

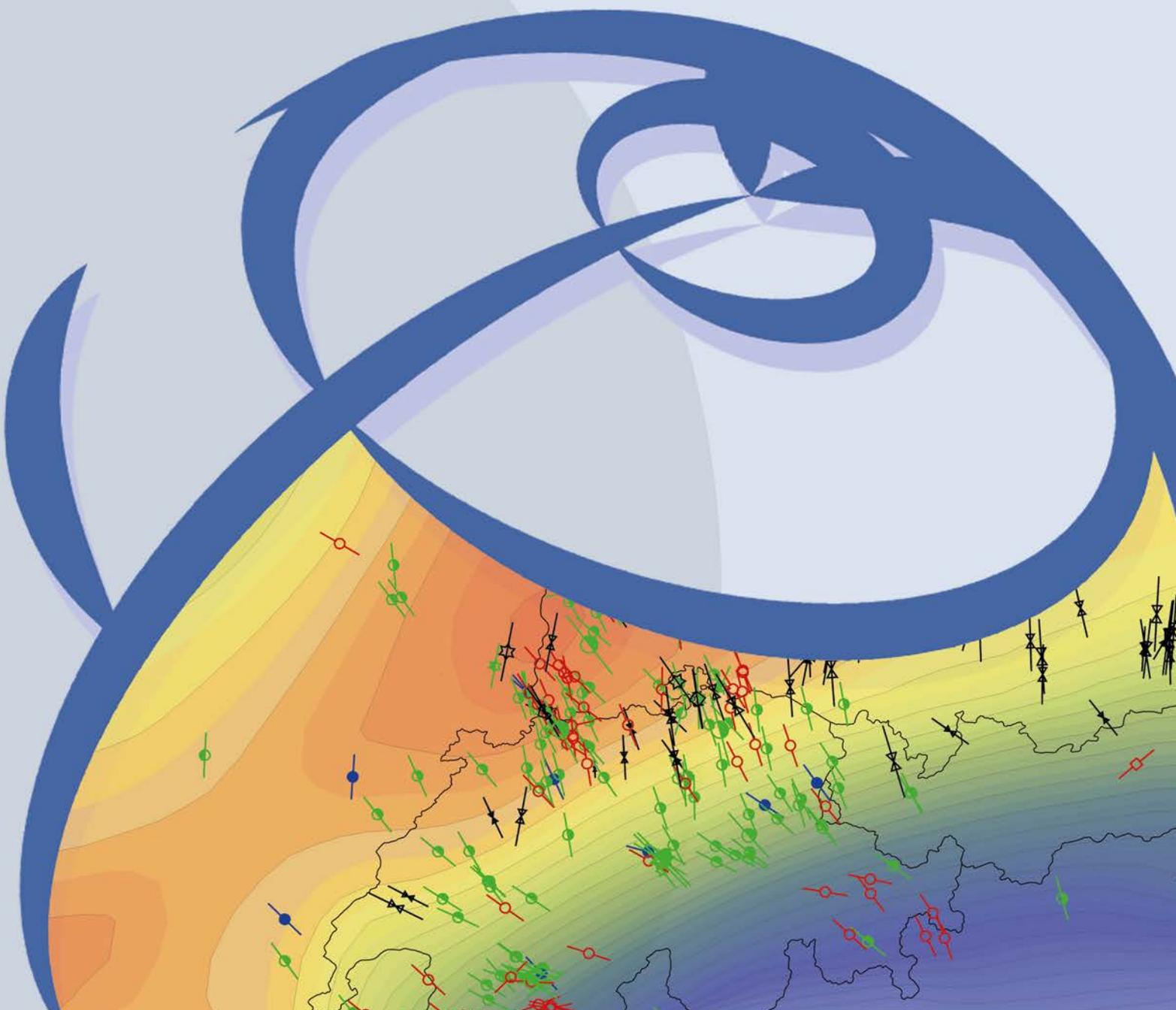


WSM WORLD STRESS MAP

WSM *Technical Report 17-02*

Manual of the Matlab Script *Stress2Grid*

Moritz Ziegler and Oliver Heidbach



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WSM Technical Report 17-02

Manual of the Matlab Script *Stress2Grid*

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Abstract

The distribution of data records for the maximum horizontal stress orientation S_{Hmax} in the Earth's crust is sparse and very unequally. To analyse the stress pattern and its wavelength or to predict the mean S_{Hmax} orientation on a regular grid, statistical interpolation as conducted e.g. by Coblenz and Richardson (1995), Müller et al. (2003), Heidbach and Höhne (2008), Heidbach et al. (2010) or Reiter et al. (2014) is necessary. Based on their work we wrote the Matlab® script Stress2Grid that provides several features to analyse the mean S_{Hmax} pattern. The script facilitates and speeds up this analysis and extends the functionality compared to the publications mentioned before.

The script provides two different concepts to calculate the mean S_{Hmax} orientation on a regular grid. The first is using a fixed search radius around the grid point and computes the mean S_{Hmax} orientation if sufficient data records are within the search radius. The larger the search radius the larger is the filtered wavelength of the stress pattern. The second approach is using variable search radii and determines the search radius for which the variance of the mean S_{Hmax} orientation is below a given threshold. This approach delivers mean S_{Hmax} orientations with a user-defined degree of reliability. It resolves local stress perturbations and is not available in areas with conflicting information that result in a large variance. Furthermore, the script can also estimate the deviation between plate motion direction and the mean S_{Hmax} orientation.

The script and several input files are provided by Ziegler and Heidbach (2017). The table below gives an overview of these input files with a short explanation.

File Name	Explanation	Page
check_input.m	Matlab subroutine that makes a data consistency check	13
qualityweight.m	Matlab subroutine that controls the data quality weight	13
methodweight.m	Matlab subroutine that controls the data type weight	13
ddistance.m	Matlab subroutine that calculates the distance between stress data record location to the grid point	-
Stress2grid.m	Matlab script Stress2Grid	17
wsm2016.xls	Excel file with the World Stress Map database release 2016	17
plates_Bird_2002_stress2grid.dat	ASCII file with closed polygons of plate boundaries from the global plate model PB2002 (Bird, 2003)	17, 22
HS3_NUVEL1A.txt	Euler poles of rigid plate motion from the Hotspot model HS3 NUVEL-1A (Gripp and Gordon, 2002)	17, 24
PB2002_orogens.txt	ASCII files with closed polygons of areas that should be excluded from the analysis	18, 24
bird_euler_poles_geo.txt	Euler poles of rigid plate motion from the global plate model PB2002 relative a fixed Pacific plate (Bird, 2003)	24
subtle.cpt	Color palette table used in GMT	26
wavelength.cpt	Color palette table used in GMT	28

1 Introduction

The World Stress Map (WSM) project provides a global database for the contemporary orientation of the maximum horizontal stress S_{Hmax} in the Earth's crust visualized in stress maps (Fig. 1, Heidbach et al., 2010, Zoback et al., 1989, Zoback 1992). The database compiles data from a wide range of stress indicators such as earthquake focal mechanism solutions, borehole breakouts, overcoring measurements, hydraulic fracturing or geological indicators (Heidbach et al., 2010, Sperner et al., 2003, Zoback, 1992). To ensure the comparability between stress orientations inferred from different stress indicators each stress data record is assigned a quality from A to E which corresponds to an expected maximum deviation between $< 15^\circ$ (A-quality) and $> 40^\circ$ (E-quality) (Heidbach et al., 2010, Sperner et al., 2003, Zoback, 1992). The qualities are assigned according to the WSM quality ranking system which depends on the stress indicator as well as inherent properties of the methods (Heidbach et al., 2010, Sperner et al., 2003, Zoback, 1992). The latest WSM database release 2016 contains 42,870 data records (Heidbach et al., 2016).

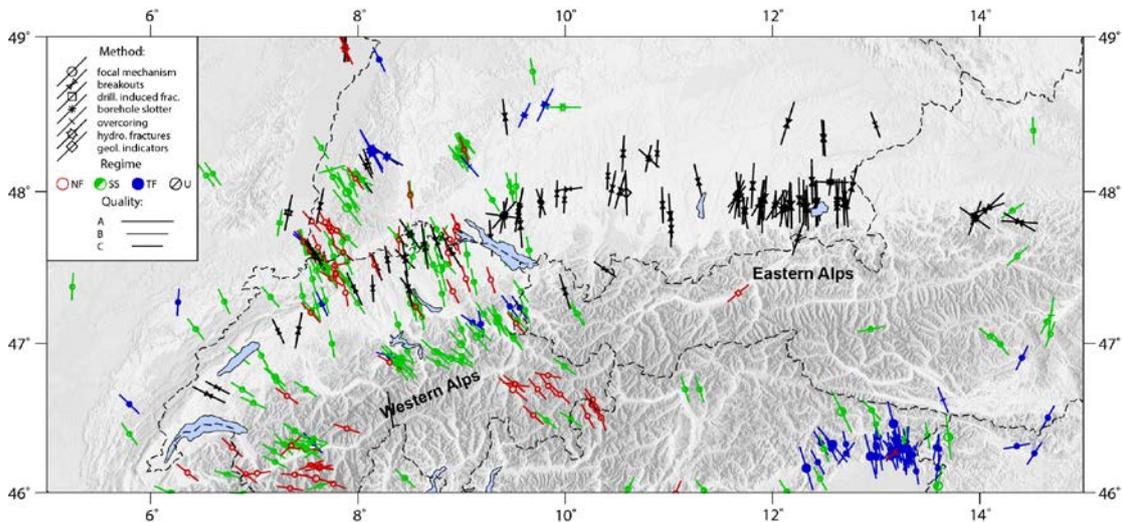


Fig. 1: Stress map of the Alpine foreland.

Lines show the orientation of maximum horizontal stress S_{Hmax} ; line length is proportional to data quality and symbols denote the stress indicator type. Colour code indicates the stress regime with red for normal faulting (NF), green for strike-slip (SS) and blue for thrust faulting (TF); black (U) means unknown stress regime and is typically assigned to data from borehole log analysis.

One option to analyse this large amount of data is to investigate spatial pattern in the orientation of S_{Hmax} . The stress pattern is estimated by the statistical interpolation of the mean S_{Hmax} orientation on a regular grid as conducted, e.g., by Coblenz and Richardson (1995), Müller et al. (2003), Heidbach and Höhne (2008), Heidbach et al. (2010) or Reiter et al. (2014). Based on their work we wrote the Matlab® script *Stress2Grid* that provides several features to analyse the mean S_{Hmax} pattern the corresponding wavelength of the stress pattern. It facilitates and speeds up such an analysis and extends the functionality compared to the work presented in the publications mentioned above.

The script provides two different concepts to calculate the mean S_{Hmax} orientation on a regular grid. The first is using a fixed search radius around the grid point and computes the mean S_{Hmax} orientation if sufficient data records are within the search radius. The larger the search radius the larger is the filtered wavelength of the stress pattern. This so-called smoothed stress

pattern can result in mean S_{Hmax} orientations with a high variance of the individual mean S_{Hmax} orientation and it may hide local perturbations (Fig. 2). Thus, the mean S_{Hmax} orientation from this approach is not necessarily reliable for a *local* stress field analysis. The second approach is using variable search radii and determines the search radius for which the variance of the mean S_{Hmax} orientation is below a given threshold. This approach delivers mean S_{Hmax} orientations with a user-defined degree of reliability (Fig. 2). It resolves local stress perturbations and is not available in areas with no data or conflicting information that result in a large variance.

Furthermore, the script can analyse the wavelength of the stress pattern, computes the plate motion from Euler vectors, and compares the mean S_{Hmax} orientation to the plate motion. These analyses can be performed either for the entire global dataset or for a user-defined sub-region. Furthermore, an optional weighting or exclusion of input data according to quality, method, tectonic plate affiliation, and/or possible plate boundary events is implemented. The analysis of the entire WSM database on a worldwide $1^\circ \times 1^\circ$ grid including all optional features executed on a standard desktop PC takes only a couple of minutes.

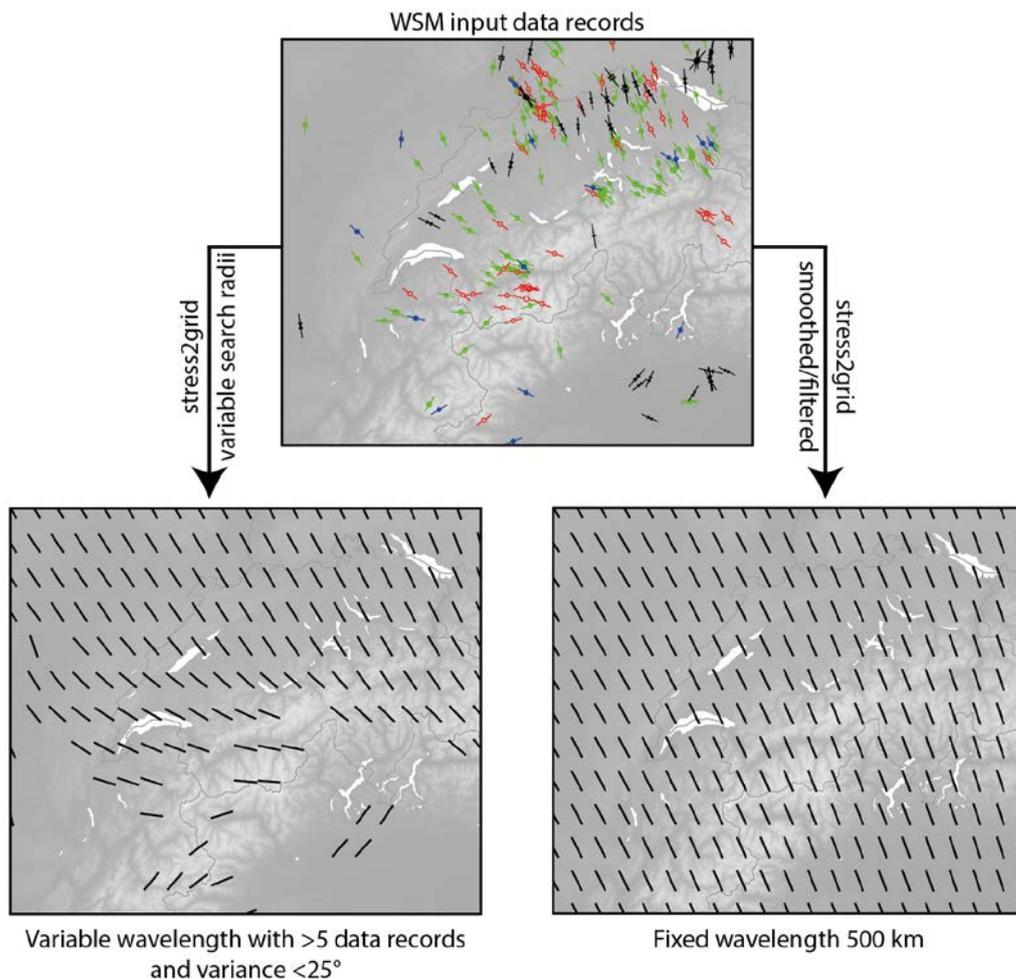


Fig. 2: From stress data records to mean S_{Hmax} orientation on a regular grid. Top: Stress map with data records from the Western Alps. Bottom: The *Stress2Grid* script derives a smoothed mean S_{Hmax} orientation with a fixed search radius of 500 km (right) and a mean S_{Hmax} orientation using different search radii and variance threshold of $< 25^\circ$

2 Theory

2.1 Statistics of bipolar data

The statistical analysis of stress data is based on the statistics for circular data (Mardia, 1972) which is used to define the mean S_{Hmax} orientation and the standard deviation s_0 as

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

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

with

$$\bar{R} = \sqrt{\bar{C}^2 + \bar{S}^2}$$

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

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

$$Z = \sum_{i=1}^N w_i$$

with θ_i the S_{Hmax} orientation of the individual data record with the number i of the N data records in total, and w_i the weighting coefficient to calculate the mean S_{Hmax} orientation (Heidbach et al., 2010).

2.2 Significance of results

The mean S_{Hmax} orientation S_{Hmean} and the standard deviation s_0 are computed for the data records within circles of increasing size around each grid point (so called search radii, see Fig. 3). The amount and size of search radii is variable and needs to be specifically adapted to each single analysis. For a regional analysis search radii between 50 km and 500 km with a step width of 50 km are recommended. Only search radii which include more than a specified amount of data records (usually 3 to 5) are thought to provide a significant result and are hence evaluated. The largest search radius which is evaluated and which at the same time results in a standard deviation of less than 25° (this threshold can be adapted) is proclaimed as the wavelength of the S_{Hmax} pattern at and around this specific grid point (Fig. 3). The estimated S_{Hmean} orientation for this search radius is used in the output as the mean S_{Hmax} orientation and the according standard deviation as the variance. If the result from even the smallest search radius includes enough data records but has a standard deviation above the threshold no mean S_{Hmax} orientation is computed but the search radius is taken as the upper bound for the wavelength of the stress pattern.

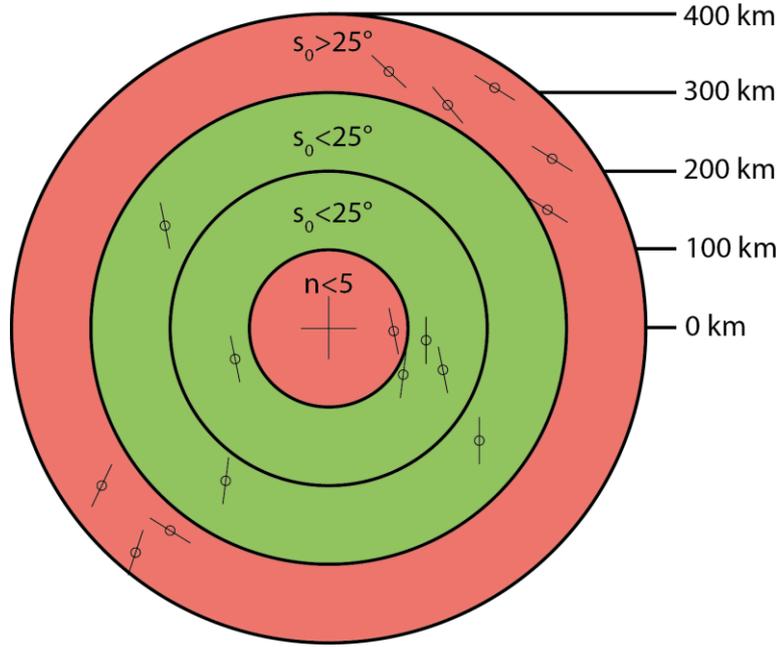


Fig. 3: Grid point with four search radii of different size.

The smallest search radius is not accepted since not enough data records are available. Within the two next larger search radii (green circles) enough data records are available and the standard deviation is smaller than the threshold of 25°. The largest search radius (outer red circle) is rejected since the standard deviation is larger than 25° even though enough data records are available. In this example the wavelength is 300 km and S_{Hmean} and s_0 for this wavelength are written to the output.

2.3 Estimation of plate motion

In this script the plate motion as specified in a set of Euler vectors for individual plates is computed for points on a regular grid. This enables the comparison between the mean S_{Hmax} orientation and the direction of plate motion either visually or as the difference between orientations.

The direction and velocity of motion at single locations can be estimated from the Euler vectors of plate rotation. This Euler vector can represent either an absolute plate motion (e.g. Gripp and Gordon, 2002) or a motion relative to a fixed plate, e.g. the fixed Pacific plate reference system as given in Bird (2003). The direction of plate motion at a given geographical location is estimated from the Euler vector of plate rotation and the geographical coordinates of the location (Keary and Vine, 1990).

For the estimation first of all the grid point locations are transferred from geographical (Lat/Lon) to Cartesian coordinates. Note that the geographical coordinates need to be in radians.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} r_{earth} \sin(90 - LAT) \cos(LON) \\ r_{earth} \sin(90 - LAT) \sin(LON) \\ r_{earth} \cos(90 - LAT) \end{pmatrix}$$

Then the geographical position (Lat_E/Lon_E) and the rotational velocity (rv in $^\circ/My$) at the Euler pole of each plate are converted to the $\vec{\omega}$ -vector.

$$\vec{\omega} = \begin{pmatrix} rv \sin(LAT_e) \cos(LON_e) \\ rv \sin(LAT_e) \sin(LON_e) \\ rv \cos(LAT_e) \end{pmatrix}$$

Now the rotation vector \vec{v} for each grid point is computed.

$$\vec{v} = \begin{pmatrix} \omega_2 z - \omega_3 y \\ \omega_3 x - \omega_1 z \\ \omega_1 y - \omega_2 x \end{pmatrix}$$

The rotation vector at each grid point can be decomposed into its north, east and vertical component.

$$d_n = -v_1 \cos(90 - LAT) \cos(LON) - v_2 \cos(90 - LAT) \sin(LON) + v_3 \sin(90 - LAT)$$

$$d_e = -v_1 \sin(LON) + v_2 \cos(LON)$$

Together the north and east component d_n and d_e define the horizontal velocity of plate motion.

$$vel_h = \sqrt{d_n^2 + d_e^2}$$

Now d_n and d_e are used to estimate the orientation of plate motion apm at the grid point as a value between 0° and 180° . This is done by the following chart.

$$\text{If } d_n^2 + d_e^2 = 0 \text{ then } apm = 0$$

$$\text{If } d_n \geq 0 \text{ and } d_e \geq 0 \text{ then } apm = \frac{180}{\pi} \arcsin\left(\frac{d_e}{vel_h}\right)$$

$$\text{If } d_n < 0 \text{ and } d_e \geq 0 \text{ then } apm = 90 + \left| \frac{180}{\pi} \arcsin\left(\frac{d_n}{vel_h}\right) \right|$$

$$\text{If } d_n < 0 \text{ and } d_e < 0 \text{ then } apm = \left| \frac{180}{\pi} \arcsin\left(\frac{d_e}{vel_h}\right) \right|$$

$$\text{If } d_n \geq 0 \text{ and } d_e < 0 \text{ then } apm = 180 - \left| \frac{180}{\pi} \arcsin\left(\frac{d_e}{vel_h}\right) \right|$$

The resulting plate motion apm at each grid point can then be displayed and/or compared to the mean orientation of S_{Hmax} at this location.

3 Data selection and weighting

3.1 Selection of data

The input stress data records are checked by *Stress2Grid* for their compliance with the requirements of the script prior to the pre-processing. This prevents the occurrence of errors due to missing or wrong input data in the later stages of the script execution. In the following all data records which have no information on the stress state (i.e. Azimuth = 999) are removed from the analysis. All data records of qualities and methods which have a weighting coefficient of 0 are deselected. Focal mechanism solutions which are flagged as possible plate boundary events (PBE) in the WSM database (or the input file) optionally are removed as well. S_{Hmax} orientations provided by PBE flagged focal mechanism solutions are considered as potentially less reliable due to the weakened strength of the crust in plate boundary regions (Heidbach et al., 2010). The user can choose additionally if all stress data records within a certain distance from a plate boundary shall be removed as well. Specific types of stress indicators can be completely removed from the analysis by the specification of their WSM abbreviations. Finally it is possible to exclude certain areas from the analysis by the specification of one or several polygons. This allows for example to exclude data from the orogenic areas as defined by Bird (2003) and prevent the evaluation of grid points in these areas.

3.2 Weighting of the input data

The significance of the results is further improved by the weighting of the input data by three different parameters. The WSM quality ranking gives a first account on the reliability of individual data records by assigning the qualities A (S_{Hmax} is believed to be within $\pm 15^\circ$), B ($S_{Hmax} \pm 20^\circ$), C ($S_{Hmax} \pm 25^\circ$), D ($S_{Hmax} \pm 40^\circ$), and E ($S_{Hmax} > \pm 40^\circ$) (Heidbach et al., 2010; Zoback 1992). This is used here to weigh the input data accordingly ($w_Q=1/15$ for A-, $w_Q=1/20$ for B-, and $w_Q=1/25$ for C-quality data). Usually it is recommended to only use A-C quality data records for interpretation, even though in some circumstances especially borehole indicators of D-quality can provide valuable information (Rajabi et al., 2016, Ziegler et al., 2016). Therefore D-quality data can be included as well ($w_Q=1/40$). Even though strongly discouraged E-quality data could be used as well given they provide a S_{Hmax} orientation other than 999.

An additional weighting mechanism according to stress indicator has been implemented. However, since the WSM quality ranking already considers the different quality of data records provided by different methods of stress indication great care needs to be exercised when applying the method weighting since it biases the results. Method weighting is mainly applied in very specific circumstances in which some stress indicators are not trusted, e.g. close to plate boundaries where FMS might have a lower confidence.

Finally, and inverse and a linear weighting according to the distance of the data record from the grid point is implemented (Fig. 4). This is based on the assumption that the closer to the grid point a data record is located the more significant is the influence of the stress state at the grid point on the data record. That means that the influence of a single data record on the mean S_{Hmax} orientation increases the closer to a grid point this data record is located. However, a data record which coincidentally lies exactly on or very close to the grid point would be overrepresented by such a distance weighting (especially if an inverse weighting is chosen). To prevent an overrepresentation of such a data record a minimum distance threshold is used to

assign the same weighting coefficient to each data record which is in a distance of less than 10% of the search radius (Fig. 4). If the user for some reason wants to have the possibility of an overrepresentation of data records, the variable `dist_threshold` can be set to zero or other values than the value 0.1 (denotes 10%). The capping is then switched off. The entire distance weighting can also be switched off by setting `dist_weight='none'` ;.

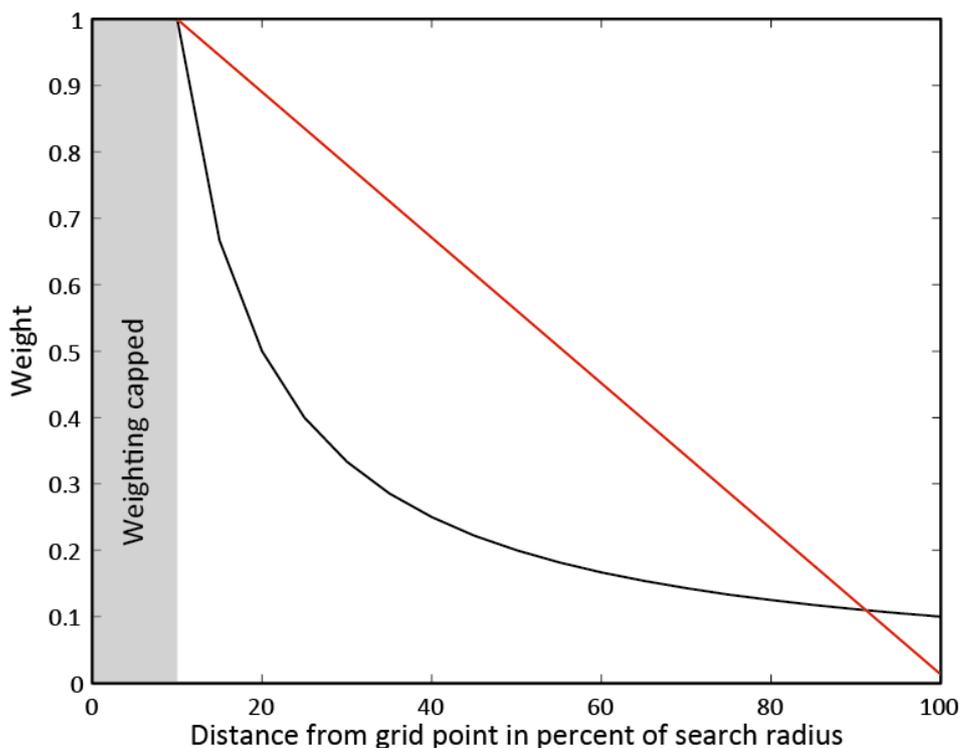


Fig. 4: Cut-off value during the distance weight.

The linear (red line) and inverse (black line) weighting of data records depends on their distance from the grid point. In this figure with a distance threshold of 0.1 all data records which are in a distance to the grid point of less than 10% of the search radius are equally weighted with 100%.

3.3 Plate boundary situation

The orientation of S_{Hmax} on two bounding tectonic plates is not necessarily identical. In fact, in some areas the orientations are clearly and significantly oblique to each other (Rajabi et al, 2016). Hence, using data from both plates close to a plate boundary can lead to severe smoothing of the potentially sharp contrast of mean S_{Hmax} orientation at the plate boundary (Fig. 5). Therefore, it is possible for the estimation to use only those stress data records which are on the same plate as the grid point. However, one should consider that this may significantly reduce the number of data records which are available for the computation. In the worst case it may even prevent an evaluation at several grid points if the number of available data records on each plate does not meet the required minimum of available data records.

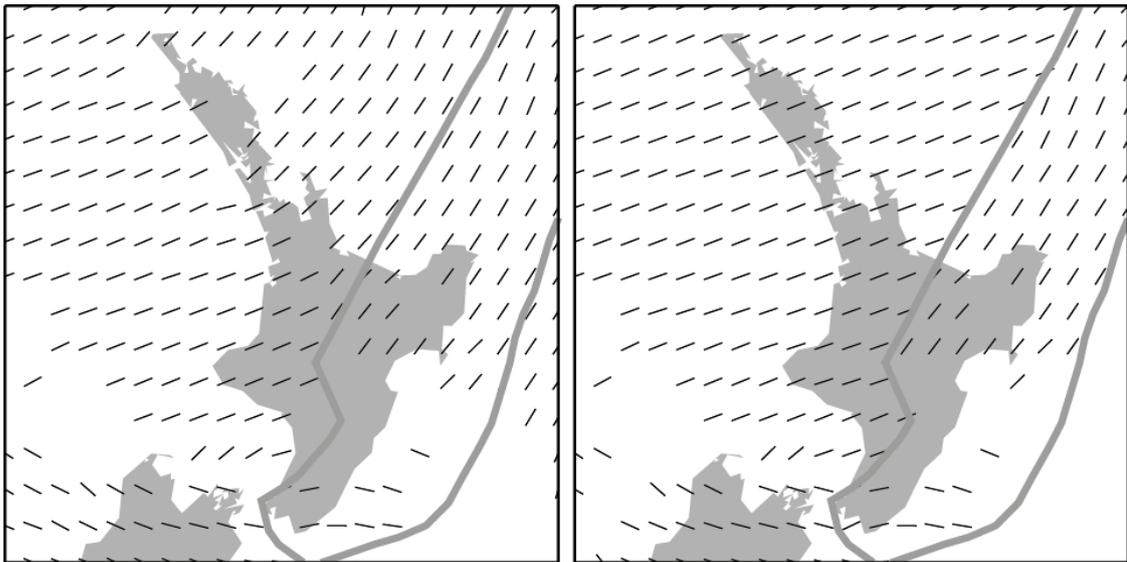


Fig. 5: Smoothing at plate boundaries.

Comparison between the mean S_{Hmax} orientation around a plate boundary on the New Zealand North Island. Left: All data records within a search radius are evaluated for each grid point. Right: Only those data records which are on the same tectonic plate as the grid point are used in the analysis.

3.4 Artefacts suppression

The computation of the mean S_{Hmax} orientation for grid points in areas with no stress data records may result in very large wavelengths which are not supported by any data records (Fig. 6). These artefacts are limited to situations in which the distance between the nearest data record and the grid point is large. Furthermore the closest data records need to have a similar S_{Hmax} orientation. Therefore this occurs mainly in oceanic areas and continental areas with very sparse data record density. Then the estimation of the mean S_{Hmax} orientation returns a low standard deviation for large search radii. However, this fact is not supported by a single data record in the vicinity of the grid point.

To prevent the occurrence of such artefacts a maximum distance of data records to a grid point is specified. If no data record is found within this distance around a grid point this grid point is not evaluated. As a basic setting a threshold of 200 km is chosen as a reasonable value for global datasets. It is highly recommended to alter this value depending on the application. As a rough estimate the threshold should be about 1.2 times the maximum spatial distance from data records within sub-regions.

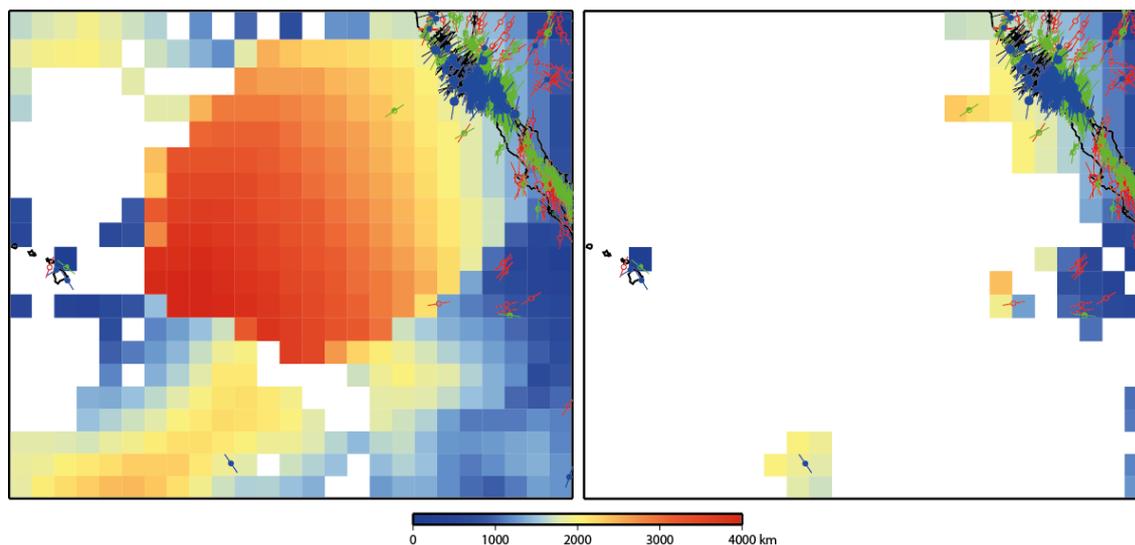


Fig. 6: Suppression of artefacts.

Wavelength on a 1° grid in the Pacific Ocean between California and Hawaii. Left: Long wavelengths which are clearly an artefact due to the missing input data in that area. Right: The artefacts vanish with the application of the artefacts suppression. Only around the actual data records wavelength of the stress pattern are estimated.

4 Software documentation

In this section the different functions of the script are described. This section will help users which are unfamiliar with Matlab to successfully run the script. Users familiar with Matlab may use this section to gain a deeper insight into the script and for troubleshooting.

The Stress2grid script combines several functions to analyse stress data on a regular grid. In the beginning the user specifies the required (and optional) input data and defines several required parameters. When the script is executed no further user input is required. The different features are initialised or dismissed automatically according to the users input information. In the following each segment and feature is briefly described

4.1 Pre-processing of the input data

The stress data records are read from an Excel file and the data is checked for consistency in the subroutine `check_input.m`. The script stops the execution should any fatal errors be inevitable due to erroneous input data. Non-fatal problems in the input file are displayed in a message to the user. After the initial input check the stress data records may be weighted according to their quality and/or method of determination. This is achieved in two subroutines `qualityweight.m` and `methodweight.m` which also transfer the string variables `Quality` and `Method` to numerical values.

Subsequently, stress data records are removed according to the user-defined criteria. Data records may be removed because they (1) do not have a sufficient quality according to the quality weighting, (2) are not determined by the right method according to the method weighting, (3) are considered as a plate boundary event (PBE), (4) are in a closer distance to a plate boundary than specified in variable `pb_exclude`, (5) are determined with a stress indication method which is deselected by the user, or (6) have no determined azimuth ($AZI = 999$). The latter is the case for most E-quality data records.

4.2 Regular grid

The regular grid for the evaluation is generated according to the user input data (`gridsize`, `west`, `east`, `south`, `north`). While the analysis is limited to grid points within the box specified by the coordinates, data records from outside the box are also included into the evaluation. Finally each grid point is assigned to a tectonic plate which is identified by a corresponding plate abbreviation according to Bird (2003).

If the user specified polygon(s) from areas which should not be used for the analysis (`exclude_poly`) both the grid points and the data records within this area are removed. That means that data records within the polygons which are by chance within an adjacent search radius from an area which is not deselected are not included in the analysis. At the same time no output is provided for the grid points within the polygon.

4.3 Computation of plate motion

This section is only initiated if the user opted to include a comparison with plate motion data. The Euler poles and rotation rate for each plate are read from the input file (`euler_poles`). The rotation vectors at the Euler poles are computed. At each individual grid point the corresponding plate's rotation vector is used to compute the plate motion direction. In case Euler poles for only a few plates are specified, e.g. 15 plates in HS3 NUVEL-1A (Gripp and

Gordon, 2002), grid points which are assigned to a plate that is not represented by an Euler pole are not assigned a plate motion direction. No comparison of the mean S_{Hmax} orientation and the plate motion is computed at those grid points.

4.4 Computation of the mean S_{Hmax} orientation

In this part of the script the mean orientation of S_{Hmax} is computed at every grid point for stress data from every search radius in R_range . For each grid point the distance between the grid point and each single data record is computed. Then follows a cascading user defined computation.

If the user activated the no artefacts feature (e.g. `artres_thres=200;`) the smallest distance between a grid point and a data record is evaluated. If the distance is larger than the specified threshold (`artres_thres`) no mean value is computed and the script continues with the next search radius. Otherwise the analysis continues.

If the user activated the plate affiliation of data records feature (`plate_affil='yes';`) the script checks each data record whether it is on the same tectonic plate as the grid point. If not this data record is excluded from any further evaluation at this grid point.

If the number of data records within a specified search radius is smaller than the minimum amount specified (`min_data`) no mean value is computed. Otherwise the mean S_{Hmax} orientation, its variance, and the mean distance radius between grid point and data record is computed.

If the user opted to compute the comparison between the mean S_{Hmax} orientation and the plate motion direction it is computed (`compare_pm='yes';`). However, if the variance is above the threshold or no plate motion direction is available for the grid point no computation is initialised.

4.5 Plot output data

Optionally the computed data can be plotted to identify possible errors and assess whether the input specifications need to be altered (Fig. 7). This helps to gain an overview of the results before any final figures are created with Generic Mapping Tool GMT (Wessel et al., 2013) or any comparable software. In total up to six subplots are created which display the Input data, the mean S_{Hmax} orientation, the absolute plate motion direction (if the user requested the computation), the search radius, the variance, and the difference between mean S_{Hmax} orientation and the absolute plate motion direction (if the user requested the computation).

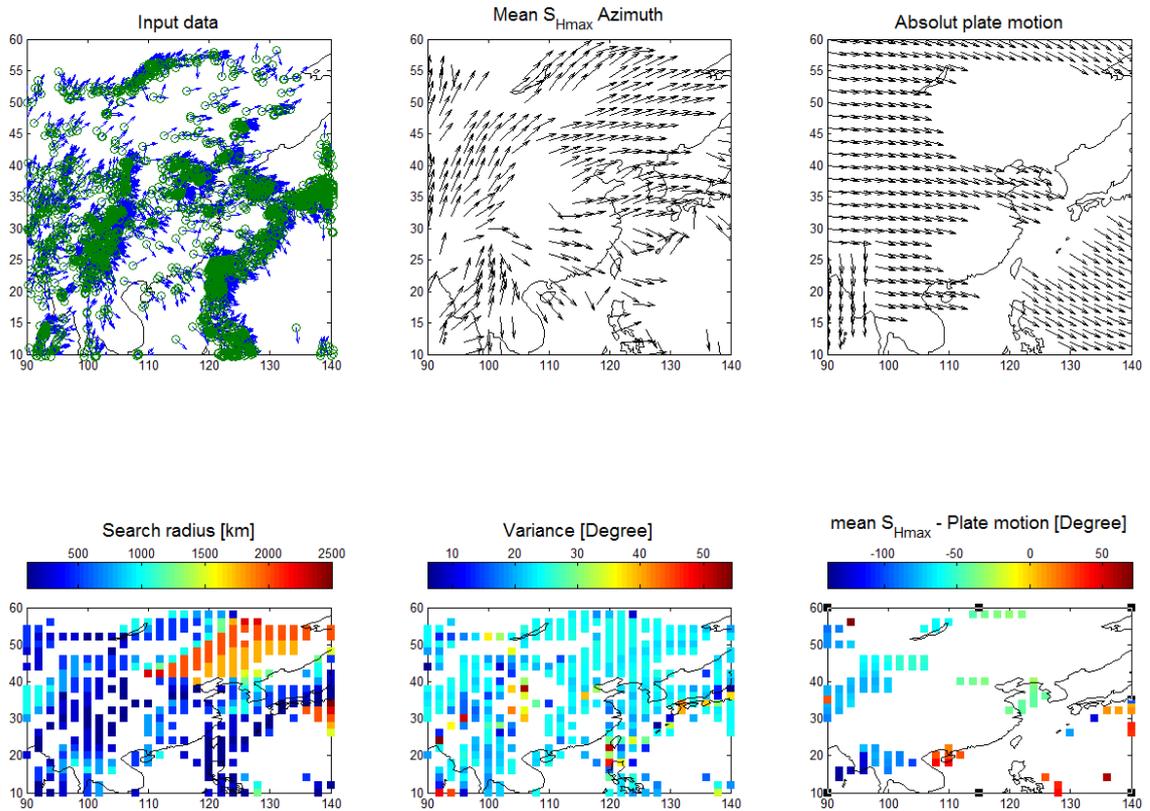


Fig. 7: Preview of the output plots generated by the script *Stress2Grid*.

Top row shows the input data from the raw data records, mean S_{Hmax} orientation on a regular grid, and the absolute plate motion direction on a regular grid. Bottom row shows the results in terms of the selected search radius as a measure for the stress pattern wavelength, the variance of the mean S_{Hmax} orientation at each grid point, and the deviation angle between the mean S_{Hmax} orientation and the absolute plate motion direction.

4.6 Export output data

Finally the output files for Excel, GMT or both are created according to the user's request. The Excel file contains all the information which was computed with the script. The GMT files however only include selected items but are ready to use with the provided GMT scripts.

The Excel file contains the coordinates of the grid points, the corresponding plate name, and the absolute plate motion. Then for each search radius the mean S_{Hmax} orientation, the difference between mean S_{Hmax} orientation and the absolute plate motion direction, the standard deviation, the search radius, the mean distance of the data records from the grid point in percent of the search radius, and the number of data records are listed.

In total up to five GMT files are written. One file each is created for the mean S_{Hmax} orientations, the stress pattern wavelengths, and the variances. Furthermore if the plate motion is considered, a file with the absolute plate motion direction at the grid points and another file with the difference between mean S_{Hmax} orientation and the absolute plate motion direction are created. Their individual content is listed in the following table.

Tab. 1: Explanation of the output files.

Left column shows the output file name of the Matlab script stress2grid and the right column gives an explanation of the content of the file, its structure and a brief explanation.

Filename	Description
mean_azi.dat	Latitude of grid point. Longitude of grid point. The mean S_{Hmax} orientation at grid points with a S_{Hmax} variance below the threshold and at least the minimum amount of required data records within the search radius. Arrow length required for the GMT command <i>psxy -SVb</i> .
wavelength.dat	Latitude of grid point. Longitude of grid point. The largest search radius which has at least the minimum amount of data records required and a S_{Hmax} variance below the threshold. (If the S_{Hmax} variance even for the smallest search radius is above the threshold the smallest search radius is printed to the file.)
variance.dat	Latitude of grid point. Longitude of grid point. The variance of the mean S_{Hmax} orientation at the grid point. The variance is the standard deviation for the largest search radius for which the standard deviation is smaller than the threshold. If the standard deviation is larger than the threshold for all search radii the standard deviation of the smallest search radius (which is then above the threshold) is written in the output file.
apm.dat	Latitude of grid point. Longitude of grid point. The plate motion direction at the grid point as computed from the Euler poles provided. Arrow length required for the GMT command <i>psxy -SVb</i> . Plate name abbreviation according to Bird (2003).
SHmax-APM.dat	Latitude of grid point. Longitude of grid point. The difference of mean S_{Hmax} and plate motion at each grid point where a mean S_{Hmax} orientation and a plate motion direction is computed. Arrow length required for the GMT command <i>psxy -SVb</i> . Plate name abbreviation.

Please note that files with the same name as the output files which already exist in the Matlab current directory will be overwritten without prior notification. Furthermore, Matlab encounters a problem if a file is currently accessed by another application while Matlab tries to write to the file.

5 User interaction

5.1 Installation

To install the Stress2grid script, unpack the compressed archive to your Matlab working directory or a convenient folder. Then open the file `stress2grid.m` with your Matlab® installation. The Stress2grid script comes with several subroutines which are necessarily called and input files which are located in the folder “`routines`”. This folder needs to be situated in the same directory where the `stress2grid.m` file is executed. If Matlab® has no access to the subroutines the execution of the script will fail.

The script is tested for Matlab® R2013a and should be compatible with newer versions. A compatibility with older releases of Matlab may not be given without alterations. The authors do not take any responsibility for the compatibility and functionality of the script.

5.2 User input

The script is controlled by the user defined variables in the first 60 lines. A detailed account on each variable and their usage is given in the following table. If no example is given the user input is structured as follows with value being a real number:

```
variable_name = value;
```

Features which can be switched on or off are usually controlled by the word `yes` (feature is active) or `no` (feature is inactive).

Tab. 2: Explanation of the user input files.

Left column shows the variable name of the Matlab script *Stress2Grid* and the right column gives an explanation of the functionality and for some variables a brief example.

Variable	Input files and settings
<code>input</code>	Define the Excle 1997-2003 (*.xls) file which contains the stress database you want to analyse. <code>input = 'wsm2016.xls';</code>
<code>plate_boundaries</code>	Define the file which provides closed polygons of the plate boundaries. <code>plate_boundaries = 'plates_Bird_2002_stress2grid.dat';</code>
<code>euler_poles</code>	Define the file that provides the Euler poles for the plate motion. <code>euler_poles = 'HS3_NUVEL1A.txt';</code>

num_plates	Enter a numerical value for the number of plates which have defined Euler poles. This number can be different from the number of plates whose boundaries are defined.
polygon_exclude	State if you want to exclude data from additional polygons. polygon_exclude = 'yes';
exclude_poly	Define the file which specifies the additional polygon(s). exclude_poly = 'PB2002_orogens.txt';
Variable	Grid parameters
gridsize	Specify the spacing of the regular grid in decimal degree.
west	The westernmost border of the area of interest in decimal degree. Range: -180 to 180.
east	The easternmost border of the area of interest in decimal degree. Range: -180 to 180.
south	The southernmost border of the area of interest in decimal degree. Range: -90 to 90.
north	The northernmost border of the area of interest in decimal degree. Range: -90 to 90.
Variable	Data processing
qual	Define the weighting of the qualities according to the WSM quality ranking scheme in decreasing order from A to E. qual = [1/15, 1/20, 1/25, 0, 0];
apply_qw	Switch the quality weighting on or off. apply_qw = 'yes';

methd	<p>Define the weighting according to different methods used for the determination of the orientation of S_{Hmax}. Define values between 0 (not considered) and 5 (very well established). The order is:</p> <ol style="list-style-type: none"> 1. Focal mechanism solutions 2. Formal inversion of focal mechanism solutions 3. Borehole Breakouts 4. Drilling induced (tensile) fractures 5. Hydraulic fractures 6. Geological fault slip inversion 7. Geological vent alignment 8. Overcoring measurement 9. Methods not considered above <p>methd = [4, 5, 5, 5, 4, 5, 4, 2, 1];</p>
apply_mw	<p>Switch the method weighting on or off.</p> <p>apply_mw = 'no';</p>
m_exclude	<p>Specify certain stress indication methods which should be disregarded in the entire analysis. Leave empty if you don't want to exclude any specific stress indicator.</p> <p>m_exclude = { 'OC', 'SW' };</p>
pbe_exclude	<p>Exclude seismic events which are flagged as plate boundary events (PBE, see Heidbach et al., 2010) from the analysis.</p> <p>pbe_exclude = 'yes';</p>
pb_dist_exclude	<p>Exclude all data records regardless the method which are closer to a plate boundary than the value (in km) specified in this variable. To switch off this function and include all data records regardless of their distance to a plate boundary set the variable to 0.</p>
dist_weight	<p>Define the distance weighting method which should be used. Specify 'none', 'linear', or 'inverse'.</p> <p>dist_weight = 'inverse';</p>
dist_threshold	<p>Specify a value between 0 and 1 to manipulate the distance weighting of the input data. If you do not want any distance weighting at all set dist_threshold to 1. A value of 0.1 (equals 10% of the search radius) is recommended.</p>

Variable	Initialise script functions
R_range	<p>Define the search radii. At least one value needs to be specified.</p> <pre>R_range=[100,250,500,750,1000,1250,1500,1750,2000];</pre> <p>Same results for:</p> <pre>R_range=[100,250:250:2000];</pre>
min_data	<p>Define the minimum amount of data records situated within a search radius which is required to compute the mean S_{Hmax} for this search radius.</p>
threshold	<p>Specify the upper bound for the variance (in degree) of the mean S_{Hmax} orientation below which the results from a certain search radius are considered and printed to the output file.</p>
plate_affil	<p>If <code>plate_affil</code> is set to 'yes' the algorithm only includes data records into the computation of the mean S_{Hmax} orientation which are on the same plate as the grid point.</p> <pre>plate_affil = 'yes';</pre>
arte_thres	<p>To suppress artefacts in areas with no data records set <code>arte_thres</code> to a value other than 0. Then <code>arte_thres</code> defines the radius around the grid point in kilometres which needs to contain at least one data record for an evaluation. Default setting is 200 km.</p>
compare_pm	<p>If you want a computation of the plate motion and the difference between the plate motion and the orientation of S_{Hmax} at the grid points set <code>compare_pm</code> to 'yes'.</p> <p>If you don't need this computation setting <code>compare_pm</code> to 'no' significantly speeds up the time required for computation.</p> <pre>compare_pm = 'yes';</pre>

Variable	Output
output	This variable controls the generation of output files. The script writes an excel file ('excel'), files ready to use with GMT ('gmt'), or both ('both'). output = 'gmt';
arrowlength	If you request files prepared for plotting with GMT the arrow length defines the size of the symbol used to plot directional data. (GMT function: <i>psxy -SVb</i>)
plot_output	Specify whether the results of the analysis should be plotted at the end of the script. plot_output = 'yes';

5.3 Input file specifications

The user can provide four different input files or use the provided data files. These are the stress data records in WSM format, closed polygons of 52 plate boundaries according to Bird (2003, Euler poles for the plate motion according to Bird (2003) or HS3 NUVEL-1A (Gripp and Gordon, 2002), and optionally closed polygons to be excluded from the analysis, e.g. the orogenetic areas according to Bird (2003). In the following the file formats are described. Please note that all files need to be present either in the "routines" folder, your current working directory, a folder that is added to the Matlab® path, or specified by its absolute location path on your hard drive.

5.3.1 Stress data records (required)

The stress data records input file is an MS Excel® 97-2003 file in the WSM format. Since Matlab® cannot read data from files in the current Excel *.xlsx format the input file is required to be in *.xls format. You can use the included `wsm2016.xls` file, provide your own stress compilation, or append your own stress data to the `wsm2016.xls` file. For a detailed description of the WSM file format see Heidbach et al. (2008, 2010) or visit the website www.world-stress-map.org. If you use your own file, note that the first row is ignored. Furthermore, only the following ten columns (Tab. 3) are relevant for the script. All other columns are non-essential and may be empty.

The input file is checked for consistency and its compliance with the required specifications. The script stops and issues a warning in case of missing/erroneous input in latitude, longitude, azimuth, quality, or PBE assignment. Missing or wrong input data in the additional parameters only lead to a warning but the script continues as the contained information is not crucial for a successful evaluation of the script.

Tab. 3: Explanation of the stress data input file from the WSM 2016 format.

The column numbering is given in numbers and characters in alphabetical order followed by a description and an example.

Column	Column Excel	Description	Example
3	C	The latitude of the data record in decimal degrees.	-32.8674
4	D	The longitude of the data record in decimal degrees.	146.689
5	E	The orientation of S_{Hmax} (0° to 180°). For E quality data records an orientation of 999 signifies the inability to derive a valid stress orientation.	82
6	F	The type of stress indicator used to derive the data record. It is composed of two or three letters.	BO
7	G	The depth of the data record in kilometres.	2.43
8	H	The Quality of the stress data record between "A" and "E" according to the WSM quality ranking scheme.	B
9	I	The tectonic stress regime is defined by two letters. A "U" indicates that the regime is unknown.	U
55	BC	A two letter code to assign the tectonic plate on which the data record is situated according to Bird (2003).	AU
57	BE	Distance to the closest plate boundary in kilometres.	512
58	BF	If the data record is a focal mechanism solution and is flagged as a plate boundary event this field is set to "PBE". Otherwise it is set to "NO"	NO

5.3.2 Plate boundaries (required for comparison with plate motion)

If any operation which includes plate motion or the assignment of plate names to the grid is chosen a file which specifies the plate boundaries is required. In order to enable Matlab® the processing of the polygon data several requirements need to be fulfilled. The file `plates_Bird_2002_stress2grid.dat` which is provided with the script fulfils these requirements. It is based on the plate boundaries defined by Bird (2003). Furthermore these plate boundaries are also used to assign plate names to the stress data records in the WSM database (column 55). Hence, to ensure continuity we encourage usage of the provided file.

- If the user wishes to apply a different plate boundary dataset a reprocessing of the input WSM stress data records should be considered. The following information and the example help to define the plate boundary file.
- Plate boundaries which cross the date line ($180^\circ E$ (180) and $180^\circ W$ (-180)) are not allowed. Therefore plates which extend on both sides of the date line are split into two

different plates in the input file (see Fig. 81). However, each part of a plate needs to be assigned a unique two-letter name. For the split plates the temporary names are returned to the original names in stress2grid.m lines 313 ff. In case of the plate boundaries defined by Bird (2003) this affects the North American, Australian, Antarctic, Pacific, Kermadec, and Balmoral reef plate.

- The plate boundary polygons have to be closed, i.e. the first and the last coordinates have to be equal. As well each plate boundary is defined twice, once for each bounding plate.
- The unique name of each plate polygon is composed of exactly two letters (no space allowed). To ensure compatibility the names are required to be identical to the plate names in the stress data record file and the file for the definition of Euler poles and plate velocity. Therefore, we encourage to use the plate name abbreviation used by Bird (2003) which is also applied in the WSM.
- In contrary to the WSM file the plate boundary file consists of the longitude and then the latitude separated by a comma.
- Each definition of a plate (part) ends with `*** end of line segment ***`.

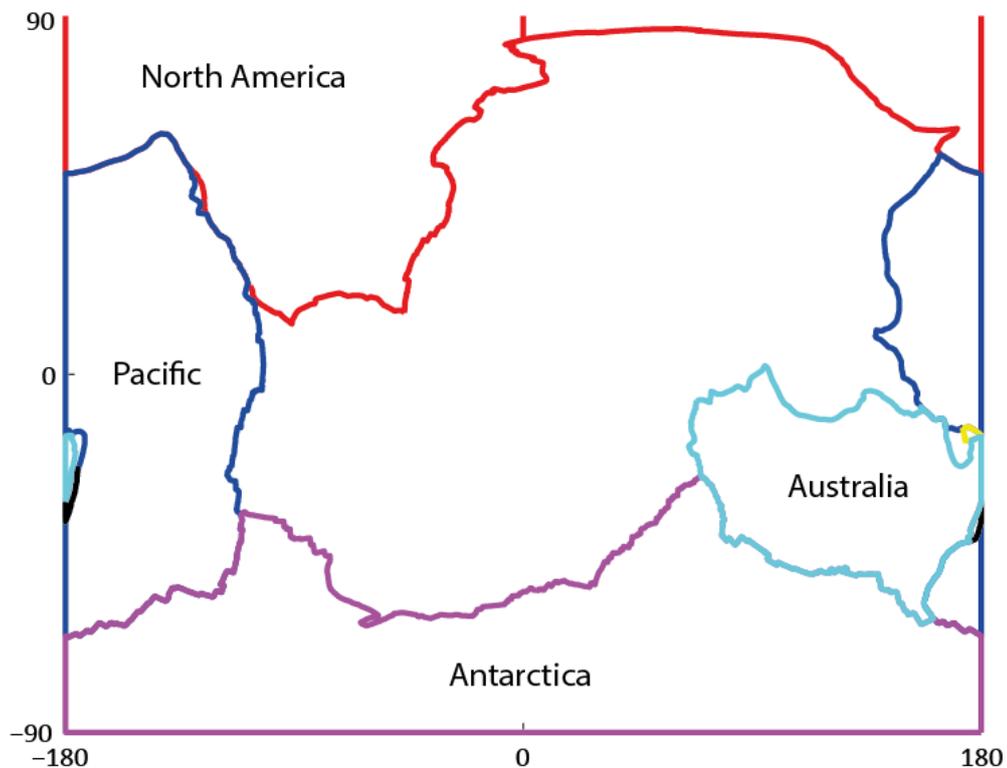


Fig. 8: Plate boundary input file requirements.

Five plate boundaries need to be altered in order to fulfil the requirement not to extend beyond the date line. Therefore artificial boundaries at -180° and 180° respectively are included. The large North American, Australian, Antarctic, and Pacific plates as well as the small Kermadec (black) and Balmoral Reef (yellow) plates are affected by this.

Example

```
AN
-180.00,-90
-0.01,-90.00
-0.01,-54.50
-0.04,-54.68
-0.44,-54.85
...
-178.79,-66.16
-179.20,-65.99
-180.00,-65.82
-180.00,-90
*** end of line segment ***
```

5.3.3 Euler poles (required for comparison with plate motion)

In this file the Euler poles and rotation rate of different tectonic plates are defined. Two files are provided with the script. `bird_euler_poles_geo.txt` is taken from Bird (2003) and specifies the relative rotation of 51 plates to a fixed Pacific plate. `HS3_NUVEL1A.txt` specifies the absolute rotation of the 15 largest plates (Gripp and Gordon, 2002).

The tab delimited file which specifies the plate rotation consists of:

- Plate abbreviation
- Latitude of Euler pole in decimal degree
- Longitude of Euler pole in decimal degree
- Rotation rate in degree per Ma
- Comment, full plate name, etc. Not relevant for the script.

Example

```
AF -43.386 21.136 0.1987 Africa
```

5.3.4 Polygons for data exclusion (optional)

Closed polygons which define areas wherein all data records are disregarded and all grid points are excluded can be defined. This can be useful to remove e.g. known zones of weakness from the analysis. The file format is the same as for the plate boundaries. The polygons are not allowed to extend over the line of 180°E (180) and 180°W (-180). The provided file `PB2002_orogens.txt` includes the orogenetic areas in which the Eulerian plate model is expected to be inaccurate (Bird, 2003).

6 Examples

In this section some examples of analyses of global to local scale conducted with `stress2grid.m` are presented. The only input data which is used is the WSM 2016 database (Heidbach et al., 2016). The settings for the script, the GMT commands used to create the images, as well as the results are presented in the following subsections.

6.1 Global wavelength analysis

The first example shows the worldwide wavelength of the stress pattern (of S_{Hmax}) in kilometres colour coded on a 2.5° grid (Fig. 9). The artefact suppression is set to 400 km and the input stress orientation data is sorted according to its affiliated plates. The orogenic areas according to Bird (2003) are displayed but not excluded. Note that within these orogenic areas mainly short to very short wavelengths are observed.

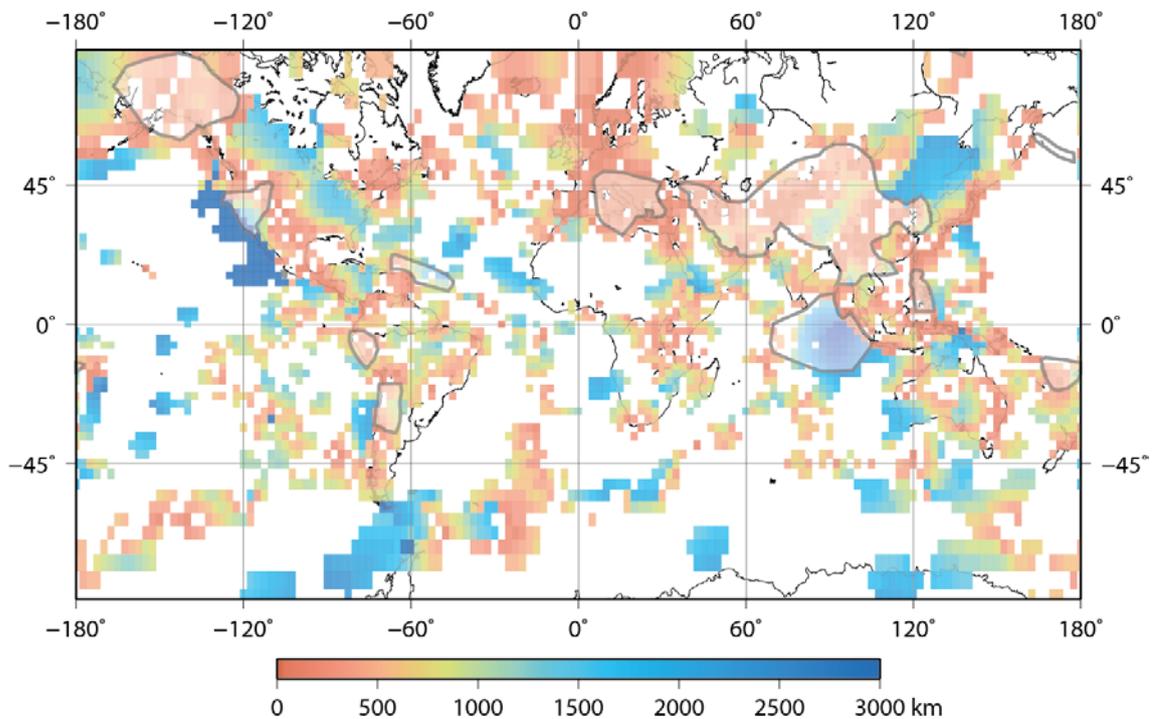


Fig. 9: Global wavelength analysis.

The S_{Hmax} wavelength on displayed in kilometres on a 2.5° grid. The bounded areas are orogenic areas as defined by Bird (2003).

***Stress2grid* input options**

```
input = 'wsm2016.xls';
plate_boundaries = 'plates_Bird_2002_stress2grid.dat';

polygon_exclude = 'no';
exclude_poly = 'PB2002_orogens.txt';

% Grid parameters
gridsize = 2.5;
west = -180;
east = 180;
south = -90;
north = 90;
```

```

% Data processing
% WSM-Quality weighting
% A B C D E
Qual = [ 1/15, 1/20, 1/25, 0, 0 ];
apply_qw = 'yes';

% WSM method weighting (from 0 to 5)
% FM BO DIF HF GF GV OC, rest
methd = [ 4, 5, 5, 4, 5, 4, 2, 1 ];
apply_mw = 'no';
m_exclude = {};

pbe_exclude = 'yes';
pb_dist_exclude = 0;

dist_weight = 'linear';
dist_threshold = 0.1;

% Initialise script functions
R_range = 100:100:3000;
min_data = 3;
threshold = 25;
plate_affil = 'yes';
arte_thres = 400;
compare_pm = 'no';

% Output
output = 'gmt';
arrowlength = 0.1;

% Plots:
plot_output = 'yes';

```

GMT file

```

#!/bin/csh
#-----
set projection = M0/0/20c
set area = -180/180/-70/70
set ps_file = global.ps
set palette = custom.cpt
#-----
xyz2grd wavelength.dat -Ggrid_results.grd -I2.5 -R${area} -:
grd2cpt grid_results.grd -Csubtle.cpt -I -Z -L0/3000 > custom.cpt

grdview grid_results.grd -C${palette} -J${projection} -Ts -R${area} -K
> ${ps_file}
pscoast -J${projection} -R${area} -Dl -W -O -K -A1000 >> ${ps_file}
psxy PB2002_orogens.txt -J${projection} -R${area} -Gwhite -W -L -O -K
>> ${ps_file}
psxy mean_azi.dat -J${projection} -R${area} -O -SVb0/0/0 -G0 -W4 -K -:
>> ${ps_file}
psscale -Dl0c/-1.2c/12c/0.4ch -C${palette} -O -K -B500 >> ${ps_file}
psbasemap -J${projection} -R${area} -Ba60f60g60/a45f45g45WSEN -O >> ${ps_file}
#-----

```

6.2 Absolute Plate motion vs. S_{Hmax} in North America

The second example is of continental size and is set in North America. The difference between the absolute plate motion according to the HS3 NUVEL1A model (Gripp and Gordon, 2002) and the mean orientation of S_{Hmax} are computed here (Fig. 10). To improve readability, the mean S_{Hmax} orientation is displayed as lines on a 2.5° grid while the difference between stress orientation and plate motion is estimated on a 1° grid and displayed as coloured patches (see Fig. 10). This requires running the script twice with two different grid sizes. In the following code the 1° grid example is displayed.

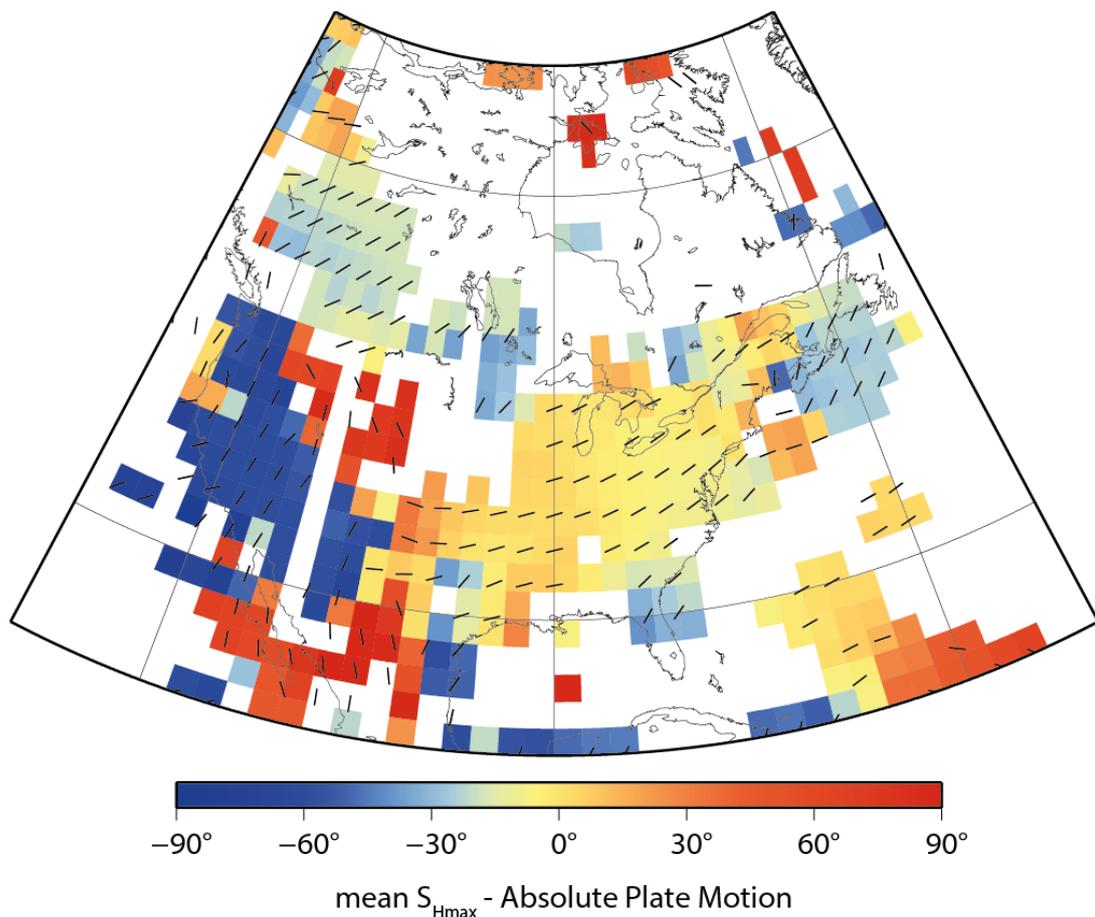


Fig. 10: Deviation between absolute plate motion direction and mean S_{Hmax} orientation. The difference between the mean S_{Hmax} orientation and the absolute plate motion direction is presented by colour coded patches on a 1° grid with the mean S_{Hmax} orientation on a 2.5° grid displayed by lines.

Stress2grid input options

```
input = 'wsm2016.xls';
plate_boundaries = 'plates_Bird_2002_stress2grid.dat';
euler_poles = 'HS3_NUVEL1A.txt';
num_plates = 15;

polygon_exclude = 'no';
exclude_poly = 'PB2002_orogens.txt';
```

```

% Grid parameters
gridsize = 2.5;
west = -145;
east = -45;
south = 20;
north = 80;

% Data processing
% WSM-Quality weighting
% A B C D E
Qual = [ 1/15, 1/20, 1/25, 0, 0 ];
apply_qw = 'yes';

% WSM method weighting (from 0 to 5)
% FM BO DIF HF GF GV OC, rest
methd = [ 4, 5, 5, 4, 5, 4, 2, 1 ];
apply_mw = 'no';
m_exclude = {};

pbe_exclude = 'yes';
pb_dist_exclude = 100;

dist_weight = 'linear';
dist_threshold = 0.1;

% Initialise script functions
R_range = [100,250,500,750,1000,1500,2000,3000];
min_data = 3;
threshold = 25;
plate_affil = 'yes';
arte_thres = 200;
compare_pm = 'yes';

% Output
output = 'gmt';
arrowlength = 0.1 ;

% Plots:
plot_output = 'yes';

```

GMT file

```

#!/bin/csh
#-----
set projection = b-90/45/35/55/1:50000000
set area = -130/-50/20/70
set ps_file = north_america.ps
set palette = custom.cpt
#-----
xyz2grd SHmax-APM.dat -Ggrid_results.grd -I2 -R${area} -F -:
grd2cpt grid_results.grd -Cwavelength_cont.cpt -Z -L-90/90 > custom.cpt

grdview grid_results.grd -C${palette} -J${projection} -R${area} -Ts -K
> ${ps_file}
pscoast -J${projection} -R${area} -Dl -W -O -K -A1000 >> ${ps_file}
psxy mean_azi_2-5.dat -J${projection} -R${area} -O -SVb0/0/0 -G0 -W4 -K -:
>> ${ps_file}
psscale -D8.6c/-1.2c/12c/0.4ch -C${palette} -O -K -B30 >> ${ps_file}
psbasemap -J${projection} -R${area} -Ba0f0g30/a0f0g30wsen -O >> ${ps_file}
#-----

```

6.3 Stress pattern in the Alpine Foreland

This example explores the variable stress field in the European Alpine mountains and surrounding regions. Therefore the mean S_{Hmax} orientation and its variance are computed and displayed on a 0.5° grid (Fig. 11). The results are plotted colour coded (variance) and with lines (mean S_{Hmax}). While the northern foreland basin is tectonically more or less quiet, Italy is tectonically highly active and diverse. This can be seen by the quite low variance values for the mean orientation of S_{Hmax} north of the Alpine mountain range which shows a homogeneous stress pattern. South of the Alps the variance is significantly higher which is also expressed in a higher variability of the mean S_{Hmax} orientations.

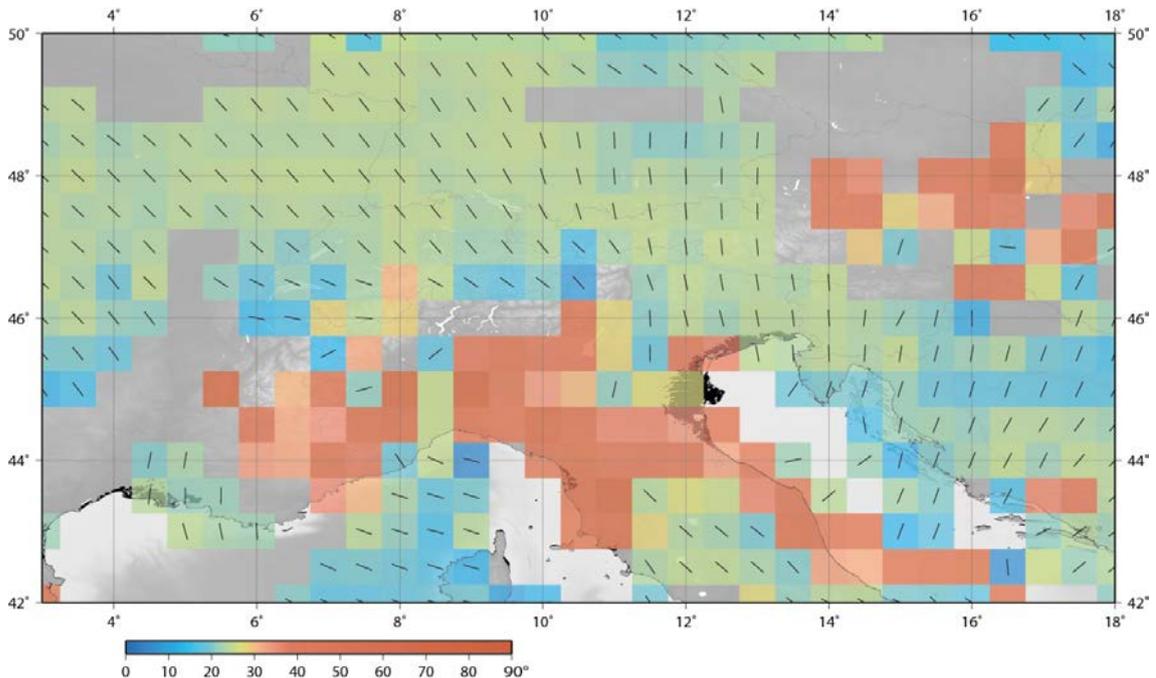


Fig. 11: Visualization of mean S_{Hmax} orientation and variance.

The mean S_{Hmax} orientation is displayed as lines. The variance of mean S_{Hmax} orientation is displayed in degree as colour coded 0.5° with topography (Amante and Eakins, 2009) and bathymetry from the GEBCO_2014 grid, www.gebco.net.

Stress2grid input options

```
input = 'Y:\WSM\WSM2016\SCRIPT\wsm2016.xls';

plate_boundaries = 'plates_Bird_2002_stress2grid.dat';
euler_poles = 'HS3_NUVEL1A.txt';
num_plates = 15;

polygon_exclude = 'no';
exclude_poly = 'PB2002_orogens.txt';

% Grid parameters
gridsize = 0.5;
west = 3;
east = 18;
south = 42;
north = 50;
```

```

% Data processing
% WSM-Quality weighting
% A B C D E
Qual = [ 1/15, 1/20, 1/25, 0, 0 ];
apply_qw = 'yes'; % If a quality weighting should be applied: 'yes'

% WSM method weighting (from 0 to 5)
% FM BO DIF HF GF GV OC, rest
methd = [ 4, 5, 5, 4, 5, 4, 2, 1 ];
apply_mw = 'no'; % If a method weighting should be applied: 'yes'
m_exclude = {};

pbe_exclude = 'yes';
pb_dist_exclude = 100;

dist_weight = 'linear';
dist_threshold = 0.1;

% Initialise script functions
R_range = [50,100,150,200,250,300,350,400];
min_data = 5;
threshold = 25;
plate_affil = 'yes';
arte_thres = 200;
compare_pm = 'no';

% Output
output = 'gmt';
arrowlength = 0.1 ;

% Plots:
plot_output = 'yes';

```

GMT file

The digital elevation model and bathymetry is not included in the provided data but can be downloaded from various sources. The according lines are commented out to ensure the functionality of the script even without topographic data.

```

#!/bin/csh
#-----
set projection = q10.5/1:5000000
set area = 3/18/42/50
set ps_file = alps.ps
#-----
xyz2grd variance.dat -Ggrid_results.grd -I0.5 -R${area} -:
grd2cpt grid_results.grd -Csubtle.cpt -Z -L0/90 > custom.cpt
#grd2cpt topo.grd -Cgrayscale02.cpt -Z -L0/4300 > topo.cpt
#grd2cpt bathy.grd -Cgrayscale02.cpt -Z -L-3000/100 > bathy.cpt

#grdimage bathy.grd -J${projection} -R${area} -Cbathy.cpt -K > ${ps_file}
#pscoast -J${projection} -R${area} -Gc -Df -K -O >> ${ps_file}
#grdimage topo.grd -J${projection} -R${area} -Ctopo.cpt -O -K >> ${ps_file}
#pscoast -J${projection} -R${area} -Q -O -K >> ${ps_file}

grdview grid_results.grd -C${palette} -J${projection} -Ts -R${area} -O -K >> ${ps_file}
pscoast -J${projection} -R${area} -Dh -N1/0.5 -W -O -K -A1000 >> ${ps_file}
psxy mean_azi.dat -J${projection} -R${area} -O -SVb0/0/0 -G0 -W4 -K -: >> ${ps_file}
psscale -D8.6c/-1.2c/12c/0.4ch -C${palette} -O -K -B10 >> ${ps_file}
psbasemap -J${projection} -R${area} -Ba2f2g2/a2f2g2WSEN -O >> ${ps_file}
#-----

```

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