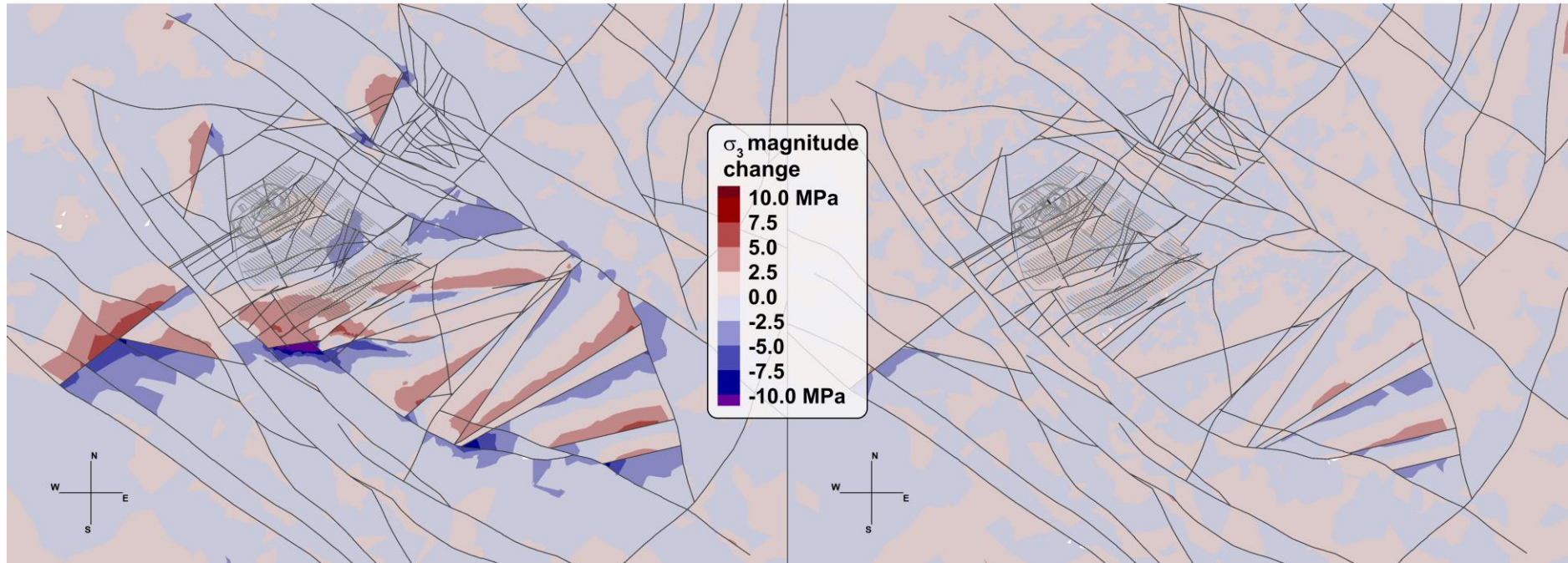


Figure A10- 9. The change in σ_3 magnitude before glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Post-glacial

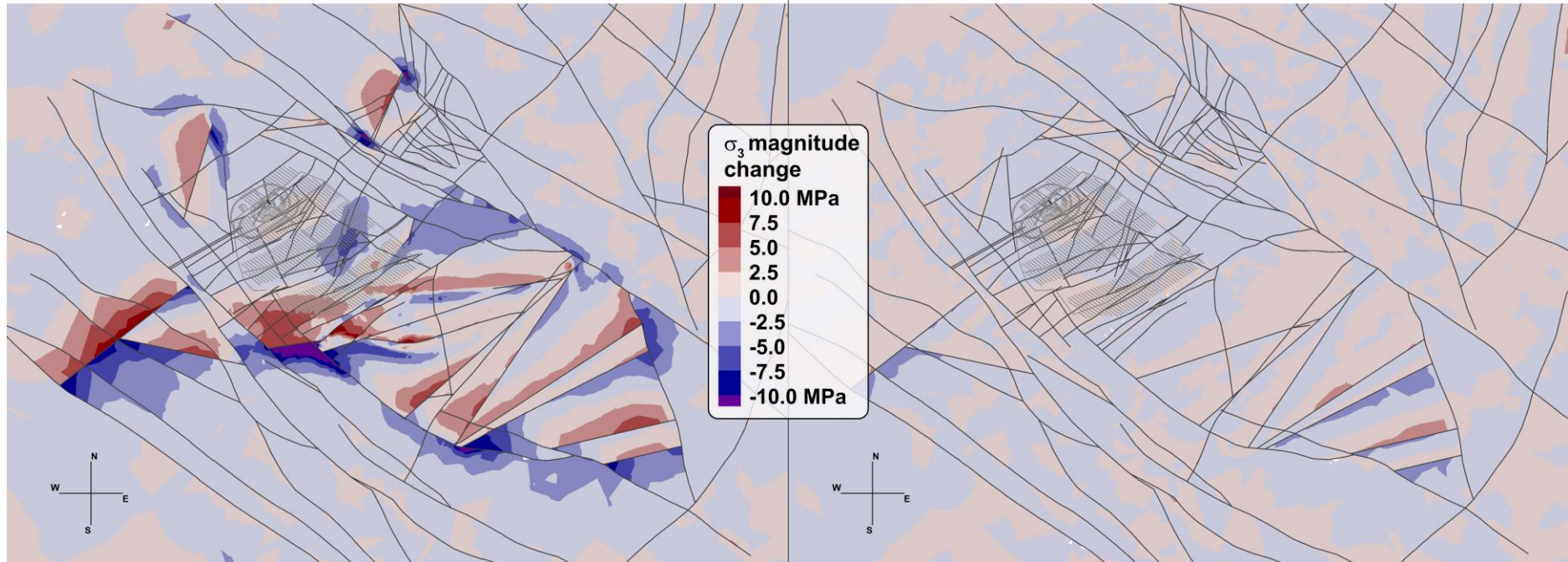


Figure A10- 10. The change in σ_3 magnitude after glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent.*

Appendix 11. Change in σ_1 trend at repository depth

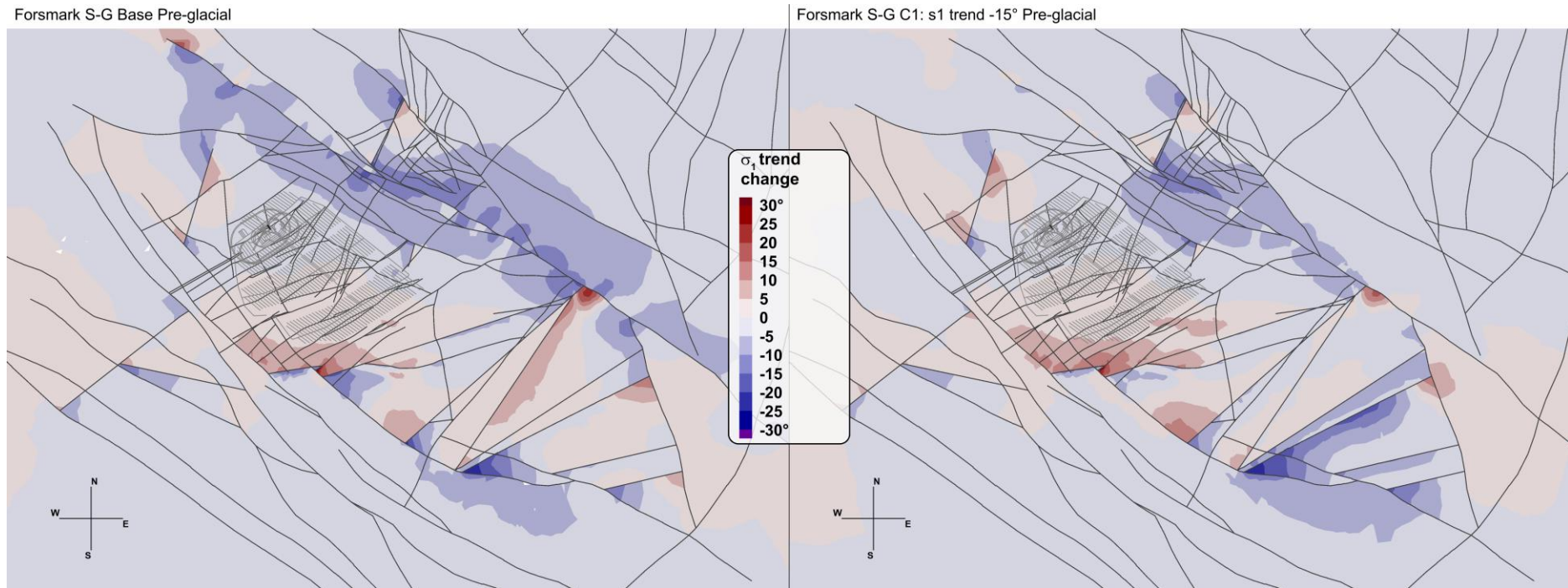


Figure A11- 1. The change in σ_1 trend before glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C1: s1 trend -15° Post-glacial

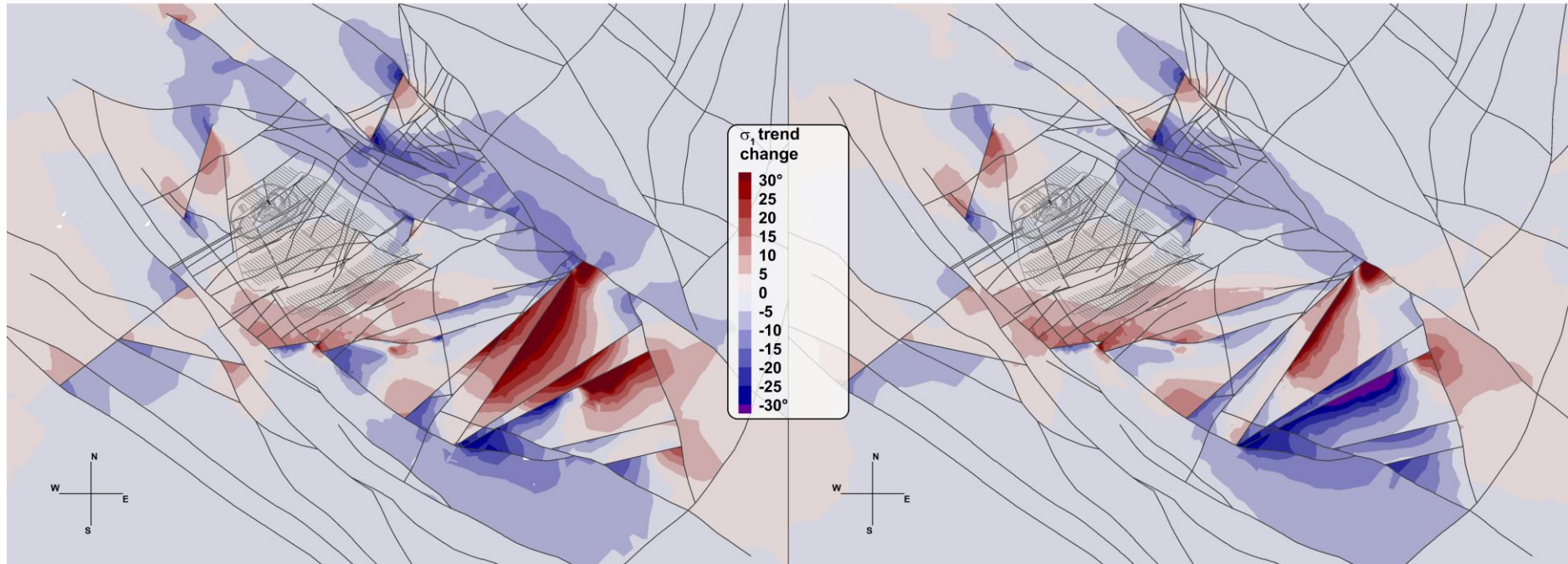


Figure A11- 2. The change in σ_1 trend after glaciation for the Base case and case 1 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C2: s1 trend +15° Pre-glacial

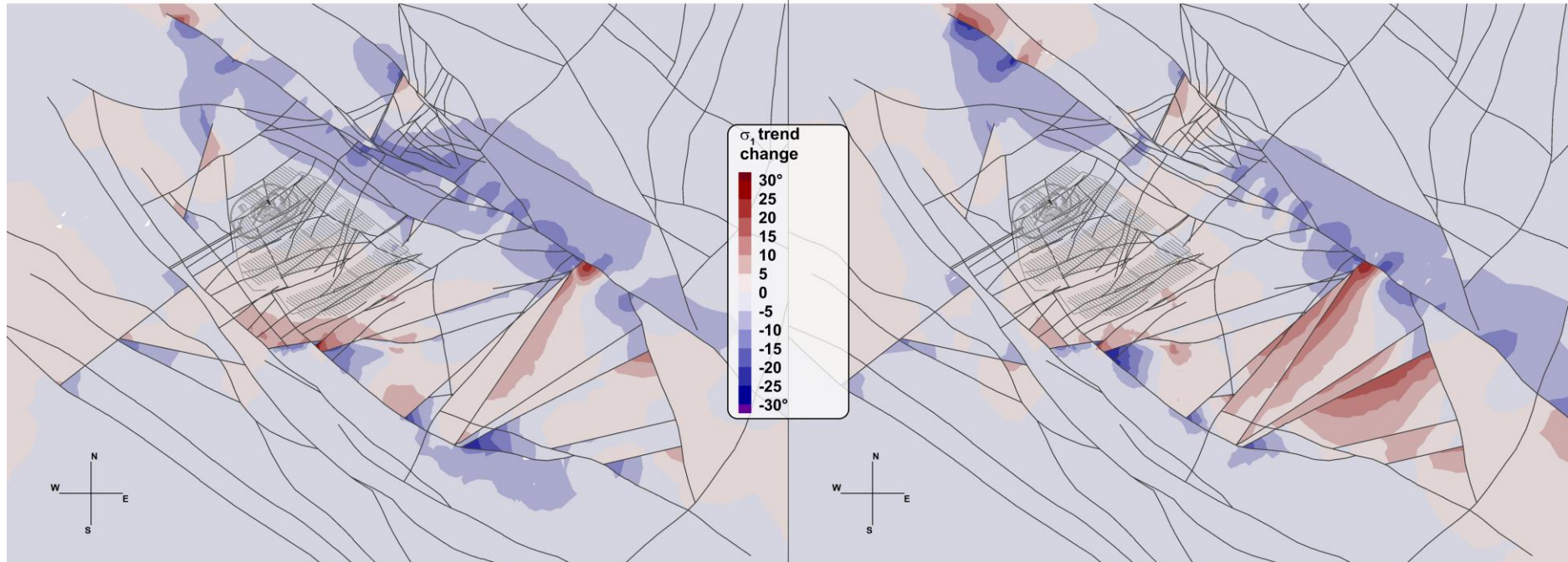


Figure A11- 3. The change in σ_1 trend before glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C2: s1 trend +15° Post-glacial

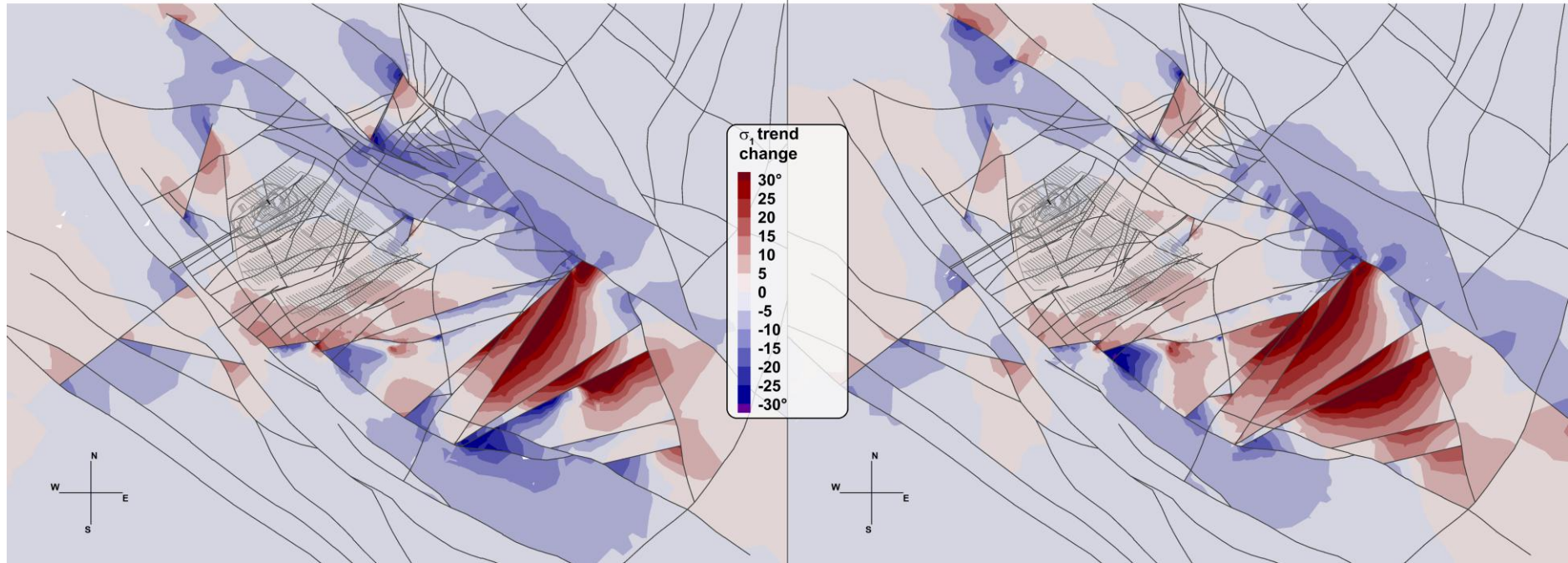


Figure A11- 4. The change in σ_1 trend after glaciation for the Base case and case 2 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Pre-glacial

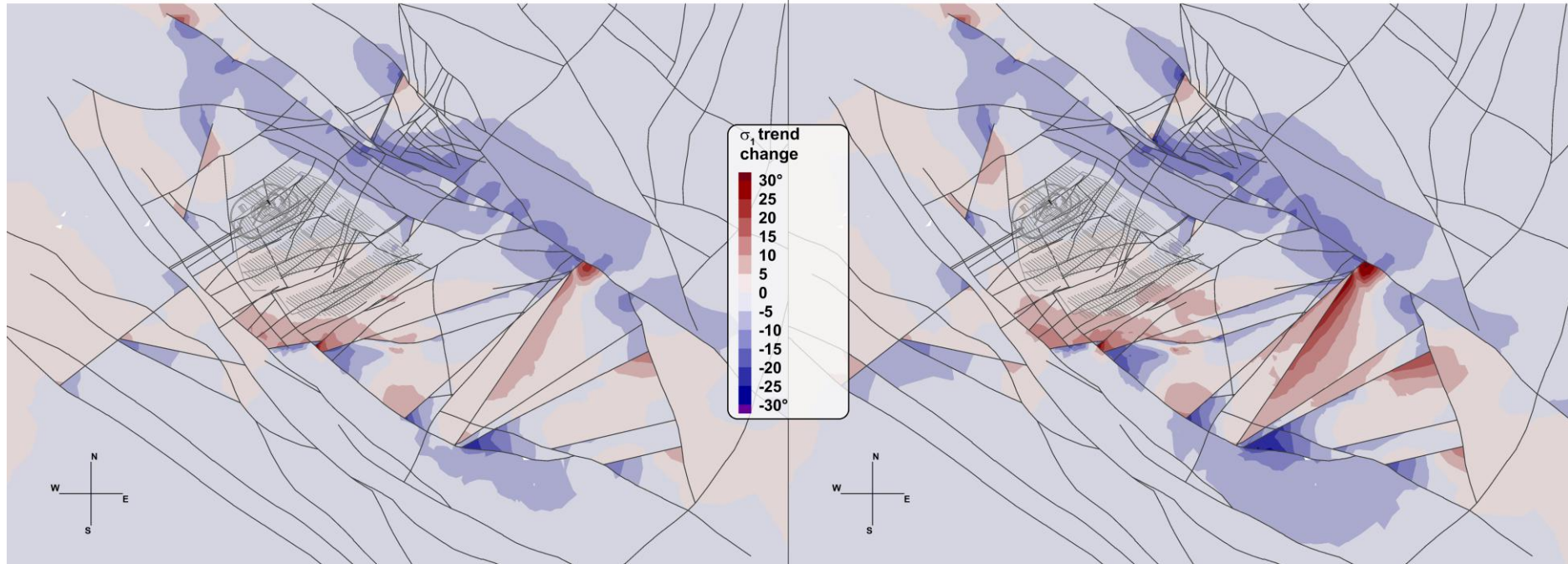


Figure A11- 5. The change in σ_1 trend before glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C3: s1 + 6MPa, s2 + 5MPa Post-glacial

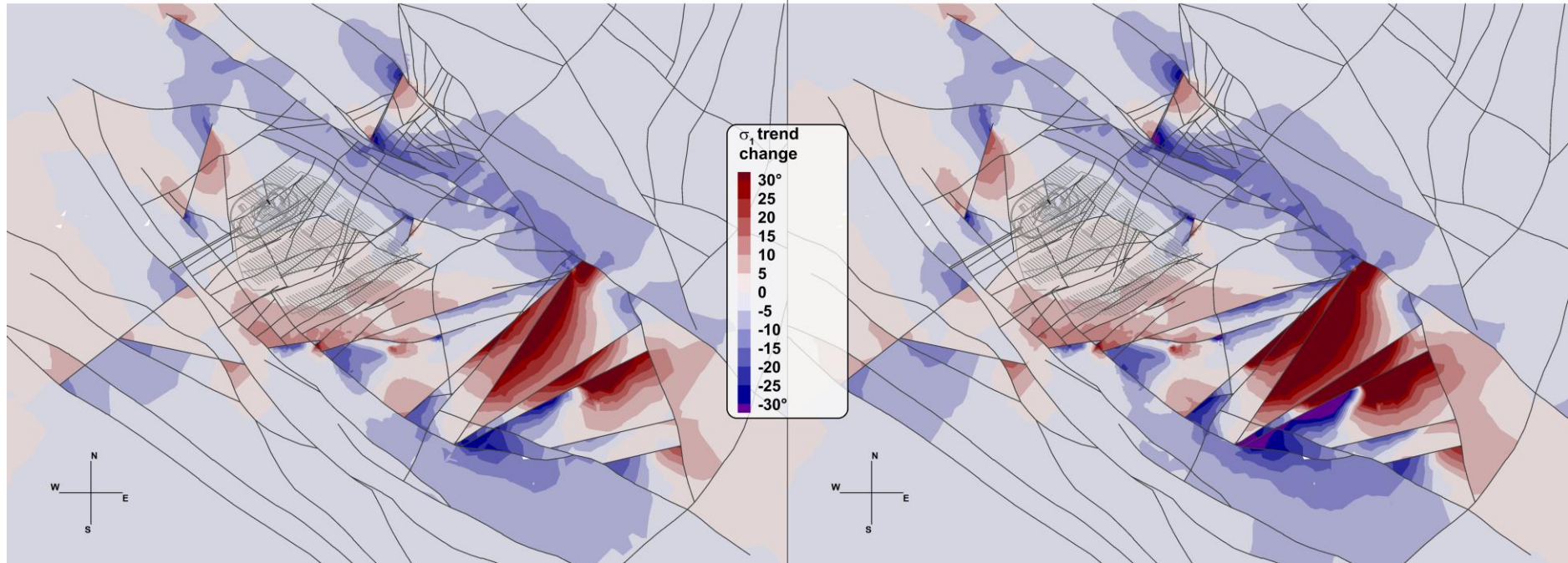


Figure A11- 6. The change in σ_1 trend after glaciation for the Base case and case 3 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Pre-glacial

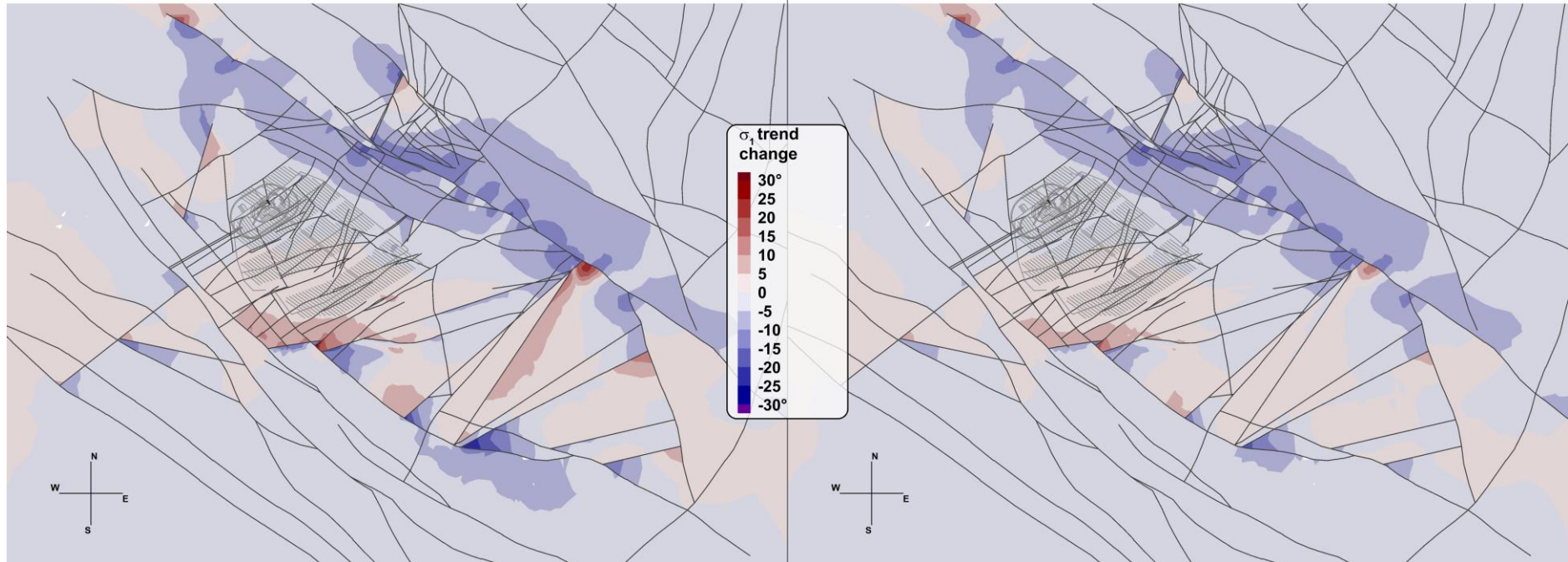


Figure A11- 7. The change in σ_1 trend before glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Post-glacial

Forsmark S-G C4: s1 - 6MPa, s2 - 5MPa Post-glacial

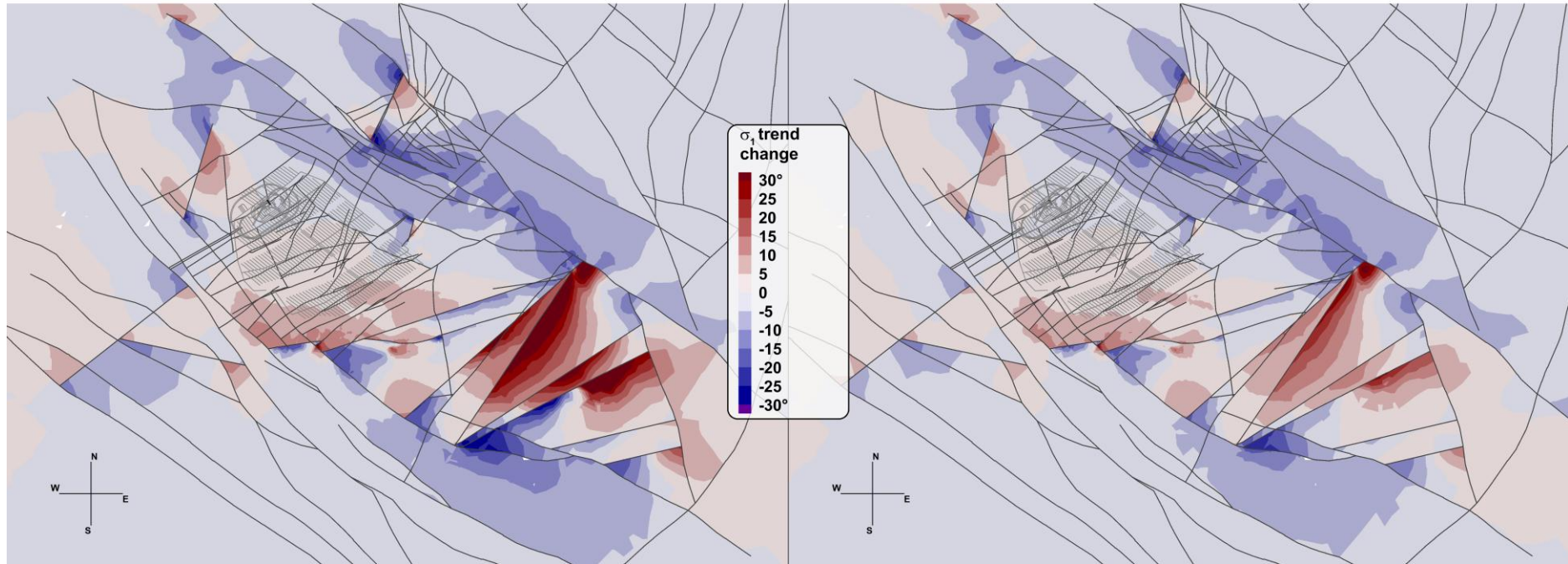


Figure A11- 8. The change in σ_1 trend after glaciation for the Base case and case 4 simulations in a horizontal cross-section at repository depth (470 m). *The reference value is case-dependent.*

Forsmark S-G Base Pre-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Pre-glacial

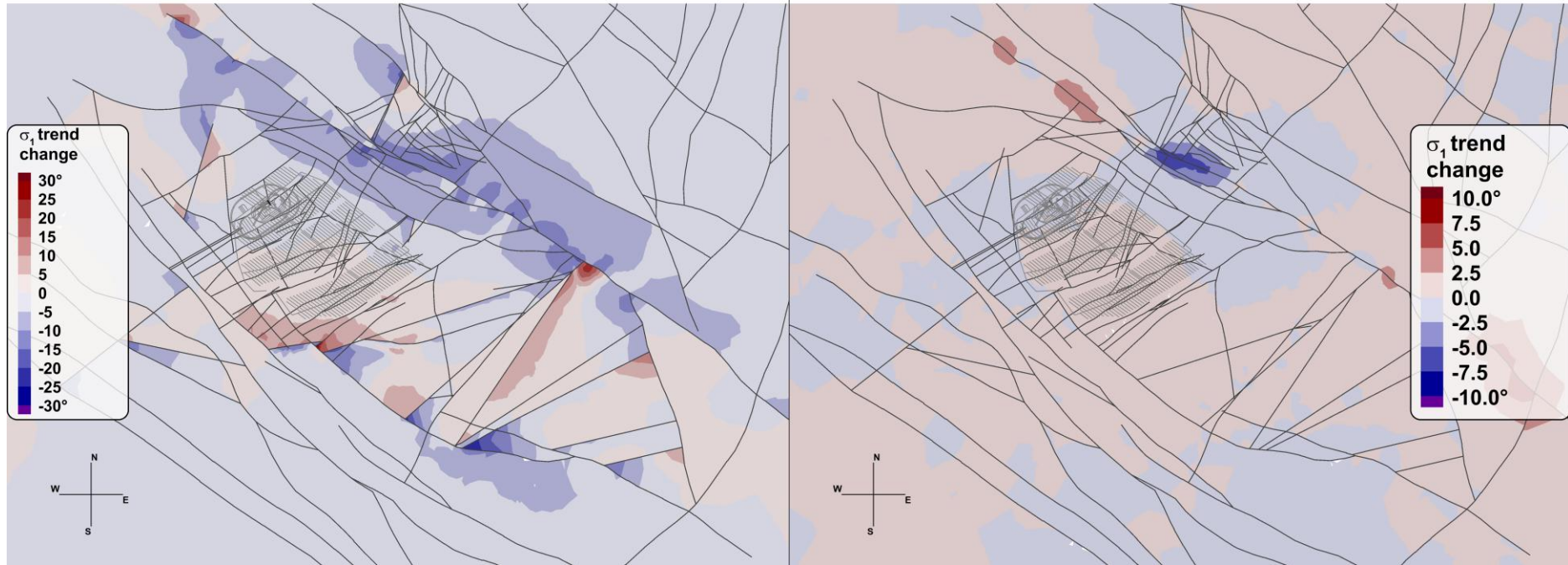


Figure A11- 9. The change in σ_1 trend before glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent. Note the case 5 scale (right) differs from the reference base case scale (left).*

Forsmark S-G Base Post-glacial

Forsmark S-G C5: KFM24 OC, s1 trend 121° Post-glacial

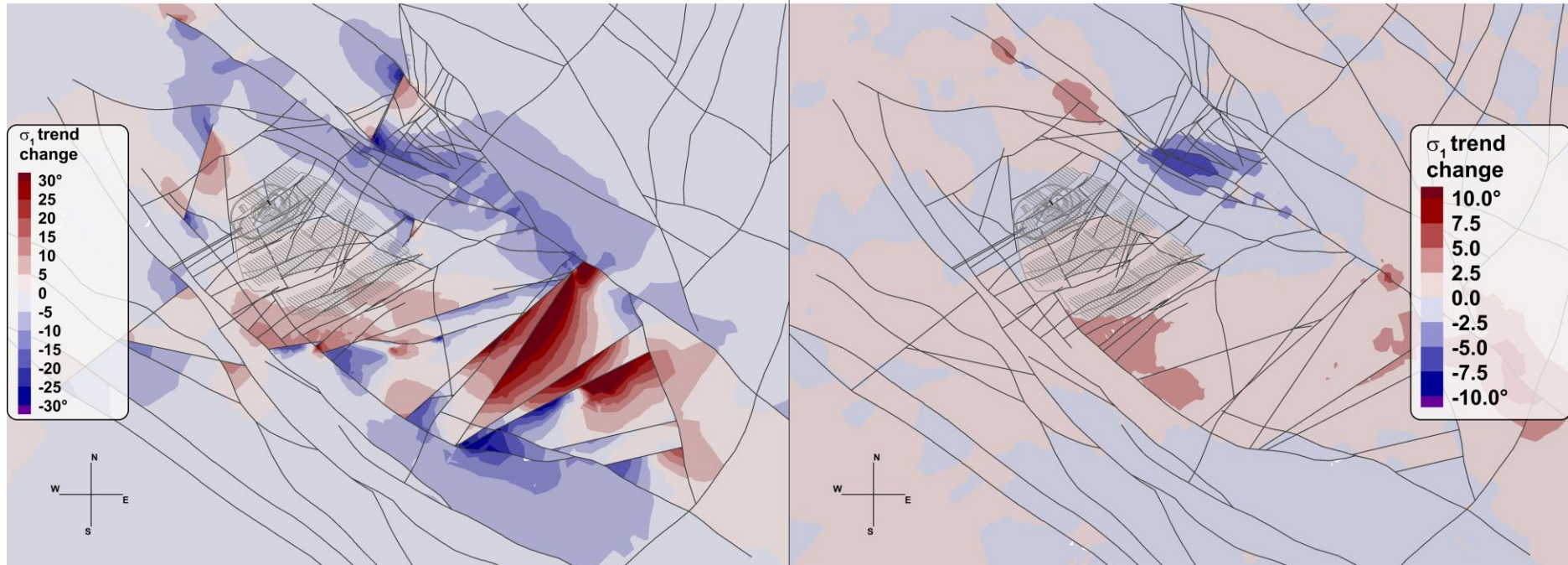


Figure A11- 10. The change in σ_1 trend after glaciation for the Base case and case 5 simulations in a horizontal cross-section at repository depth (470 m) for base case and at KFM24 OC stress measurement depth (560m) for case 5. *The reference value is case-dependent. Note the case 5 scale (right) differs from the reference base case scale (left).*