



Patterns of crustal stress derived from the World Stress Map database 2025

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Abstract. Knowledge of the present-day stress field of the Earth's crust is essential for understanding geodynamic processes, as well as for the exploration and management of geo-reservoirs. The World Stress Map (WSM) project provides the only open-access global database of crustal stress information. To mark the project's 40th anniversary, the WSM database has been substantially updated, and now contains more than twice the number of data records on the orientation of maximum horizontal stress (S_{Hmax}) in comparison to the previous release in 2016. The new database includes 100,842 quality-ranked data records documenting the S_{Hmax} orientation in the Earth's crust. As stress data records are clustered around plate boundaries and in sedimentary basins, we provide mean S_{Hmax} orientation estimates on regular global grids of 2°, 1°, 0.5° and 0.2° to facilitate the analysis of stress patterns. The results reveal that in intraplate regions, where stress data density has increased significantly, the earlier hypothesis that plate boundary forces and relative plate motion primarily control S_{Hmax} orientation needs to be revised. S_{Hmax} rotates by more than 50° over spatial scales of 50-500 km. Two notable examples include an ~50° rotation of S_{Hmax} in the Alpine foreland, from N-S in the East to NNW-SSE in the West, and several S_{Hmax} rotations > 50° over distances of less than 100 km in eastern Australia.

1 Introduction

The present-day stress field of the Earth's crust is a key physical quantity for understanding geodynamic processes, such as global plate tectonics and earthquakes. With the anticipated increase in subsurface use, such as the exploration of deep geothermal reservoirs and geo-energy storage, new and modified utilisation concepts place additional demands on geomechanical integrity and long-term stability, making knowledge of crustal stress equally essential for applied research (Addis, 2017; Zoback, 2010; Ziegler et al., 2024; Segall and Fitzgerald, 1998).

Stress data for the upper crust were first collected in the 1930s using surface relief methods. In the 1950s, flat jack and borehole relief methods were introduced, followed by hydraulic fracturing in the 1970s to measure the magnitude of the least principal stress (Amadei and Stephansson, 1997). The late 1970s saw the use of borehole breakouts as additional stress indicators by interpreting borehole breakouts as stress-induced features (Bell and Gough, 1979; Plumb and Hickman, 1985;



Hottman et al., 1979). Furthermore, the expansion of global seismological networks in the 1960s, originally established to detect nuclear weapons tests, and the development of global digital seismograph networks in the 1970s, led to an increase in earthquake focal mechanisms used as stress indicators for the deeper part of the Earth's crust (Dziewonski et al., 1981). These advancements, along with other stress indicators from engineering, geological, and geophysical methods, ultimately led to the initiation of the World Stress Map (WSM) project in 1986 as a task force of the International Lithosphere Program. The initial objective of the WSM was to test Voight's mid-1960s hypothesis that plate tectonics forces predominantly control the orientation of the maximum horizontal stress (S_{Hmax}) in the Earth's crust (Voight et al., 1968). This hypothesis was broadly supported by the first release of the WSM database in 1989, which included approximately 3,600 quality-ranked data records (Zoback et al., 1989). However, the subsequent 1992 release, containing more than 7,300 data records, revealed second-order contributions from lateral density and strength contrasts, producing stress patterns with wavelengths on the order of several hundred kilometres (Zoback, 1992). A further expanded WSM version, comprising 15,969 data records, confirmed these second-order patterns and also showed examples of S_{Hmax} rotation on smaller scales (Heidbach et al., 2007). The new 2025 release of the WSM, with 100,842 data records, allows these local rotations to be resolved in greater detail. This paper presents the 2025 release of the WSM project, and a revised quality-ranking scheme for S_{Hmax} orientations. Because the stress data are strongly clustered, we also provide 13 datasets of the mean S_{Hmax} orientation on global grids, filtered for different wavelengths of the crustal stress pattern.

2 New World Stress Map 2025 based on an update of the quality-ranking scheme

The backbone of the WSM is its quality-ranking scheme for in-situ stress data, which allows comparison of rock stress information obtained from different methods that sample very different rock volumes (Ljunggren et al., 2003). Most techniques used to estimate individual components of the 3D stress tensor rely on observed deformations, from which the relevant stress information is derived (Schmitt et al., 2012; Amadei and Stephansson, 1997; Zang and Stephansson, 2010; Zoback, 2010). For this reason, the WSM uses the term *stress indicator* for the methods rather than *stress measurement*. The only exception is microhydraulic fracturing tests in boreholes, where fluid pressure is directly measured as an equivalent of the minimum principal stress magnitude (Haimson and Cornet, 2003; Schmitt and Haimson, 2018; Thiercelin et al., 1996; Desroches et al., 2023).

The new WSM employs eight established stress indicators: overcoring (OC), hydraulic fracturing (HF), borehole breakouts (BO), drilling induced tensile fractures (DITF), geological fault slip (GFI), volcanic alignments (GVA), earthquake focal mechanisms (FMS), and inversions of several earthquake focal mechanisms (FMF) (Zoback and Zoback, 1991; Zoback, 1992; Sperner et al., 2003; Heidbach, 2016). These stress indicators act on scales ranging from 10^{-3} m^3 (OC) to 10^9 m^3 (FMS) (Ljunggren et al., 2003; Zang and Stephansson, 2010). Each method also carries implicit assumptions about how stress information is derived. To enable the integration of these diverse stress indicators, the WSM uses a quality-ranking scheme based on the number, accuracy, and depth of the information provided.



The quality-ranking scheme was initially introduced by Mary-Lou Zoback and Mark Zoback (1989), summarized by Mary-Lou Zoback (1992), refined and extended by Sperner et al. (2003), and updated by Heidbach et al. (2010). Each data record is assigned a quality between A and E, with A representing the highest quality and E the lowest. An A-quality indicates that the S_{Hmax} orientation is accurate within $\pm 15^\circ$, B-quality within $\pm 20^\circ$, C-quality within $\pm 25^\circ$, and D-quality within $\pm 40^\circ$. For most stress indicators, these quality classes are defined based on the standard deviation of S_{Hmax} , with E-quality data records typically exceeding a standard deviation of 40° . In general, data records assigned to A-, B-, and C-quality classes are considered reliable for analysing stress patterns and interpreting geodynamic processes.

For the 2025 release of the WSM, the quality-ranking scheme was refined to reflect the latest technical developments and to define clearer rules for quality assignment in a format suitable for implementation in Python routines. This enables the automated assignment of quality in the new WSM database infrastructure MaRS (Management and Repository of Stress) (Rajabi et al., 2025). In addition, three stress indicators that are now rarely used, i.e., borehole slotter BS, average of focal mechanisms, FMA, and petal centerlines PC, were removed from the quality-ranking scheme. We also introduce a new X-quality class, assigned to data records with missing information (X_{mi}), data records derived from rarely used stress indicators (X_{ru}), and data records derived from stress indicators that are not well established (X_{ne}). Further details on the updated WSM quality-ranking scheme, descriptions of stress indicators, new guidelines for the analysing of borehole logs, and technical details of the WSM 2025 database are provided in the WSM Technical Report 25-01 (Rajabi et al., 2025).

As outlined above, the new WSM 2025 database contains 100,842 data records (Table 1), more than double the number in the previous 2016 release (Heidbach et al., 2018). This expansion is largely due to the integration of the global compilation of earthquake focal mechanisms from the International Seismological Commission (ISC) (Lentas et al., 2019), and the addition of more than 4,000 new stress data records derived from boreholes across the world.

Table 1. Data records of the new WSM database 2025 sorted in classes of data quality and stress indicators. The discrepancy of 792 data records to the entire WSM 2025 dataset with 100,842 data records is due to the missing data records from stress indicators that are rarely used (X_{ru} -quality for BS, PC, FMA) and those from methods that are not yet established as reliable stress indicators (X_{ne} -quality). Details are given the WSM Technical Report TR 25-01 (Rajabi et al., 2025).

Stress indicator/Quality	A	B	C	D	E	X_{mi}	Total
Overcoring (OC)	2	20	64	239	576	14	925
Hydraulic Fracturing (HF)	65	117	168	445	140	125	1,060
Borehole Breakout (BO)	385	1,099	1,728	2,455	1,674	124	7,465
Drilling Induced Tensile Fracture (DITF)	205	309	257	818	111	89	1,789
Geological Fault Inversion (GFI)	137	144	237	156	515	31	1,220
Geological Volcanic Alignment (GVA)	23	26	89	8	119	0	265
Focal Mechanism Single (FMS)	0	0	71,152	4,804	9,993	7	85,956
Inversion of Focal Mechanisms (FMF)	940	183	0	0	169	78	1,370
Total	1,757	1,898	73,695	8,925	13,278	478	100,050

Furthermore, in this release, the earlier depth limit of 40 km for data compilation has been replaced by a global crustal model from Szwillus et al. (2019) to determine if a data record lies within or below the crust. According to this model, the thickness of the crust varies between 7.2 km and 74.9 km, with standard deviations between 0.1 and 11.9 km. We used the reported



depth and its standard deviation to assess whether an earthquake focal mechanism occurred within the crust or not. For certain special study areas that have been investigated in more detail, comprehensive local compilations of earthquake focal mechanisms are used instead of the ISC dataset for the relevant time period. Full details and references for these areas are provided in the WSM Technical Report WSM TR 25-01 (Rajabi et al., 2025).

95 Figure 1 presents the global stress map using 77,385 A-C quality data records from the new WSM 2025 database. Plotting the data of the entire crust in map view is justified, as S_{Hmax} rotations with depth are not observed beyond the prevailing standard deviation of the data records. Exception are observed in some boreholes when they are drilled through faults, such as the San Andreas fault (Hickman and Zoback, 2004), and some intraplate settings (Rajabi et al., 2016; Rajabi et al., 2017b; Heidbach et al., 2025). However, the vast majority of data from deep boreholes show no significant S_{Hmax} rotation with
100 depth. Likewise, no systematic rotations are observed when comparing borehole data from the upper crust with data records derived from earthquake focal mechanisms from greater depth, confirming this earlier observation (Heidbach et al., 2010; Pierdominici and Heidbach, 2012; Zoback, 1992).

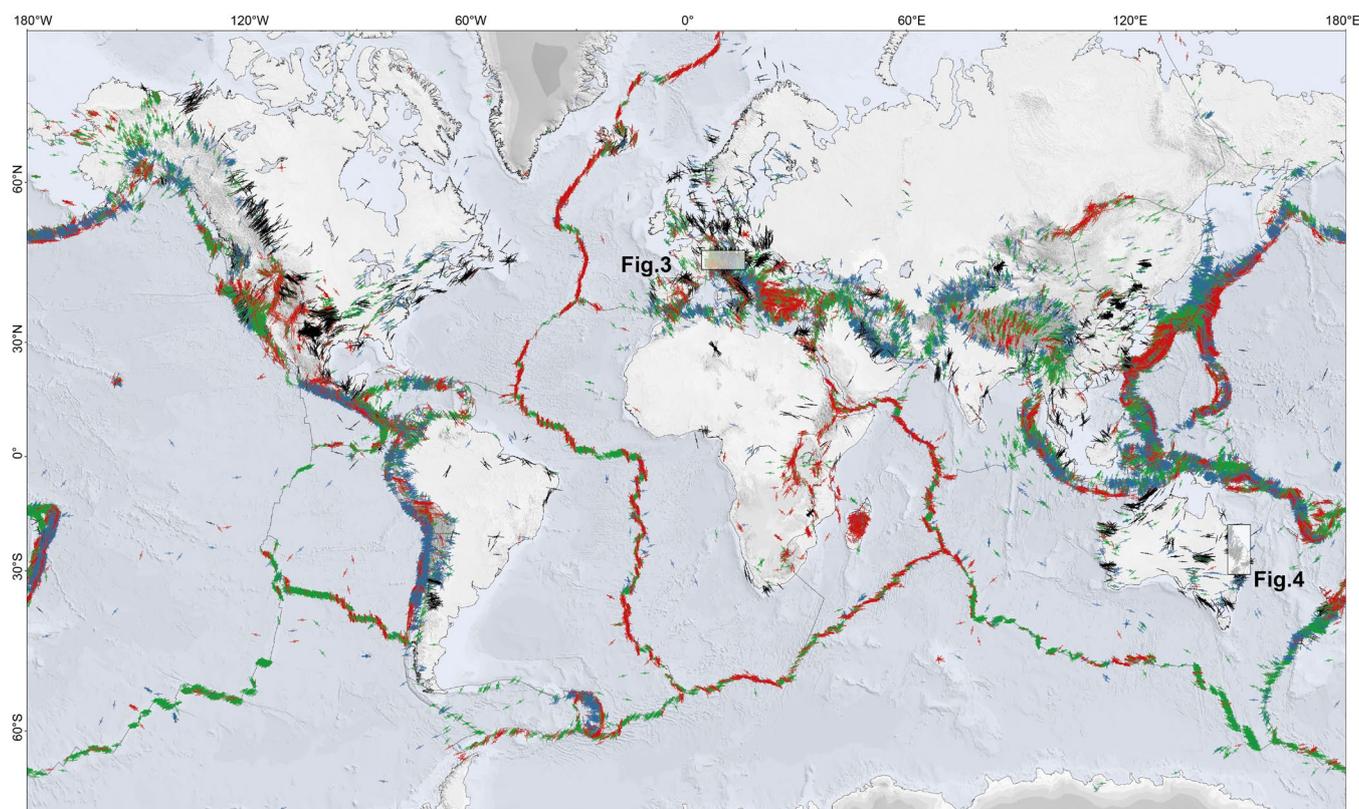


Figure 1. World Stress Map 2025. Lines indicate the orientation of maximum horizontal stress (S_{Hmax}). Colours of the lines indicate normal faulting stress regime (red), strike-slip stress regime (green), thrust faulting stress regime (blue), and black for unknown stress regime. Displayed are the 77,365 data records with A-C quality. Grey lines are the plate boundaries from the global tectonic model PB2002 of Bird (2003). Topography and bathymetry is taken from Tozer et al. (2019). Plotting order of the data is from deep to shallow.



The data on Fig. 1 are plotted according to their depth resulting in a map where the shallowest data are plotted on top. The azimuth of the lines in Fig. 1 represent the S_{Hmax} orientation, and the colour of the lines indicate the stress regime: red for normal faulting, green for strike-slip, blue for thrust faulting, and black for unknown stress regime. The vast majority of data records with stress regime assignment are from earthquake focal mechanisms, which means the displayed stress regime reflects conditions at greater depths. Analysis of stress magnitudes in several boreholes around the world have shown that the stress regime changes with depth (Rajabi et al., 2017a; Qin et al., 2024; Nagra, 2024; Brudy et al., 1997). The horizontal stress magnitudes are controlled by gravity and lateral surface forces from the plate boundaries, whereas the vertical stress, S_V , is controlled solely by gravity. Thus, at shallow depths, the horizontal stresses are larger than S_V , resulting in a thrust faulting stress regime. Consequently, the stress regime shown in the maps represent the conditions prevailing at the depths where earthquakes nucleate, not necessarily those at shallow depth of a few kilometres, where is most relevant for practical applications in geo-reservoirs. This is particularly important for deep geological repositories for radioactive waste, which are typically planned at depth between 400-1000 m, where stress regime changes are more likely (Nagra, 2024) and can directly impact the design of underground facilities (Fuchs and Muller, 2001; Brady and Brown, 2004).

3 Global stress patterns using the mean S_{Hmax} orientation on regular grids

As shown in Fig. 1, most stress data records are clustered around plate boundaries and within sedimentary basins. To analyse the pattern of S_{Hmax} orientation across different spatial scales, we provide estimates of the mean S_{Hmax} orientation on regular global grids of 2° , 1° , 0.5° and 0.2° . The mean S_{Hmax} orientation and its standard deviation (s_0), on these grids, are calculated using circular statistics for axial data (Mardia and Jupp, 2000):

$$mean S_{Hmax} = \frac{\arctan 2(\bar{S}, \bar{C})}{2} \text{ mod } 180^\circ \quad (1)$$

$$s_0 = \frac{\sqrt{-2 \log_e \bar{R}}}{2} \frac{180^\circ}{\pi} \quad (2)$$

with

$$\bar{R} = \sqrt{\bar{C}^2 + \bar{S}^2} \quad (3)$$

$$\bar{C} = \frac{1}{Z} \sum_{i=1}^N w_i \cos 2\theta_i \quad (4)$$

$$\bar{S} = \frac{1}{Z} \sum_{i=1}^N w_i \sin 2\theta_i \quad (5)$$

$$Z = \sum_{i=1}^N w_i \quad (6)$$

where θ_i is the S_{Hmax} orientation of individual data records i among the total number N of data records, and w_i is the weighting coefficient used to calculate the mean S_{Hmax} orientation. The value for the mean S_{Hmax} orientation is estimated for a given search radius and a minimum required number of data records within that radius. For the estimation of the mean S_{Hmax} orientation we use the tool stress2grid v1.1 from Ziegler and Heidbach (2019).

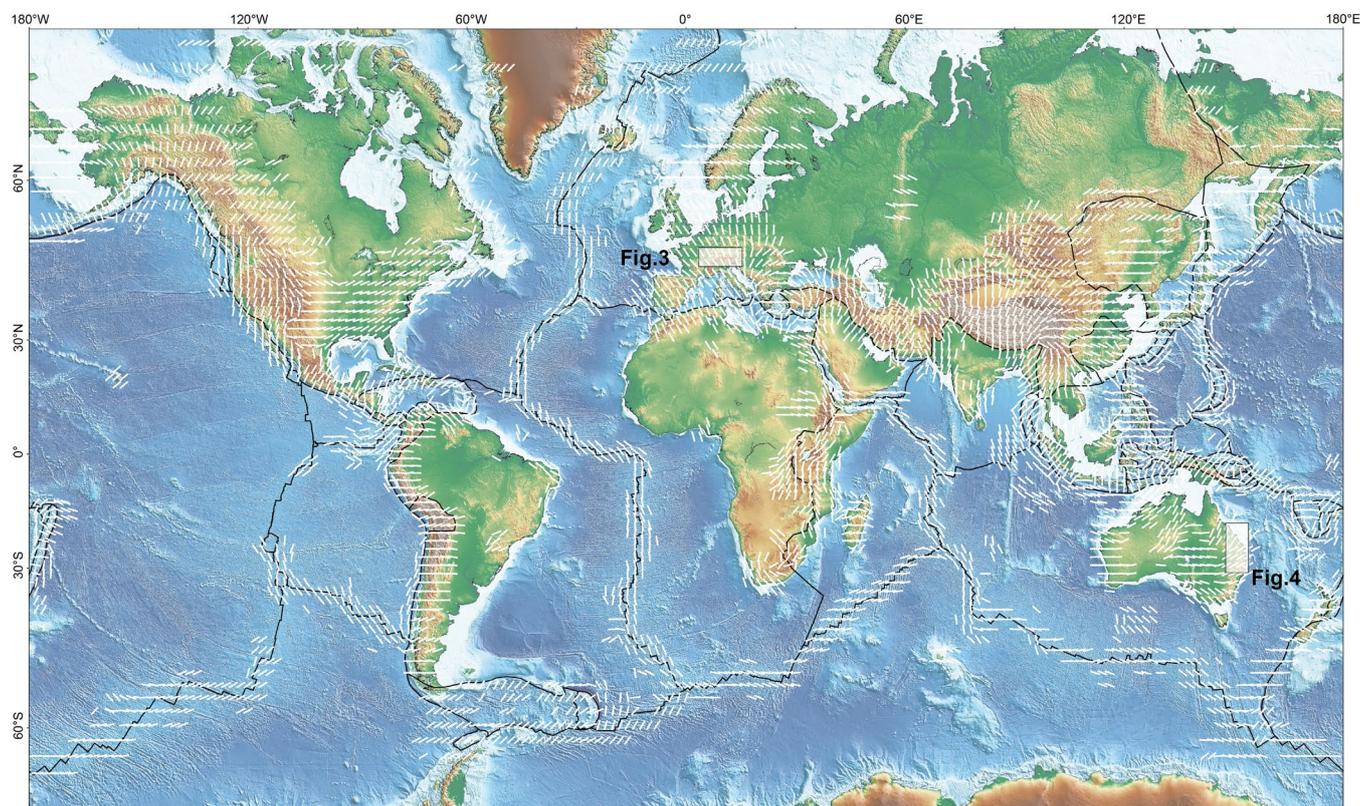


Using a fixed search radius effectively filters the S_{Hmax} data records according to the wavelength defined by the chosen search radius and, thus, does not resolve rotations of the mean S_{Hmax} orientation at spatial scales smaller than the employed search radius. Therefore, we provide 13 global datasets of the mean S_{Hmax} orientation calculated with search radii of 500 km, 250 km, 100 km, and 50 km (Heidbach and Rajabi, 2026). We use grids of 2° , 1° , 0.5° , and 0.2° for the search radius of 500 km and 250 km, and grids of 1° , 0.5° , and 0.2° for the 100 km search radius. For the 50 km search radius we only use grids of 0.5° and 0.2° . Within each search radius, a minimum of five data records is needed and that these data records are located on the same tectonic plate as the grid point using the global plate boundary model PB2020 from Bird (2003).

The significance of the S_{Hmax} estimates in the 13 datasets is further improved by weighting the input data using three different parameters:

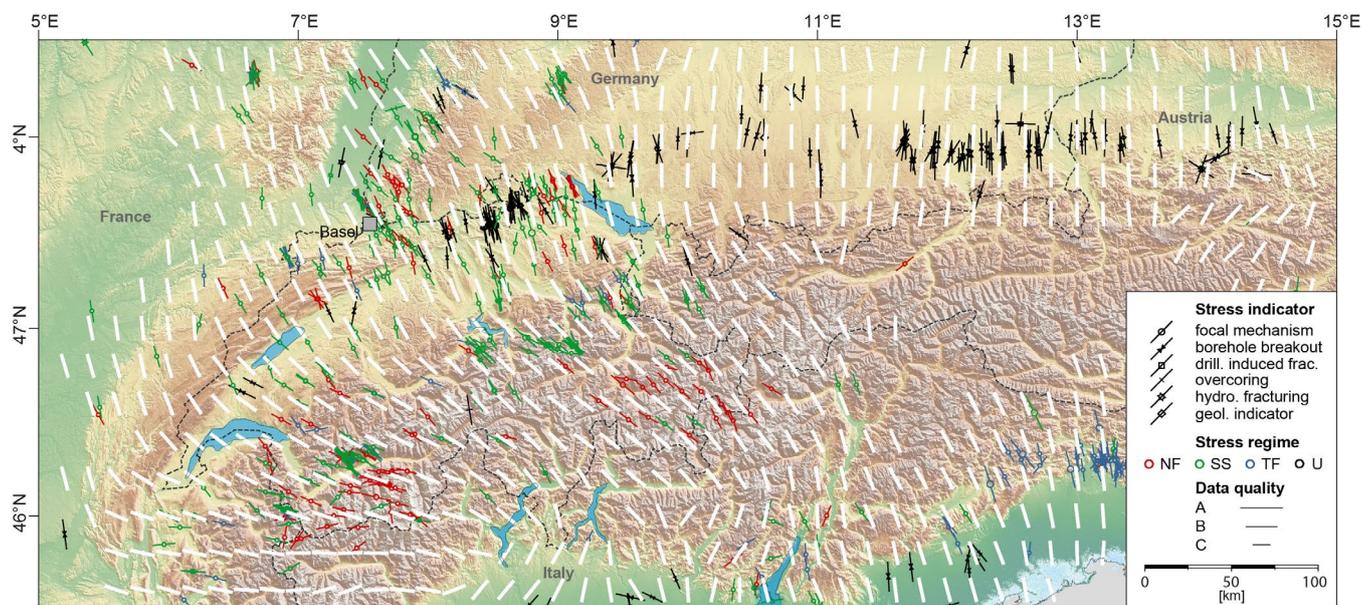
1. Data quality weighting with $w_Q=1/15$ for A-, $w_Q=1/20$ for B-, and $w_Q=1/25$ for C-quality data.
2. Inverse distance weighting relative to the grid point. This is based on the assumption that the closer a data record is to a grid point, the more strongly the stress state at the grid point influences that data record. Consequently, the contribution of an individual data record to the mean S_{Hmax} orientation increases with decreasing distance to the grid point.
3. Minimum distance threshold: Data records located very close to a grid point would be overrepresented by the distance weighting. To avoid this, a minimum distance threshold is applied such that all data records within 10% of the search radius are assigned the same weighting coefficient.

Figure 2 presents a global stress map of the mean S_{Hmax} orientation with using dataset of the 2° grid with a search radius of 500 km. The map shows that within intraplate regions, substantial rotations of the S_{Hmax} orientation occur. This observation now confirms, with the data, the earlier hypothesis that second-order effects arising from lateral variations in rock stiffness and density can cause rotations of S_{Hmax} , locally overriding the primary control of plate tectonic forces (Heidbach et al., 2007; Rajabi et al., 2017c; Zoback, 1992).



155 **Figure 2.** Mean S_{Hmax} orientation on a 2° grid using the search radius of 500 km and the A-C quality data displayed in Fig. 1. Black lines are the plate boundaries from the global plate boundary PB2002 (Bird, 2003) and global topography and bathymetry is from Tozer et al. (2019).

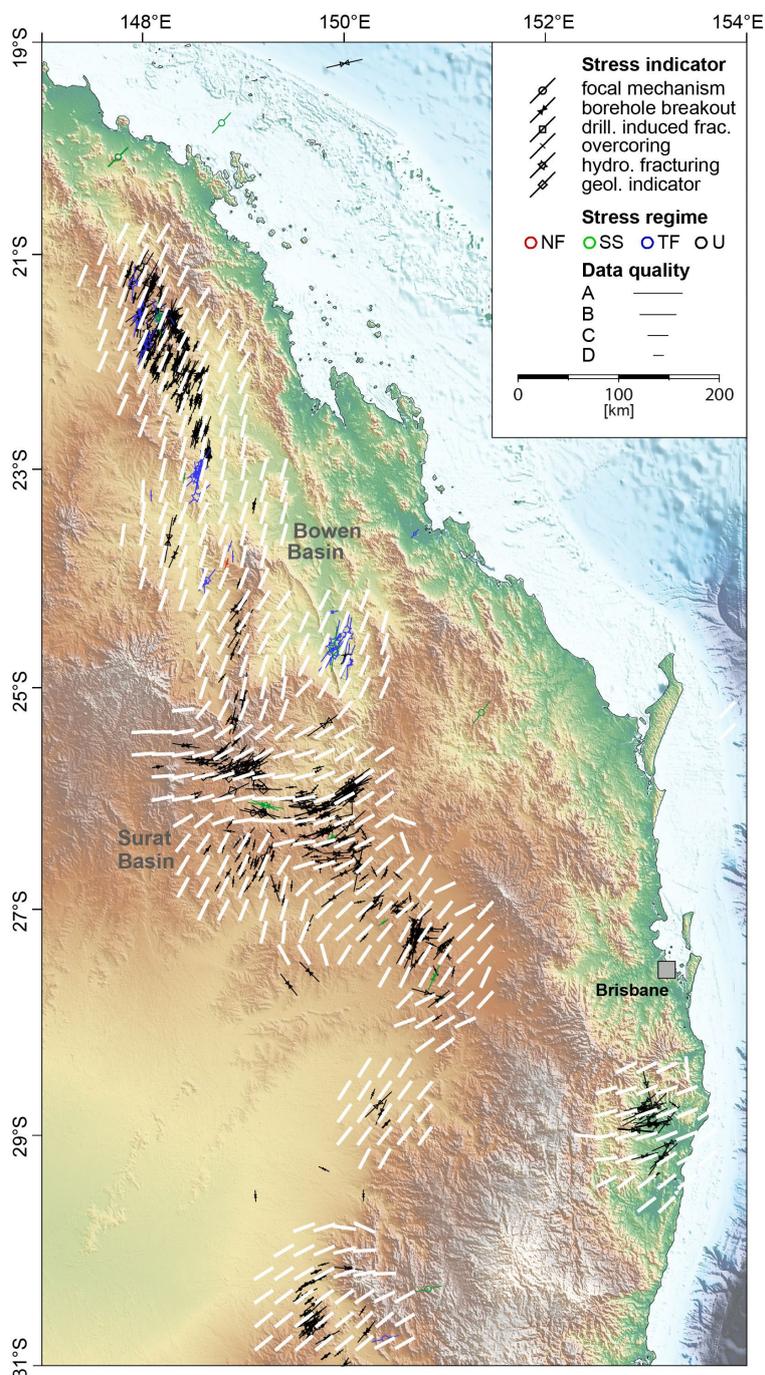
This effect is particularly evident in the forelands of high topography, where the excess of gravitational potential energy results in S_{Hmax} orientations perpendicular to the strike of the mountain belts (Zoback and Mooney, 2003). In the Alpine foreland, for example, S_{Hmax} rotates by approximately 50° from a north-south orientation in the east to about $130^\circ N$ in the Western Alps (Fig. 3) as explained earlier by Reinecker et al. (2010) and in more detail by Heidbach et al. (2025) for 160 Switzerland and its surrounding areas, and in the western part of Austria by Levi et al. (2019). Comparable stress patterns are observed for example in the greater Himalaya region (Hu et al., 2017) and in the Rocky Mountains of Canada (Reiter et al., 2014). Besides this obvious topography control there are also intraplate regions with low lateral density contrasts, i.e. low topography, that show S_{Hmax} rotations on spatial scales of hundreds of kilometres or less.



165 **Figure 3. Stress map of the Alpine foreland. Lines indicate the 677 data records of the orientation of maximum horizontal stress (S_{Hmax}) with A-C quality with line length according to data quality. Colours of the lines mark the stress regime with red for normal faulting (NF), green for strike-slip faulting (SS), blue for thrust faulting (TF), and black for unknown stress regime (U). White bars on the 0.2° grid show the dataset of the mean S_{Hmax} orientation with a search radius of 50 km. Dashed black line denote the national boundaries.**

A prominent example is north-eastern Australia, where the new WSM database 2025 includes 968 data records (Fig. 4).
170 Mean S_{Hmax} orientation estimated using a 50 km search radius on a 0.2° grid reveals rotations exceeding 50° over distances of < 100 km. The northern part of the Bowen Basin in north-eastern Australia provides insight into why some regions exhibit large S_{Hmax} rotations whereas others do not. An exceptionally dense dataset from 680 vertical boreholes distributed over an area of 300×100 km² shows no lateral or vertical variation in S_{Hmax} orientation despite the presence of a fault network and lateral stiffness contrast (Rajabi et al., 2024). The mean S_{Hmax} orientation for the entire dataset of this region is $18^\circ N$ with a standard deviation of $\pm 18^\circ$.
175 By contrast, further south in the southern part of the Bowen Basin and in the overlying Surat Basin, S_{Hmax} rotations of up to 60° within 100 km are observed (Rajabi et al., 2017c; Rajabi et al., 2017b).

Similar intraplate rotations of S_{Hmax} are also identified in the greater Texas-New Mexico region, where the data density is also high (Lund Snee and Zoback, 2020). In both regions, these rotations occur in the absence of significant topography and show no correlation with fault occurrence. Moreover, the rotations are gradual, supporting the interpretation that faults exert
180 limited control on the stress field beyond distances of a few kilometres, if at all (Reiter et al., 2024; Velagala et al., 2026). Since the data density even in areas with high resolution is only on the order of one data record per 100 km², rotations of S_{Hmax} on lateral spatial scales < 10 km cannot be resolved. Furthermore, the rotation should be larger than the standard deviation of individual data records, which is for most data records $20\text{-}25^\circ$.



185 **Figure 4. Stress map of north-eastern Australia. Lines indicate the 968 data records of the orientation of maximum horizontal stress (S_{Hmax}) with A-D quality with line length according to data quality. Colours of the lines mark the stress regime with red for normal faulting (NF), green for strike-slip faulting (SS), blue for thrust faulting (TF), and black for unknown stress regime (U). White bars on the 0.2° grid show the dataset of the mean S_{Hmax} orientation with a search radius of 50 km.**



Nevertheless, there are still large intraplate regions such as central western Europe or north-eastern North America that show remarkably uniform S_{Hmax} orientation over distances > 1000 km, parallel to the direction of absolute plate motion. Here, plate tectonic forces are the key control for the S_{Hmax} orientation and for the larger differences in horizontal stress magnitudes. However, in regions where several plate tectonic forces superimpose such that the horizontal differential stress between the magnitudes of the minimum horizontal stress S_{hmin} and S_{Hmax} is small, regional and local topography as well as stiffness contrasts exert a relatively stronger control on the S_{Hmax} orientation. For example, in north-eastern Australia, plate tectonic forces along the Solomon subduction and the New Guinea collision zone appear to dominate the stress pattern, whereas further south, superposition with the plate tectonic forces related to the New Hebrides subduction zone may generate a stress state characterized by low horizontal stress differences. In such a setting regional and local stress-controlling factors have a relatively larger impact and can lead to substantial rotations of the S_{Hmax} orientation (Ziegler et al., 2017).

4 Conclusions and outlook

The rotations of the S_{Hmax} orientation can be used as proxies to quantify with geomechanical-numerical models the relative importance of plate boundary forces that control the long wave-length pattern in comparison to regional and local controls of the crustal stress state. These rotations also have significant implications for evaluating tectonic fault criticality and for ensuring the safe and efficient application of subsurface technologies essential to the energy transition (Ziegler et al., 2024; Segall and Fitzgerald, 1998; Jolie et al., 2021). A detailed assessment of the relative contributions of plate tectonic forces, gravitational potential energy, and regional to local stiffness contrasts requires geomechanical-numerical modelling (Coblentz et al., 2024; Rajabi et al., 2017b; Peña Clavijo et al., 2024). In regions displaying significant lateral S_{Hmax} rotations, such observations provide valuable constraints on model parameters and model boundary conditions (Reiter, 2021; Ziegler et al., 2017). However, in regions with sparse data coverage or uniform S_{Hmax} orientation, stress magnitudes data become essential for geomechanical model calibration (Laruelle et al., 2026; Lecampion and Lei, 2010; Ziegler et al., 2016). Accordingly, while the compilation of S_{Hmax} orientation data will continue, the WSM is being expanded to include stress magnitude data. Initial efforts have focused on analysing and compiling stress magnitudes from Germany and neighbouring countries and on developing a quality-ranking scheme that will form an additional backbone for the future development of the WSM (Morawietz et al., 2020).

Data availability

The new WSM database 2025 is available at <https://doi.org/10.5880/WSM.2025.001>. User-defined stress maps can be plotted using the online tool CASMO (Heidbach et al., 2004) on the WSM project website (world-stress-map.org). The 13 datasets of the mean S_{Hmax} orientation on regular global grids are available at <https://doi.org/10.5880/WSM.2026.001>.



Code availability

The tool stress2grid that is used to estimate the mean S_{Hmax} orientation is available at <https://doi.org/10.5880/wsm.2019.002> and documented in the WSM Technical Report 19-02 (<https://doi.org/10.2312/wsm.2019.002>).

220 Author contributions

O.H. and M.R. conducted the estimation of the mean S_{Hmax} orientation on regular global grids, analysed the stress pattern, and wrote the paper.

Competing interests

The authors declare no competing interests.

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