Updated In Situ Rock Stresses in Norway Based on Recent Estimations and Measurements

A.L.L. Simonsen[1,2] & C.C. Li[1]
1. Norwegian University of Science and Technology, Trondheim, Norway
2. Bane NOR SF, Oslo, Norway

ABSTRACT: This paper presents the current in situ rock stresses in Norway. Information about the stress state was obtained by estimations from focal mechanism, borehole breakout and drilling-induced fractures, and via overcoring and hydraulic fracturing measurements. A N–S and a WNW–ESE major horizontal stress orientations dominated the estimation data from offshore Norway and western, mid and eastern Norway. This is consistent with the ridge push effect from the mid-Atlantic ridge. The measurement data from onshore Norway had scattered orientations, probably caused by local factors like topography. The major horizontal stress generally exceeded the vertical stress in the Norwegian region with an average ratio of 1.2. The stress gradients appeared to decrease with increasing overburden. The influence of topography on the principal stresses seemed to decrease inwards the rock mass. It is intended to update the Fennoscandian in situ rock stress database with the data collected.

1 INTRODUCTION

In situ rock stress is an important parameter that needs to be considered in underground excavation. The in situ stresses play a fundamental role for stability of man-made structures in rock. The current stress state in the Earth's crust is a result of the overburden, the making processes of rock, the plate tectonics, geological structures and the topography. Mountainous topography significantly changes the stress state locally. This paper presents the current in situ rock stresses in Norway with recent data obtained with estimation and measurement methods. The magnitudes and orientations of the principal stresses, stress state related to bedrock, as well as topography will be discussed.

2 IN SITU STRESS ESTIMATION AND MEASUREMENT METHODS

The stress data collected was obtained with both estimation and measurement methods. Estimation methods are methods that observe rock mass behaviour without disruptions. Measurement methods disturb the in-situ conditions by inducing strain, deformation or open fractures (Ljunggren et al., 2003).

2.1 *Estimation methods*

The estimation methods the data was obtained with were focal mechanism, borehole breakout and drilling-induced fractures. The data records were obtained at depths of about 1-50 km.

2.1.1 *Focal mechanism*

Focal mechanism is an estimation method that utilises earthquake records to determine in situ stress orientations. The principal stress orientations can be derived from fault geometry (Amadei

& Stephansson, 1997). The data obtained by focal mechanism, used the primary wave (P-wave) first motion to identify fault geometry. The direction of motion of the first component of the P-wave recorded by seismographs, is related to the direction of slip on the fault that caused the earthquake. If the first motion is uwards, it is an compressional wave and the fault is moving towards the sesimograph. Whereas if the first motion is dowwards, it is a dilatational p-wave and the fault is moving away from the seismograph (Cronin, 2010).

2.1.2 *Borehole breakout and drilling-induced fractures*

Borehole breakouts are elongations of the borehole cross section that occur under high stress concentration. These elongations can be used to estimate the orientation of the principal stresses acting perpendicular to the borehole axis. The spalling occurs at the points of maximum compressive stress concentration, and the breakouts will develop perpendicular to the major principal stress along the axis of the minor principal stress (Haimson & Herrick, 1986). Borehole breakouts are illustrated to the left in Figure 1. Borehole breakouts are illustrated to the left and drilling-induced fractures are illustrated to the right. S1 represents the major principals stress perpendicular to the borehole axis, while S3 represents the minor principal stress.

Drilling-induced-fractures (DIF) occur when the stress concentration around a borehole goes into tension that exceeds the tensile strength of the rock (Zoback & Zoback, 2002). Just as with borehole breakouts, the fractures can be used to estimate the orientation of the principal stresses acting perpendicular to the borehole axis. The fractures are narrow and will develop perpendicular to the minor principal stress, along the axis of the major principal stress. DIFs are illustrated to the right in Figure 1.

Figure 1. Borehole breakouts are illustrated to the left and drilling-induced fractures to the right. S1 represents the major principals stress perpendicular to the borehole axis, while S3 represents the minor principal stress.

2.2 *Measurement methods*

The measurement methods utilised to determine stress orientations and magnitudes were overcoring and hydraulic fracturing. Data obtained with these methods were retrieved at overburdens of 11 to 1300 m.

2.2.1 *Overcoring*

Overcoring in-situ stress determination methods are methods that isolate rock cores from the rock mass to destress the cores and monitor its responses. To monitor the response of the core, strain gauges are used to measure elastic strain. It follows from Hooke’s law that strain is linear related to stress. Stress can be calculated from strain if the elastic properties of the rock are known (Amadei & Stephansson, 1997). Both stress orientations and magnitudes can be calculated with overcoring methods. The ovecoring data collected was obtained with both two- and three-dimensional methods.

2.2.2 *Hydraulic fracturing*

Hydraulic fracturing is a two-dimensional method where orientation and magnitude of the stresses perpendicular to the borehole axis are measured. Hydraulic fracturing is carried out by injecting fluid into at sealed-off, fracture-free section of a borehole to create fractures in the walls. The fractures are initiated when the rock mass fails in tension, the orientations of the fractures are related to the in-situ stress field. The fractures will initiate at the points in the borehole that offer least resistance. This will be parallel with the major principal stress perpendicular to the borehole axis (same fracture types as DIFs) (Ljunggren et al., 2003). A flowmeter is used to measure flow with time, and in opposition to overcoring, stress is measured directly.

3 THE COLLECTED DATA

A total of 115 data records have been collected from on- and offshore Norway, and from Svalbard. Data from estimation methods makes up 64% of the data, while 36% is from measurement methods. The distribution of stress determination method is presented in Figure 2.

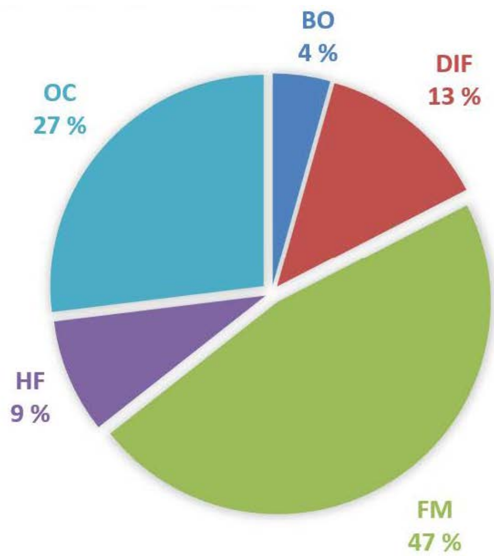

Figure 2. Distribution of stress determination among the collected data. BO = borehole breakout, DIF = drilling-induced fractures, FM = focal mechanism, HF = hydraulic fracturing and OC = overcoring.

4 ANALYSIS OF THE COLLECTED DATA

4.1 *Orientation of major horizontal stress*

In Figure 3, a stress map produced and analysed by Fejerskov et al. (2000) is presented. From the figure it can be seen that there is a consistent N-S σ_H orientation in the Barents Sea north of the mainland and in northern Norway. In the Norwegian Sea further south, and at the same latitudes on mainland Norway, Fejerskov et al. (2000) identified a rotation of σ_H towards a NW-SE to WNW-ESE orientation. In Figure 3, it is evident that the data is scattered in western Norway and northern North Sea. Still, according to Fejerskov et al. (2000), a WNW-ESE σ_H trend could be identified from the data.

Figure 4 presents σ_H orientations from the stress data collected. In Figure 4 and to the left in Figure 5 the borehole breakouts and DIFs records from the Barents Sea (above the 70° North line) have N-S to NNW-SSE orientations. Thus, the N-S σ_H orientation Fejerskov et al. (2000) found can be recognised in this data. This orientation can be a result of the ridge push effect from the mid-Atlantic ridge. The ridge push effect creates compressional stresses that act perpendicular to the crest of the ridge (Zoback et al., 1989).

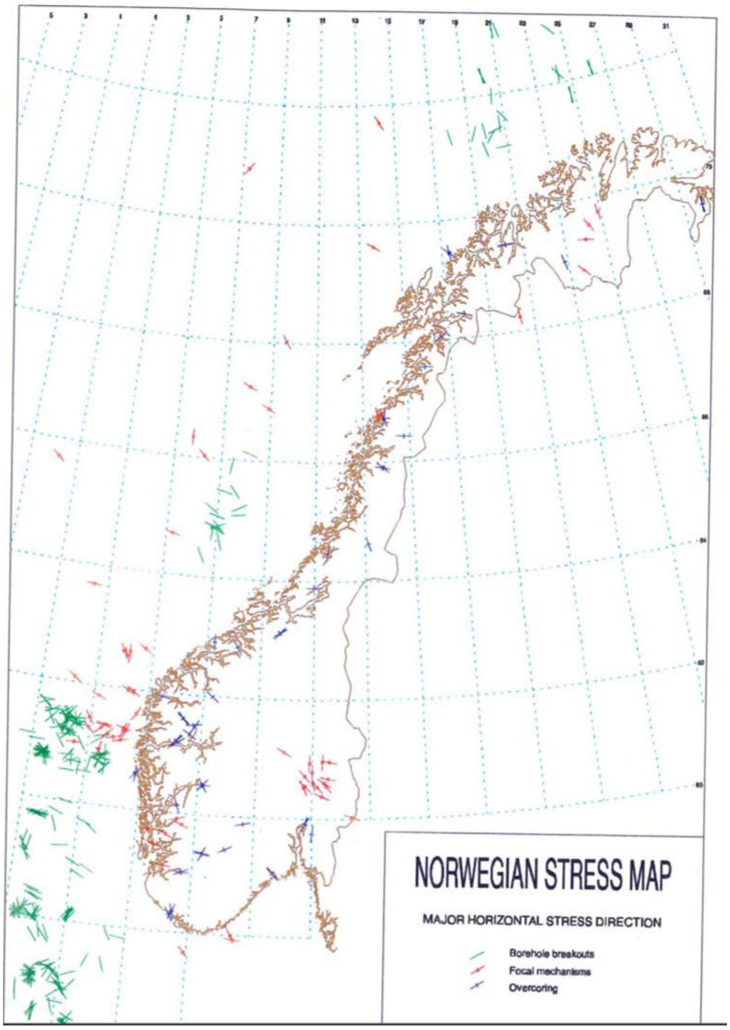

Figure 3. Norwegian stress map (Fejerskov et al., 2000).

In the Norwegian Sea, a WNW-ESE trend can be identified (data presented from 62° to 70° North in Figure 4 and to the middle in Figure 5). This orientation coincides with the findings of Fejerskov et al. (2000). They concluded that this orientation was likely caused by the rotation of the mid-Atlantic ridge in this area and the corresponding ridge push effect. However, a coast-perpendicular compressive σ_H orientation can also be a result of sedimentary loading on the continental shelf. Sediment loading creates compressional horizonal stresses beneath the load that act perpendicular to the coast (Fejersko & Lindholm, 2000). According to Fejerskov & Lindholm (2000), the sediment rate in the Norwegian Sea in Pliocene may have been high enough to create bending stresses. Onshore at the same latitudes, the data is scattered and there is difficult to identify any stress trends.

In Figure 4 from 58°-62° North, two different σH trends can be identified in the North Sea: W-E and WNW-ESE orientations. A WNW-ESE orientation correlates well with both the ridge push effect and sediment loading. However, the sediment rate here has been lower than in the Norwegian Sea, and its effect is therefore more unclear.

By comparing the rosettes in Figure 6, it may look like the σ_H orientations onshore in eastern, western, mid and eastern Norway are dependent on the overburden of the data points. The middle rosette in Figure 6 shows data from these areas obtained with focal mechanism at depths of 5–50 km. From this rosette, a WNW–ESE σ_H trend can be identified. To the right in Figure 6, measurement data with overburdens of 25–700 m are presented and there is no WNW–ESE trend. This can be a consequence of local factors that can affect the stress field more at shallow depths, while with increasing depths the stress field may be more a result of tectonic stresses.

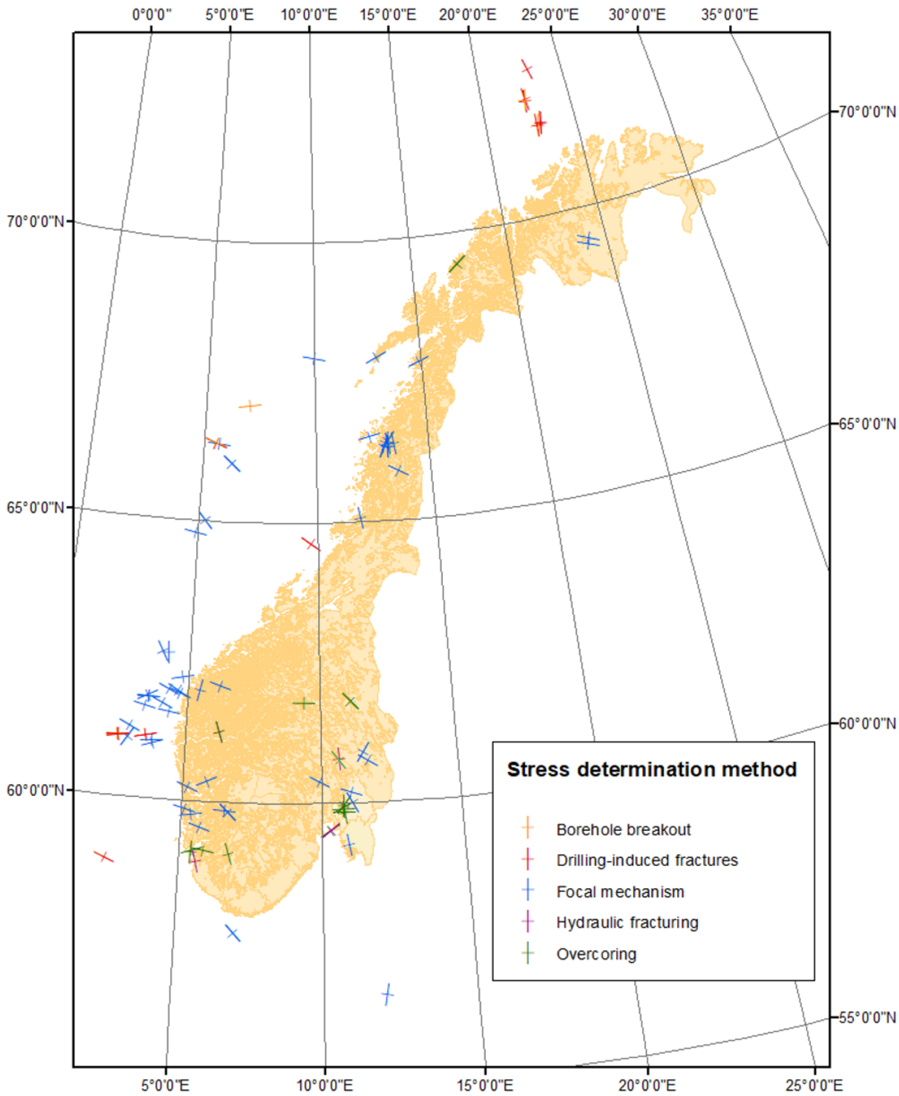

Figure 4. σ_H orientations from the collected data for Norway.

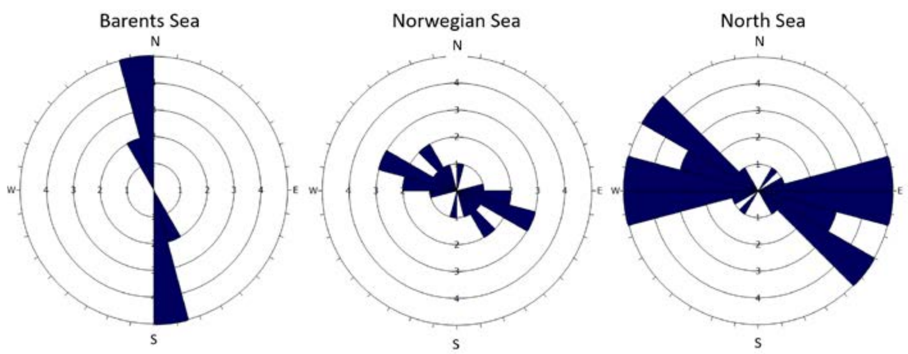

Figure 5. Collected σ_H orientation from the Norwegian continental shelf presented in rosette plots. Each arc segment has a width of 15 degrees and each circle represents one data point.

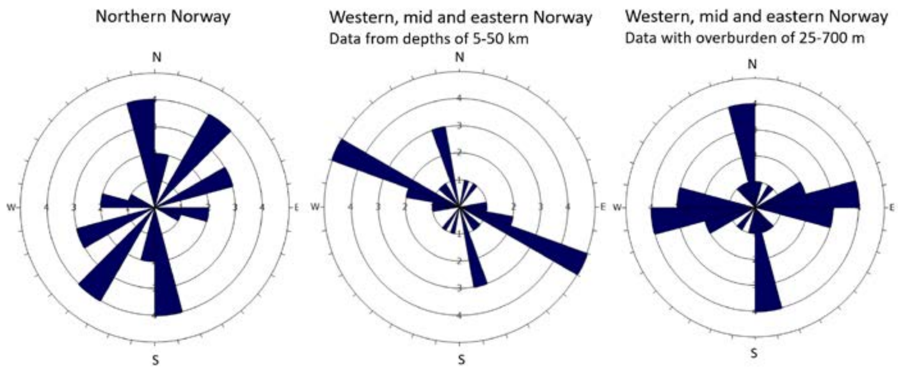

Figure 6. Collected σ_H orientation from mainland Norway presented in rosette plots. Each arc segment has a width of 15 degrees and each circle represents one data point.

4.2 *Stress magnitudes*

In Figure 7, the relationship between the major horizontal stress and the vertical stress from the data collected is presented. From the figure it is evident that the major horizontal stress is bigger than the vertical with a ratio of 1.2. This suggests that the in-situ stress state in Norway is a result of more than gravitation. If the in-situ stress field was purely gravitational, σ_H would be smaller than σ_V. The ridge push effect may be the main source for the high horizontal stresses observed in the Norwegian region. That σ_H exceeds σ_V in the Norwegian region correlate well with other stress analysis performed among others by Myrvang (1996) and Hanssen (1997).

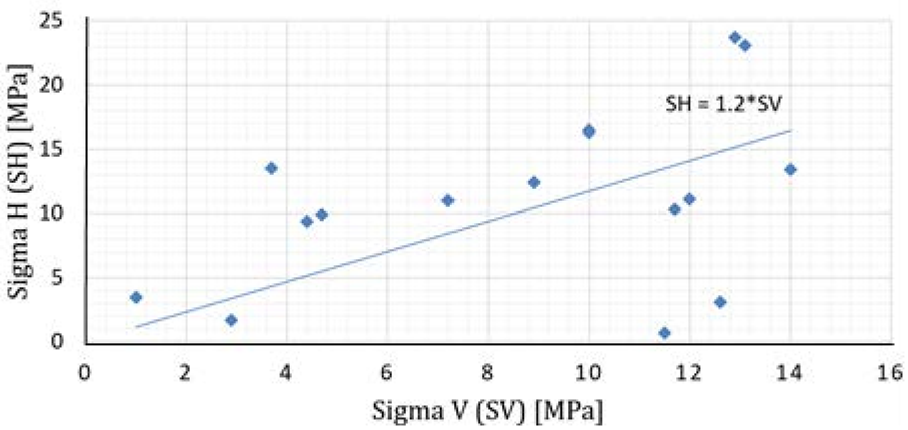

Figure 7. The major horizontal stress plotted against the vertical stress.

4.3 *Bedrock*

Table 1 shows stress gradients and the relationship between the principal stresses sorted by lithology and geological age of the rock mass. From Table 1, it can be seen that the ratio of σ_1/σ_2 for sedimentary rocks is higher than for igneous and metamorphic rocks. Most of the data from sedimentary rocks was conducted with two-dimensional overcoring, and it was therefore not enough data to calculate the other ratios. A higher stress ratio implies that the stress field is more anisotropic. Sedimentary rocks can often show clear anisotropy due to layering. Igneous rocks are on the other hand not known to be anisotropic, and the data from metamorphic rocks is mainly located in gneisses which usually have a low degree of anisotropy. This can imply that rock anisotropy contributes to a more anisotropic stress field.

From Table 1, it can also be observed that the stress gradients for the sedimentary rocks are higher than for igneous and metamorphic rocks. This has been evaluated to be related to the overburden of the data points. Analysis of all the 35 data points with information about stress magnitudes showed that the deeper points often had smaller gradients. The sedimentary data points are located at depths of 11 - 400 m, while data from igneous and metamorphic rocks have overburdens of 15–1300 m. The probable dependence of the stress gradient on overburden could be caused by local factors like topography, geological structures and discontinuities. The local factors usually affect the stress field more at shallow locations than at depth in the Earth's crust.

By sorting the data according to the geological age of the rock mass, the gradients for Precambrian rocks are higher than those from Cambrian-Silurian age. This coincides with the results of Myrvang (1996) who stated that Precambrian rocks and Permian intrusion in general have higher stresses than the average in Norway, while Cambrian-Silurian rock types have lower stresses than the average.

It is worth noticing that the results in Table 1 are based on relatively small data sets. There are only six points from sedimentary rocks, 21 from igneous and metamorphic, ten from Cambium-Silurian and 13 in Precambrian rock mass. This reduces the reliability of the results presented in Table 1.

Table 1. Different stress gradients or ratios for all entries, lithology and geological age.

Stress ratios	All data points	Lithology		Geological age	
		Sedimentary	Igneous & Metamorphic	Cambrian-Silurian	Precambrian
σ_1/Z	0.047	0.054	0.044	0.043	0.047
σ_2/Z	0.031	0.0.38	0.029	0.028	0.030
σ_3/Z	0.023		0.023	0.017	0.025
σ_2/σ_3	1.45		1.42	1.78	1.36
σ_1/σ_2	1.44	2.06	1.36	1.46	1.35
σ_1/σ_3	1.90		1.86	2.24	1.80

4.4 *Topographical effects*

The four data points presented in Figure 8 have been analysed to see what effect topography has on the in-situ stress field. Valleys and mountain sides will often change the stress field. The principal stresses σ_1 and σ_2 will be rotated to become parallel with the slope surface, while σ_3 will be reoriented perpendicular to the surface. This was also the case for two of the four points shown in Figure 8. However, the point to the left in the figure and the point to the right did not coincide with the theory. These data points are located far from the slope surface. Therefore, it seemed that the effect of topography on the in-situ stress field decreases with increasing in the distance to the ground surface.

5 CONCLUSION

Two main σ_H orientation trends were found in Norwegian region from the estimation data. A N–S orientation dominates in the Barents Sea, while a WNW–ESE orientation dominates in the Norwegian and North Sea, and at the corresponding latitudes onshore. These trends are consistent with the ridge push effect from the mid-Atlantic ridge. The measurement data were scatted, likely due to local features such as topography since the measurement points are located at shallower depths than those determined by the estimation methods. The horizontal stress generally exceeds the vertical in the Norwegian region with a ratio of 1.2. Tectonic stresses from the mid-Atlantic ridge could also be the reason for this. Sedimentary rocks have higher stress gradients than igneous and metamorphic rocks. Based on the comparison of the data, it seems that the gradients are dependent on the overburden of the data points. The gradients decrease with increasing overburden. The sedimentary rocks also have more stress anisotropy, which may indicate that stress anisotropy is correlated to rock anisotropy. Rocks of Precambrian age have higher stress gradients than rocks of Cambrian-Silurian age. However, the sorting data after lithology and geological age are relatively small, which reduces the reliability of the results. It seems that the effect of topography on the principal stress orientations decreases inwards in the rock mass.

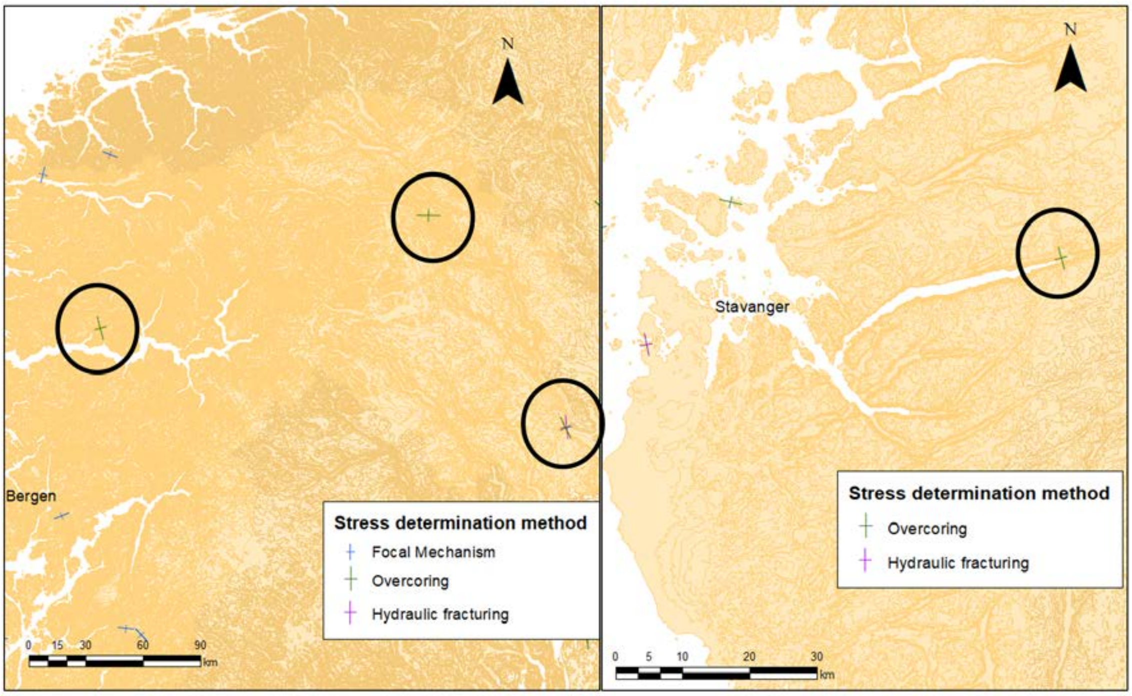

Figure 8. Four points located in mountainous topography in western Norway. The symbols show σH orientation.

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